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Khadija Khatun
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Shen Chen
Faculty of Engineering Sciences, Kyushu University

Tanimoto, Jun
Faculty of Engineering Sciences, Kyushu University

https://doi.org/10.5109/7395538

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 11, pp.337-342, 2025-10-30. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

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Khadija Khatun[1,3], Shen Chen[2] and Jun Tanimoto[2]
[1]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-Koen, Kasuga-shi, Fukuoka 816-8580, Japan
[2]Faculty of Engineering Sciences, Kyushu University, Kasuga-Koen, Kasuga-shi, Fukuoka 816-8580, Japan
[3]Department of Applied Mathematics, University of Dhaka, Dhaka-1000, Bangladesh
khadija.apm@du.ac.bd

Abstract: *Reciprocity and repeated games have proven essential in the examination of the genesis of human cooperation. Population structure enhances reciprocity-based cooperation among equals, yet the effects of power asymmetry within these structured interactions remain unexplored. We explore the asymmetric power of individuals in an infinite population mixing with a positive assortment. We observed that power asymmetry destabilizes and reduces the level of cooperation in the structured population. These results have important implications for institutional design, suggesting that organizations and communities seeking to foster cooperation should implement mechanisms that mitigate power imbalances, as inequality in influence or resources fundamentally undermines collaborative potential even in otherwise cooperation-promoting network structures.*

Keywords: Population structure; Direct reciprocity, Power asymmetry

1. INTRODUCTION

Understanding how cooperation emerges and persists among self-interested individuals constitutes one of the most enduring challenges in evolutionary game theory, with profound implications spanning biology, economics, and the social sciences [1], [2]. This puzzle is particularly compelling because cooperation violates the fundamental principle of natural selection, which favors strategies that maximize individual fitness, even at the expense of others.

One of the most powerful mechanisms proposed to resolve this paradox is reciprocity, wherein individuals condition their behavior on the actions of others [3], [4]. Through repeated interactions, reciprocity creates opportunities for conditional strategies to flourish. The classic Tit-for-Tat strategy, for example, rewards cooperative partners while punishing defectors, transforming short-term costs into long-term gains [5]. These reciprocal dynamics are reinforced when individuals expect to meet again in the future—an effect known as the "shadow of the future."

The structure of the population in which these interactions occur provides another crucial dimension influencing the evolution of cooperation. In structured populations—defined by spatial networks, social groups, or assortative matching—interactions are non-random, allowing cooperators to cluster together [6], [7]. Such positive assortment increases the likelihood that cooperators interact with one another, thereby shielding themselves from defectors and creating evolutionary "refugia" where cooperation can be sustained [8], [9].

Despite the theoretical strengths of reciprocity and population structure, both mechanisms often assume symmetry among interacting individuals. However, social, and biological systems are rife with power asymmetries. These occur when individuals systematically differ in their ability to influence outcomes or extract rewards, even when contributing similar efforts [10]–[12]. From corporate hierarchies to political institutions, dominant individuals often secure disproportionate benefits, raising fundamental questions about the stability of cooperation in unequal settings.

Recent theoretical work by Colnaghi et al. [13] has directly addressed this issue within the framework of evolutionary game theory. Using models of repeated Prisoner's Dilemmas in well-mixed populations, they show that even modest asymmetries in benefit distribution can destabilize reciprocity-based cooperation. Specifically, when high-power individuals receive greater benefits from the same cooperative acts as low-power individuals, while costs remain equal, the incentive to reciprocate diminishes. As the degree of asymmetry increases, the parameter space that supports stable cooperation shrinks rapidly, often collapsing entirely under high inequality.

These findings align with broader theoretical and empirical literature highlighting the importance of fairness, norm enforcement, and institutional design in supporting cooperation. Fehr and Fischbacher [14] argue that altruistic behavior is heavily influenced by perceived fairness and expectations of norm enforcement. Gintis et al. [15] provide evidence across disciplines that moral sentiments and institutional arrangements are central to maintaining cooperative norms. In a similar vein, Henrich et al. [16] demonstrate through cross-cultural experiments that cooperative behavior is deeply sensitive to contextual norms of fairness. Theoretical perspectives from Binmore [17] and Kandori [18] further emphasize the role of social justice, reputational dynamics, and community enforcement in stabilizing cooperation, particularly in repeated strategic interactions.

