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Reputational preference-based payoff punishment promotes cooperation in spatial social dilemmas

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Abstract. To explore the incentive mechanisms of cooperation in social dilemmas. Motivated by preference for reputation in indirect reciprocity, we propose a reputational preference-based payoff punishment mechanism, under which an individual is punished if his reputation is lower than the average one of direct neighbors and his current game strategy is defection. The cost of punishment is shared by the immediate neighbors. Simulation results show that in spatial prisoner's dilemma game and snowdrift game, the punishment mechanism reduces the fitness of both cooperators and defectors in the micro-perspective, whereas it significantly promotes the evolution of cooperation from the macro view. Furthermore, it is easier for cooperation to emerge and sustain in snowdrift game, and compared to prisoner's dilemma game, within the most range of model parameters, the system is in the coexistence state of cooperators and defectors.

1 Introduction

"How cooperation evolves" is listed as one of the top 25 most important scientific puzzles by Science [1]. Comprehending the occurrence and evolution of cooperation among selfish individuals denotes one of the crucial challenges in behavioral sciences and evolutionary biology [2–6]. Evolutionary game theory [7–9] supplies an important approach to uncover the problem of cooperation. Over the past few decades, diverse game models have been proposed to study the origin and evolution of cooperation [10–12], including prisoner's dilemma game (PDG) [13–15], snowdrift game (SDG) [16–18] and public goods game (PGG) [19–21]. PDG and SDG have been widely used to investigate the evolution of cooperative behavior, in which each player has a choice between two game strategy, cooperation (C) or defection (D). In 2006, Nowak proposed five rules for the evolution of cooperation [22], including indirect reciprocity, direct reciprocity, kin selection, network reciprocity and group selection. It was previously found that reputation fuels the engines of indirect reciprocity [22]. Moreover, it has been revealed that people generally take reputational information into account in social interactions [23–25]. As a result, people are presumably willing to provide help to individuals with good reputation, but may refuse to help others having bad ones. Besides, repeated games generally involve reputation, if players have cognitive abilities [26].

Inspired by spatial games [16,27], evolutionary games on graphs is first proposed by Nowak and May [28], considering that individuals situated on the nodes of a network, and the edges between nodes representing game interactions between them. Moreover, over the past decades, a variety of network models have been explored as a metaphor of population structure, including random networks [12], scale-free networks [29–31] and small-world networks [32–34].

In evolutionary games on graphs [28], defection is fostered by natural selection [15]. Hence, an incentive mechanism is needed for the emergence of cooperative behavior. In real world social systems, to sustain cooperation in the population, individuals are inclined to punish other's defective behavior. Previous results have shown that cooperation may arise if free riders are punished [35,36]. A large amount of literature have studied the impacts of punishment on the evolution of cooperation from a diverse perspective [37–49]. Wang et al. [37] conducted an empirical research on the basis of public goods game. They found that in the presence of a costly punishment opportunity almost complete cooperation can be achieved and maintained. In particular, Fehr and Gächter demonstrated that the altruistic punishment of defectors is an essential incentive for the promotion of cooperation [38]. By extending the experiment of Fehr and Gachter, Masclet et al. discovered that the average level of earnings and contributions can be increased if the possibility of non-monetary punishment is existed [39]. Andreoni et al. [40] explored

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the demands for punishments and rewards, as well as their effects on cooperation. They revealed that when devising incentive systems, it is important that both reward and punishment be present. Moreover, Helbing and Szolnoki et al. [41,42] investigated the evolution of cooperation based on public goods games, taking punishing defectors (PD) or punishing cooperators (PC) as an additional strategy. The results suggest that cooperation may spread under their mechanism. Notably, Szolnoki et al. [43] studied the effectiveness of pool punishment in spatial public goods games. They found that the impact of institutionalized punishment on cooperation evolution is greatly different from that of peer punishment. Szolnoki and Szab et al. [44] initially compared the efficiency of individual (peer) and institutional (pool) punishments based on public goods game. Their results indicate that peer punishers are more efficient in eliminating "tragedy of the commons" when all players choose defective strategy. Szolnoki and Perc [45] explored the efficiency of conditional punishment in facilitating public cooperation when compared to unconditional punishment. They have shown that when the punishment is costly, conditional punishment is more effective in deterring defectors, which makes unconditional punishers become extinction. Chen et al. [46] investigated how altruistic punishers evolve in public goods game. They demonstrated that sharing a costly altruistic prosocial punishment, either probabilistic or periodic, solves the problem of costly punishment. Besides, Perc and Szolnoki [47] studied the benefits and pitfalls of heterogeneous punishment in evolutionary inspection games. The benefit is that the crime evolution is controlled and is unable to dominate the whole population. The disadvantage is that punishment creates contexts that favor cyclic dominance, which prohibits the abolition of crime. Chen et al. [48] uncovered the punishment and inspection for governing the commons in a feedback-evolving game. The results indicate that cooperators should focus on the growing capacity of extendable resources, which is also important beside a subtly modified punishment. Additionally, Szolnoki and Perc [49] detected how second-order free-riding on antisocial punishment reinstates the efficiency of prosocial punishment. They revealed that when the synergistic impacts are high enough to support cooperation on the basis of network reciprocity alone, public cooperation will not be prevented by antisocial punishment.

In this work, our focus is to investigate the effects of reputational preference-based payoff punishment on the emergence and evolution of cooperation in PDG and SDG. The main difference between our work and the previous studies is that in our model, the punishment decision is not only associated with an individual's current game strategy, but is also closely related to his cooperative performance in the past games. More precisely, one's reputation records his cooperative history, which is a crucial mechanism for evaluating his cooperative willingness in the future. Furthermore, the point of punishment is to promote an individual's cooperative willingness in the future, which benefits his direct interaction partners. Thus, one's immediate neighbors should share the cost of his punishment. Results from numerical simulations show that the payoff punishment mechanism greatly facilitates the emergence and survivability of cooperation. Moreover, compared with prisoner's dilemma game, it is easier for cooperators to emerge and survive in snowdrift game.

The rest of this paper is organized as follows. The materials and methods are given in Sect. 2. The simulation results and discussions are presented in Sect. 3. Conclusions are drawn in Sect. 4.

2 Materials and Methods

In the current study, we take into account the classical two-strategy PDG and SDG. Initially, 50% individuals are designated to be randomly distributed cooperators. It is assumed that the number of nodes and edges of the network remain constant throughout the game process. Besides, we assume that individuals have local information about reputations. Furthermore, individuals are assumed to have certain cognitive abilities and social attributes, such as memory ability, reputational preference and punishment ability.

Game players are located on a square lattice of size $L \times L$ with periodic boundary conditions, each individual plays repeated PDG or SDG with four fixed immediate neighbors. Consistent with the previous studies [27,50], the model parameters for PDG is set to be $R = 1, P = S = 0$ and $T = b$ $(1 < b < 2)$. As a result, the payoff matrix $\boldsymbol{M_{PDG}}$ of PDG has single parameter b [27,51], representing the temptation to defect,

$$\boldsymbol{M_{PDG}} = \begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix}, \tag{1}$$

where the larger the value of b, the more profit an individual can obtain by selecting defective strategy.

The payoff matrix $\boldsymbol{M_{SDG}}$ of SDG is as following,

$$\boldsymbol{M_{SDG}} = \begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1-\rho/2 & 1-\rho \\ 1 & 0 \end{pmatrix}, \tag{2}$$

where parameter $\rho \in (0, 1)$ represents the cost-to-benefit ratio of mutual cooperation.

The game is simulated in accordance with the Monte Carlo simulation (MCS), which is composed of the following elementary steps. It is noteworthy that every full MCS step involves each player.

Firstly, at each time step, the total payoff P_x for every player is the accumulation of payoffs gained from playing PD or SD games with immediate neighbors, which can be described as,

$$P_x = \sum_{y \in \Omega_x} \boldsymbol{s_x}^T M \boldsymbol{s_y}, \tag{3}$$

where Ω_x represents the neighborhood set of player x. The strategy of x and his neighbor y is denoted by $\boldsymbol{s_x}$ and $\boldsymbol{s_y}$, respectively.