Together, these perspectives suggest that cooperation is not solely governed by strategic incentives or network topology but is equally shaped by the broader moral and institutional contexts in which individuals operate. This highlights the need for formal models that can accommodate structural inequality as a central feature of social environments.

While Colnaghi et al.'s findings mark a critical step forward, they primarily focus on well-mixed populations,

where interaction partners are drawn randomly. This leaves open an important theoretical question: Can population structure and positive assortment mitigate the disruptive effects of power asymmetry? In other words, does the presence of structured interactions, which has been shown to promote cooperation in symmetric settings, retain its efficacy under conditions of unequal power?

To address this gap, we develop a novel model based on an asymmetric iterated Prisoner's Dilemma, where power differences are represented as heterogeneous benefit structures. Specifically, high-power, and low-power individuals provide different levels of benefit to their partners when cooperating, while maintaining symmetric cost structures. By embedding these asymmetric interactions into a positively assorted population, our framework isolates the specific effects of power asymmetry on the evolution of reciprocal cooperation, while controlling for other potential confounds.

To address this gap, we develop a novel model based on an asymmetric iterated Prisoner's Dilemma, where power differences are represented as heterogeneous benefit structures. Specifically, high-power, and low-power individuals provide different levels of benefit to their partners during cooperation, while incurring identical costs. By embedding these asymmetric interactions within a positively assortative structured population, our framework allows us to isolate the specific effects of power asymmetry on the evolution of reciprocal cooperation, independent of other confounding factors. Through this approach, we observe that power asymmetry not only reduces the level of cooperation but actively destabilizes it, even in structured populations traditionally known to support cooperative behavior. This finding highlights the fragility of cooperation in the face of inequality and emphasizes the need to consider power dynamics as a fundamental factor in models of cooperative evolution.

2. MODEL

2.1 Game dynamics

We consider a population of individuals who differ in power levels, interacting through an iterated, asymmetric simultaneous donation game. In the standard symmetric version of this game, everyone has the option to incur a cost c to provide a benefit b to their social partner [2]. In the asymmetric extension of this model, we introduce power-dependent variation in the benefit an individual can contribute, such that individuals with higher power can provide greater benefits than those with lower power. This modification leads to a bi-matrix game formulation [6], where the payoffs for everyone are determined by the relative power of the interacting individuals, creating an asymmetry in the interaction dynamics. The payoff matrix is defined as [13]:

		High power	
Low		C	D
power	C	$b_H - c, b_L - c$	$b_H, -c$
	D	$-c, b_L$	$0, 0$

Where the benefit of a high-power individual is $b_H = (1+\alpha)b$, and the benefit of a low-power individual is $b_L = (1-\alpha)$; α is the degree of asymmetry with $0 \leq \alpha \leq 1$. C is cooperation and D is defection.

To examine the impact of population structure, we relax the assumption of purely random interactions. Instead, individuals are matched according to a probabilistic assortment rule. Specifically, an individual employing the strategy S is paired with another individual using the same strategy with probability $\beta + (1-\beta)x_S$, where x_S is the frequency of strategy S in the population, and $\beta \in [0,1]$ is the assortment parameter [19]. This parameter governs the degree of non-random matching: when $\beta = 0$, interactions are entirely random, while $\beta = 1$ corresponds to a perfect assortment by strategy. Importantly, β also represents the probability that a rare mutant will interact with another individual expressing the same strategy, making it a key metric for analyzing the evolutionary stability of strategies under structured interactions.

Additionally, to investigate the role of direct reciprocity, we assume that repeated interactions occur with a probability of δ, representing the likelihood of continuing to engage with the same partner across rounds. We have considered an infinite strategy space: $ALLD$, $ALLC$ and conditional cooperation (defection) strategies such X is not always defective (cooperate at least once in repetition), $GRIM$, and Y is not always cooperative (defects at least once in repetition), where any strategy encodable by a finite state automaton represents a possible mutant.

2.2 The existence and stability of equilibria

To analyze stability, we will apply three well-known concepts: equilibrium, evolutionarily stable strategy (ESS), and neutrally stable strategy (NSS). The strategy S can be defined with the following definitions:

(a) An equilibrium, if for every strategy S' $\beta\,\Pi(S',S') + (1-\beta)\Pi(S',S) \leq \Pi(S,S)$, where $\Pi(S,S)$ is the average payoff of the symmetric strategy S.

(a) Evolutionary stable strategy (ESS), for $S \neq S'$,
(i) $\beta\,\Pi(S',S') + (1-\beta)\,\Pi(S',S) \leq \Pi(S,S)$,
(ii) if inequality (i) becomes equal, then $\Pi(S',S') - \Pi(S',S) < \Pi(S,S') - \Pi(S,S)$, and

(b) Neutrally stable strategy (NSS), for $S \neq S'$,
(i) $\beta\,\Pi(S',S') + (1-\beta)\,\Pi(S',S) \leq \Pi(S,S)$,
(ii) if inequality (i) becomes equal, then $\Pi(S',S') - \Pi(S',S) \leq \Pi(S,S') - \Pi(S,S)$.

In repetition, at first, we consider the interaction between $ALLD$ and X, where $ALLD$ play a D every round. If two $ALLD$ one from high and another from low power population meet each other, then the game looks:

$ALLD$ D D D …
$ALLD$ D D D …

Therefore, it receives a payoff 0 at every round. So the average payoff of $ALLD$ is $\Pi(ALLD_H, ALLD_L) = \Pi(ALLD_L, ALLD_H) = 0$.

The strategy X does not always play defection if it meets itself. Therefore, it plays C at least once in an infinite round (at nth round say).

X D … C QQQ …
X D … C QQQ …

If all the Q marks were C's, they will come in pairs of C or a pair of D. In a repeated game, the payoff of X_H is $\delta^n\{(1+\alpha)b - c\}$ and payoff of X_L is $\delta^n\{(1-\alpha)b -$

$c\}$. Hence, the maximum payoff of playing X between a high and a low individual will be $\Pi(X_H,\ X_L) \le \delta^n\{(1+\alpha)b-c\}$ and $\Pi(X_L,\ X_H) \le \delta^n\{(1-\alpha)b-c\}$.
When, X meet with $ALLD$, the game looks like:

X	D	...	C	QQQ ...
$ALLD$	D	...	D	DDD ...

In this scenario, the best choice for X is playing C at most once, and the worst choice is playing C for all Q marks. Therefore, the average payoff of high and low populations will be $\Pi(X_H,\ ALLD_L) \le (1-\delta)\delta^n\ (-c)$, $\Pi(ALLD_H, X_L) \ge (1-\delta)\ \delta^n\ (1+\alpha)b$, and $\Pi(X_L,\ ALLD_H) \le (1-\delta)\delta^n\ (-c)$, $\Pi(ALLD_L, X_H) \ge (1-\delta)\delta^n\ (1-\alpha)b$.
In a high-powered population:
$\beta\ \Pi(X_H, X_L) + (1-\beta)\Pi(X_H, ALLD_L) \le \Pi(ALLD_H, ALLD_L)$, so that $\beta \le \frac{-c+b\ \delta+\alpha\ b\ \delta}{-b-\alpha\ b+b\ \delta+\alpha\ b\ \delta}$, hence $ALLD_H$ is an ESS.
In a low population:
$\beta\ \Pi(X_L, X_H) + (1-\beta)\Pi(X_L, ALLD_H) \le \Pi(ALLD_L, ALLD_H)$, so that $\beta \le \frac{c-b\ \delta+\alpha\ b\ \delta}{b-\alpha\ b-b\ \delta+\alpha\ b\ \delta}$, hence $ALLD_L$ is an ESS.
Theorem 1: In the whole population, $ALLD$ will be an ESS, if
$\beta \le Max(\frac{-c+b\ \delta+\alpha\ b\ \delta}{-b-\alpha\ b+b\ \delta+\alpha\ b\ \delta},\ \frac{c-b\ \delta+\alpha\ b\ \delta}{b-\alpha\ b-b\ \delta+\alpha\ b\ \delta})$.
Similarly, for whole population, we can prove the following theorems:
Theorem 2: X is not an NE, if
$\beta \le Max\left(\frac{c-b\delta-b\alpha\delta}{b+b\alpha-2b\delta+c\delta-2b\alpha\delta}, \frac{c-b\delta+b\alpha\delta}{b-b\alpha-2b\delta+c\delta+2b\alpha\delta}\right)$.
Theorem 3: $ALLD$ is not NE and $GRIM$ is NSS, if
$Max\left(\frac{-c+c\delta}{-b-b\alpha+c\delta}, \frac{-c+c\delta}{-b+b\alpha+c\delta}\right) \le \beta \le Max(\frac{c}{b-b\alpha-b\delta+c\delta+b\alpha\delta}, \frac{c}{b+b\alpha-b\delta+c\delta-b\alpha\delta})$.
Theorem 4: Y can not be an NE,
if $\beta \ge Max(\frac{c+b\delta-c\delta+b\alpha\delta}{b+b\alpha}, \frac{-c-b\delta+c\delta+b\alpha\delta}{-b+b\alpha})$.
Theorem 5: $ALLC$ is an ESS,
if $\beta \ge Max(\frac{c}{b-b\alpha-b\delta+c\delta+b\alpha\delta}, \frac{c}{b-b\alpha-b\delta+c\delta+b\alpha\delta})$.