The times player x cooperates with immediate neighbors in the past games is defined as his reputation $R_x(t)$ [26], which reads,

$$R_x(t) = \begin{cases} R_x(t-1) + \Delta R, \; if \; \boldsymbol{s_x} = C \\ R_x(t-1), \qquad\quad if \; \boldsymbol{s_x} = D \end{cases}, \tag{4}$$

where ΔR denotes the reputation score player x obtains through a single game step. Parameter ΔR=1 if x cooperates at time t, otherwise ΔR=0. For cooperators and defectors, the initial reputation score is set to be 1 and 0, respectively.

Secondly, every game player attains a reputation score in accordance with Eq. 4. Then for player x, the average reputation score of his nearest neighbors can be calculated as,

$$\overline{R_{\Omega}^{x}} = \frac{\sum_{y=1}^{k_x} R_y}{k_x}, \tag{5}$$

where parameter k_x denotes the full number of individual x's direct neighbors.

In most real-world situations, reputation is normally taken into consideration by people in social interactions [23–25]. In our model, the punishment decision is not only depend on an individual's current game strategy, but also the number of times he cooperates in the past games, which is recorded by his reputation. This decision-making mechanism protects players from punishment when they occasionally choose defection because of irrational factors, which is consistent with our daily-life experience. Most importantly, punishment is normally costly. If one's reputation score is smaller than the average one of nearest neighbors, it implies that in the past games, his cooperative willingness is lower than the average one of neighbors. The essence of punishment is to promote one's cooperative willingness in the future, which is beneficial for his direct neighbors. That's why one's immediate neighbors should share the cost of his punishment, then the fitness of player x and his nearest neighbor y can be defined as Eqs. 6 and 7, respectively,

$$F_x = \begin{cases} P_x - \delta, \; if \; R_x < \overline{R_{\Omega}^{x}} \; and \; \boldsymbol{s_x} = D \\ P_x, \; otherwise, \end{cases} \tag{6}$$

$$F_y = \begin{cases} P_y - \delta/k_x, \; if \; R_x < \overline{R_{\Omega}^{x}} \; and \; \boldsymbol{s_x} = D \\ P_y, \; otherwise \end{cases}, y \in \Omega_x, \tag{7}$$

where parameter $\delta \in [0,1]$ denotes the punishment fine, representing the influence intensity of payoff punishment on fitness. Larger values of δ represent greater effect, which also means higher punishment, and smaller ones imply the reverse. The impact of payoff punishment mechanism is not taken into consideration and the model degenerates to the traditional PDG or SDG if $\delta = 0$.

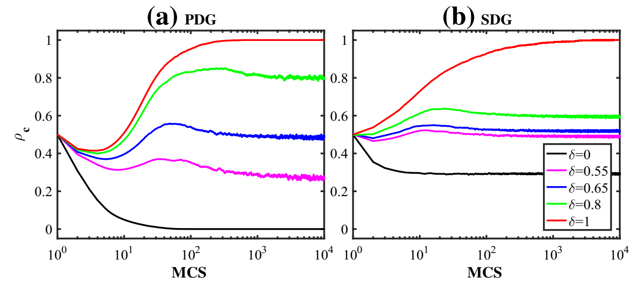

Fig. 1 Fraction of cooperators ρ_c at each time step under different values of punishment fine δ (a) PDG; (b) SDG. Other parameters setup is $K = 0.1$, $b = 1.2$ and $\rho = 0.7$

Thirdly, at each MCS step, every player has a chance once on average to update fitness according to Eq. 6.

Finally, at every game iteration, each player has an opportunity once on average to learn from an immediate neighbor, who is randomly chosen with a probability given by the Fermi Function [50]:

$$P(\boldsymbol{s_x} \leftarrow \boldsymbol{s_y}) = \frac{1}{1 + \exp[(F_x - F_y)/K]}, \tag{8}$$

where parameter $K \in [0, +\infty]$ represents the intensity of selection, $K \to 0$ denotes the deterministic imitation dynamics. A player makes a decision randomly when $K \to +\infty$. Consistent with previous works, we set $K = 0.1$ in our model.

The numerical results were obtained on a square lattice of size 50×50. The whole number of simulation steps is set to be 1×10^4. The cooperative behavior is characterized by the average percentage of cooperators ρ_c in an evolutionary stable state, which was computed within the last 10^3 full MCS steps. Besides, to reduce the influence of disturbances, we run over up to 20 independent simulations for all data.

3 Results and discussions

3.1 Fraction of cooperators over time evolution

We start the simulation by first inspecting the fraction of cooperators under distinct punishment fine at different MCS. As is shown in Fig. 1, in the traditional PDG ($\delta = 0$), natural selection favors defection, cooperation rapidly decreases as time going and finally becomes extinction (the black line in panel (a)). However, once the payoff punishment mechanism is introduced, the cooperation level in the entire population is significantly promoted. When punishment fine δ takes the maximum value one, cooperators are able to occupy the whole system in a short time. In contrast, in the traditional SDG, the cooperation level maintains approximately at 0.3 when δ=0. The key factor of the result

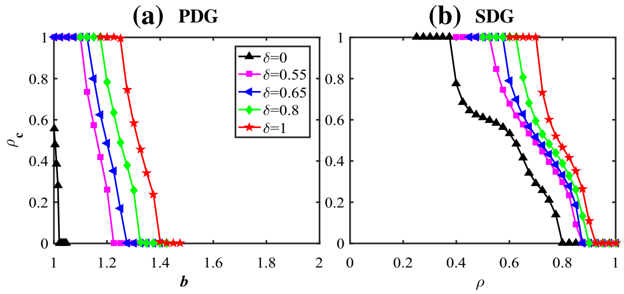

Fig. 2 Fraction of cooperators ρ_c as a function of temptation to defect b or cost-to-benefit ratio ρ under distinct values of punishment fine δ (**a**) PDG; (**b**) SDG. Other parameter is set to be $K = 0.1$

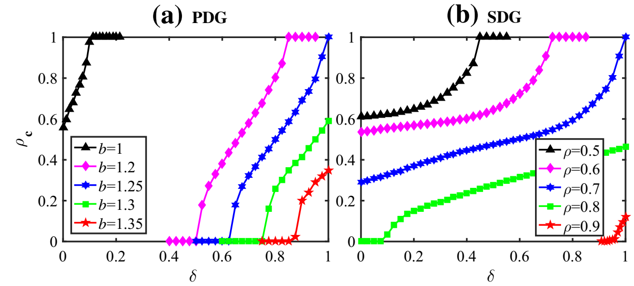

Fig. 3 Fraction of cooperators ρ_c as a function of punishment fine δ for distinct temptation to defect b or cost-to-benefit ratio ρ values (**a**) PDG; (**b**) SDG. Other parameter is set to be $K = 0.1$

is that in SDG, the Nash equilibrium is (C, D) and (D, C). That is to say, the cooperative behavior will never becoming extinction in the system. Most importantly, in snowdrift game, the proportion of cooperators also displays a steady increase with the rise of punishment fine δ in SDG.

3.2 Effects of the temptation to defect b and the cost-to-benefit ratio ρ on the evolution of cooperation

In Fig. 2, we unveil the relationship between cooperators' frequency and temptation to defect b under different punishment fine δ. Notably, under such reputational preference-based payoff punishment mechanism, cooperation level dramatically drops with increasing b in prisoner's dilemma game. Moreover, for fixed δ, firstly a critical value for b can be observed, above which the system changes from full cooperation (C) to the coexistence state of cooperators and defectors (C+D). Hereafter, a threshold value of b where cooperation becomes extinction can be seen. It is worth stressing that both of the threshold rises with the increase of punishment fine δ. These results suggest that with increasing δ, the sustainability of cooperation is significantly promoted, which indicates that the punishment mechanism favors the maintenance of cooperation in PDG. In snowdrift game, the situation is similar to that in PDG. The main difference is that the critical value of cost-to-benefit ratio ρ is much higher than that of temptation to defect b. It is noteworthy that compared with PDG, the coexistence state of C+D lasts longer in SDG, since it provides a more favorable context for the survivability of cooperation.