3. RESULTS

Our theoretical analysis successfully delineates the stability boundaries for different equilibrium strategies across the parameter spaces. In the symmetric baseline case ($\alpha = 0$) [19] Figure 1 demonstrates how the stability regions of various strategies depend on the repetition probability (δ) and the degree of positive assortment (β).
The results reveal three distinct regions of evolutionary stability. Under conditions of low repetition probability and weak positive assortment, the defection strategy ($ALLD$) dominates as an evolutionarily stable strategy, occupying the red region in Figure 1. This reflects the classical result that cooperation struggles to emerge when interactions are infrequent, and population mixing is random.
As both repetition probability and assortment strength increase, conditional cooperation strategies—including X (not always defective), $GRIM$ (permanent retaliation), and Y (not always cooperative)—become evolutionarily stable within an intermediate parameter range (gray region). This transition occurs because repeated interactions enable reputation-based strategies to effectively punish defectors while rewarding cooperators, particularly when positive assortment increases the likelihood of cooperators encountering other cooperators. Finally, unconditional cooperation ($ALLC$) achieves evolutionary stability only when the assortment parameter exceeds a critical threshold value, regardless of the repetition probability. This threshold represents the minimum degree of positive assortment required for unconditional cooperators to survive invasion by defectors, highlighting the crucial role of population structure in sustaining cooperation without the need for conditional strategies.

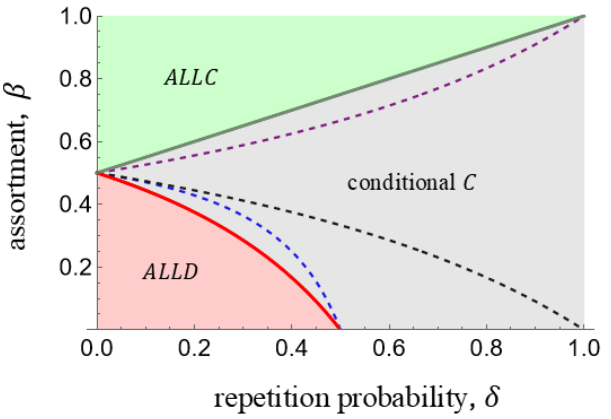

Figure 1: Evolutionary stability regions in symmetric interactions ($\alpha = 0$). The parameter space is defined by repetition probability (δ, x-axis) and positive assortment strength (β, y-axis). Three distinct evolutionary outcomes emerge: (i) $ALLD$ (defection) dominates under low repetition probability and weak assortment (red region); (ii) conditional cooperation strategies (X, $GRIM$, Y) achieve stability in intermediate parameter ranges with moderate to high repetition and assortment (gray region); and (iii) $ALLC$ (unconditional cooperation) becomes evolutionarily stable only when assortment exceeds a critical threshold, independent of repetition probability (green region). The boundaries delineate transitions between different evolutionary equilibria in structured populations without power asymmetry. Parameter values are set as $b = 4$, and $c = 2$.