3.3 Impacts of the punishment fine δ on the evolution of cooperation

In social dilemmas, greater punishment fine strengthens the severity of punishment and influences the game behavior of players. Thus, in Fig. 3, we examine the impacts of punishment fine δ on the evolution of cooperation, as well as the relationship between δ and cooperators' frequency under different b and ρ. Clearly, when temptation to defect b and cost-to-benefit ratio ρ is fixed, cooperator's density monotonically rises with increasing δ, and the larger b is, the greater the threshold value of δ is. The major cause of the results is that under the payoff punishment mechanism, cooperators becomes evolutionarily competitive both in PDG and SDG. Most importantly, it is much easier for cooperation to emerge and maintain in SDG. Taking an example, when the payoff punishment mechanism is absent ($\delta = 0$) and the cost-benefit ratio $\rho \geq 0.5$, cooperators are able to survive in snowdrift game. It is worth noting that the population is in the coexistence state of cooperators and defectors for a large range of parameter ρ.

3.4 Strategy distribution over time evolution in PDG

In prisoner's dilemma game, the only Nash equilibrium is (D, D), which indicates that compared to snowdrift game, it is harder for cooperation to evolve in PDG. Therefore, in Fig. 4, we exhibit the characteristic snapshots between cooperators and defectors in PDG in a microscopic perspective. In the first row of panels, the value of punishment fine is relatively small ($\delta = 0.3$), which implicates that the effect of payoff punishment mechanism on individuals' strategy behavior is little. In such a situation, originally, cooperators and defectors coexist with equal percentage at $t = 0$, and the randomly distributed cooperators are unable to agglomerate giant cooperative clusters, which indicates that it is hard for cooperators to survive. Nevertheless, the disadvantageous situation for cooperators is drastically improved when parameter δ is increased (the second line of panels). In such a case, although cooperators can only occupy the minority of the population, but they achieve coexistence with defectors. These findings imply that when the intensity of punishment is promoted, the persistence of cooperation is facilitated. Then with punishment fine is further increased from 0.55 to 0.8 (the third line of panels), giant cooperative clusters can be found at $t = 50$. Finally, when parameter δ takes the maximum value one, cooperators can gradually agglomerate and form compact clusters to defend

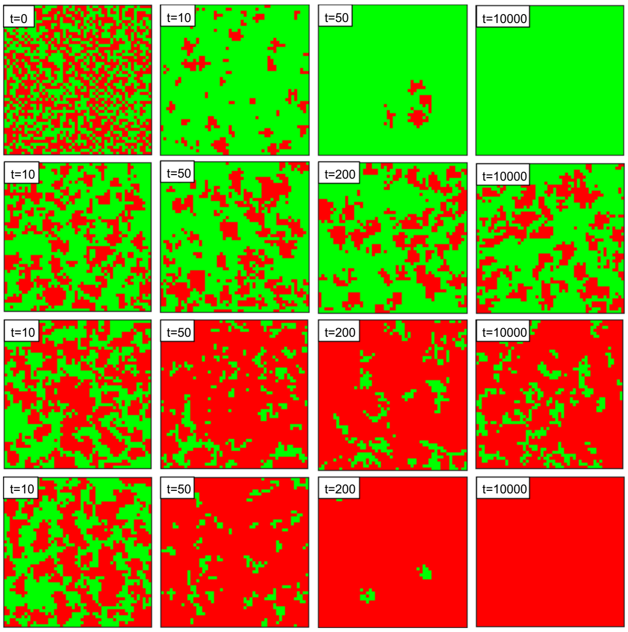

Fig. 4 Characteristic snapshots between cooperators (red) and defectors (green) at different MCS in PDG. From top to bottom, punishment fine is set to be $\delta = 0.3$; $\delta = 0.55$; $\delta = 0.8$; $\delta = 1$, respectively. Other parameters are set to be $K = 0.1$ and $b = 1.2$