As power asymmetry increases ($\alpha > 0$), we observe a systematic contraction of the parameter space supporting cooperative equilibria, accompanied by a corresponding expansion of the defection-dominated region. This asymmetry-induced erosion of cooperation represents a fundamental departure from the symmetric baseline case.
Figure 2(a) illustrates the impact of moderate asymmetry ($\alpha = 0.2$), revealing a substantial reduction in the cooperative parameter space compared to the symmetric case shown in Figure 1. Both conditional cooperation strategies and unconditional cooperation ($ALLC$) experience diminished stability regions, while the domain of defection ($ALLD$) expands significantly. Notably, at this level of asymmetry, the stability boundary of the conditional strategy X begins to converge with the boundary marking the loss of equilibrium status for the defection strategy $ALLD$, indicating a critical transition zone where strategic dynamics become extremely sensitive to parameter variations.

This pattern of cooperation erosion intensifies progressively as asymmetry increases, as demonstrated in panels 2(b) and 2(c). The cooperative regions continue to shrink systematically with each increment in power imbalance, while defection maintains evolutionary stability across an increasingly broad range of parameters. The critical threshold occurs at representing 50% asymmetry in benefit distribution between high- and low-power individuals. At this critical point, cooperation becomes evolutionarily unstable across all parameter combinations of repetition probability and assortment strength. The system transitions to a purely defective state where no cooperative strategy can achieve evolutionary stability, regardless of the strength of population structure or the frequency of repeated interactions. This complete collapse of cooperation underscores the destabilizing effect of extreme power imbalances in reciprocity-based mechanisms that typically sustain cooperative behavior.