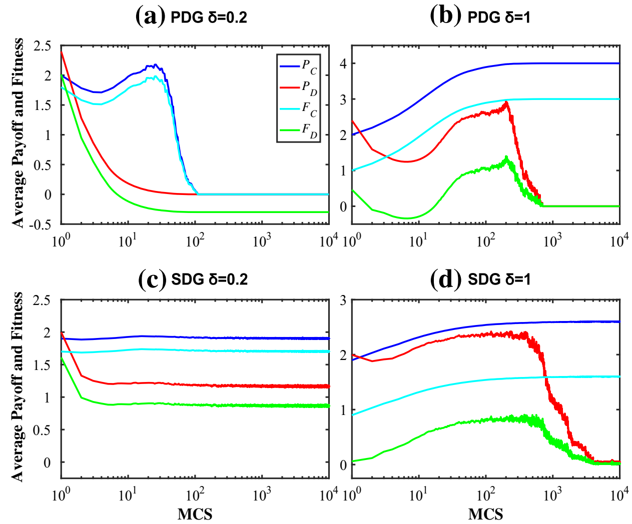

Fig. 5 Average payoff and fitness of cooperators (P_C, F_C) and defectors (P_D, F_D) at each MCS time step. From panel (**a**)–(**d**), punishment fine δ is set to be (**a**) PDG, $\delta = 0.2$; (**b**) PDG, $\delta = 1$; (**c**) SDG, $\delta = 0.2$; (**d**) SDG, $\delta = 1$, respectively. Other parameters are set to be $K = 0.1$, $b = 1.2$ and $\rho = 0.7$

the invasion of defectors. That is the main reason for the promotion of cooperation.

3.5 Influence of the punishment mechanism on the average payoff and fitness

Finally, we investigate the effects of costly punishment on the average payoff and fitness of players in a microcosmic view. Notably, in prisoner's dilemma game, when the punishment fine is small, the average payoff of defectors rapidly drop to zero at $\delta = 0.2$ [panel (a)]. Since defective players share the cost of their direct neighbors' punishment, defectors' average fitness is lower than zero level when the system reaching evolutionary state. In such a situation, the average payoff and fitness of cooperators ultimately decrease to zero, indicating that the punishment mechanism is insufficient to support the maintenance of cooperation. However, it can be observed that both P_C and F_C are greatly increased at $\delta = 1$ [panel (b)], which implies that the survivability of cooperation is promoted when the punishment fine is risen. Nevertheless, since the punishment is costly and all nearest neighbors share the cost, thus FC is smaller than PC. In such a case ($\delta = 1$), P_D and F_D finally drop to zero, indicating that the population achieves full cooperation in the end. In snowdrift game, the primary difference is that the system is already in the coexistence of cooperators and defectors at $= 0.2$. Furthermore, the coexistence state lasts longer than that in PDG when $\delta = 1$, implying that it is easier for cooperators to survive in SDG.

4 Conclusions

To summarize, in order to explore the evolution of cooperation, we proposed a reputational preference-based payoff punishment mechanism, in which the punishment decision is not only relies on one's current game strategy, but is also strongly associated with his cooperative performance in the past games. Most importantly, the cost of punishment is shared by an individual's immediate neighbors. A considerable amount of literature have studied the impacts of punishment on the sustainability of cooperation [43–47], which mainly focus on pool and peer punishment [43,44], conditional and unconditional punishment [45], altruistic punishment [46], heterogeneous punishment [47], and public goods game. In the present work, our aim is to identify the effects of costly payoff punishment on the evolution of cooperation. According to the definition of reputation [26], the number of times an individual cooperates in the past games is recorded by his reputation. The higher the reputation, the lower the uncertainty of cooperation. In other words, when a player's reputation is smaller than the average one of his direct neighbors, it indicates that his willingness for cooperation is lower than the average one of neighbors. The primary aim of punishment is to promote one's cooperative willingness in the future, which provides a potential profitable partnership for his neighbors. Hence, the cost of punishment should be shared by one's immediate neighbors. Simulations are carried out in prisoner's dilemma game and snowdrift game. Our findings reveal that compared to traditional PDG and SDG, the payoff punishment mechanism significantly facilitates the evolution of cooperation, although it reduces the fitness of cooperators and defectors from the micro view. Compared with PDG, it is more easy for cooperation to emerge and maintain in snowdrift game. The system is in a coexistence state of cooperators and defectors within the most range of punishment fine in SDG. The present results may provide a new perspective in establishing incentive mechanisms of cooperative behavior. One of the future investigations is to explore how to maintain cooperation after the payoff punishment mechanism is turned off after the system reached an evolutionary state.

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Author contributions

Conceptualization, XW; methodology, PX and S-TD; software, XW and G-HY; validation, S-TD and H-YP; writing-original draft, XW; writing-review and editing, H-YP and PX. All authors have read and agreed to the published version of the manuscript.

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