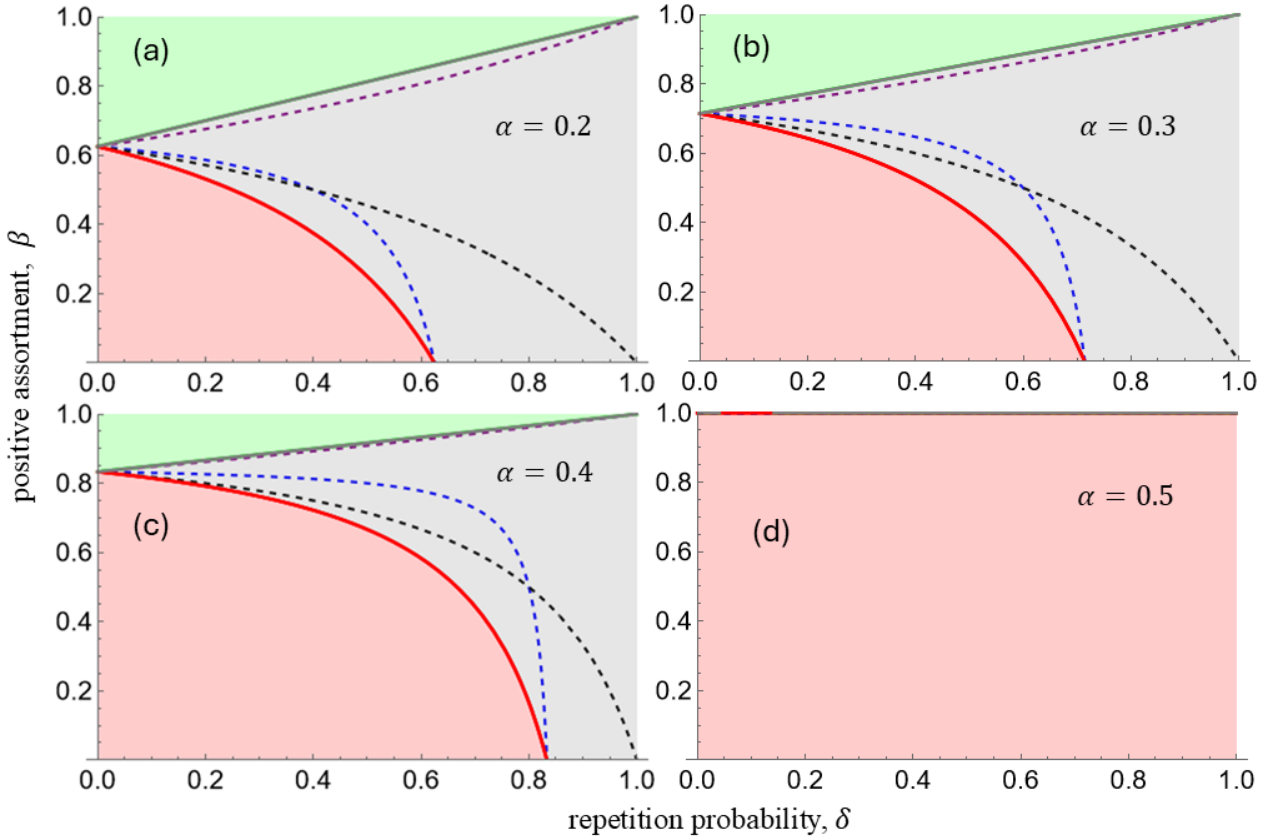

Figure 2: Progressive destabilization of cooperation under increasing power asymmetry. Evolutionary stability regions are shown for different degrees of asymmetry: (a) $\alpha = 0.2$, (b) $\alpha = 0.3$, (c) $\alpha = 0.4$, and (d) $\alpha = 0.5$. As power asymmetry increases, the parameter space supporting cooperative equilibria (both conditional and unconditional cooperation) systematically contracts while the defection-dominated region expands. The critical threshold occurs at $\alpha = 0.5$ (panel d), where complete cooperation collapse renders all cooperative strategies evolutionarily unstable across the entire parameter space of repetition probability (δ) and assortment strength (β). Parameter values are set as $b = 4$, and $c = 2$.

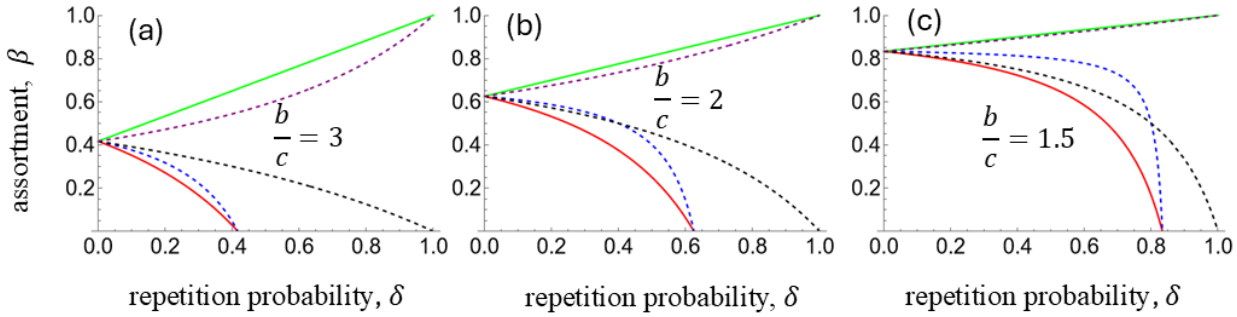

Figure 3: Effect of cost-benefit ratio on evolutionary stability regions under power asymmetry ($\alpha = 0.2$). Evolutionary stability boundaries are shown for different cost-benefit ratios: (a) $b/c = 3$, (b) $b/c = 2$, and (c) $b/c = 1.5$, where b represents the benefit of cooperation and c represents the cost. Line colors represent strategies: green for ALLC, red for ALLD, and blue dashed for conditional cooperation.

Figure 3 demonstrates that the interaction between power asymmetry and cost-benefit ratios creates a compound effect on cooperation stability. Under moderate asymmetry ($\alpha = 0.2$), decreasing cost-benefit ratios

severely constrain cooperative regions. In panel (a), with high benefits relative to costs ($b/c = 3$), cooperative strategies maintain substantial stability regions, with $ALLC$ achieving stability at moderate assortment levels and conditional strategies occupying intermediate parameter space. However, as the cost-benefit ratio decreases to $b/c = 2$ (panel b) and further to $b/c = 1.5$ (panel c), the cooperative parameter space contracts dramatically.

Notably, at $b/c = 1.5$ under 20% power asymmetry, unconditional cooperation requires an extremely high assortment ($\beta > 0.8$) to achieve stability, while conditional cooperation becomes viable only under combinations of high repetition probability and strong assortment. This demonstrates that power imbalances amplify the negative effects of unfavorable economic conditions, creating a double burden that makes cooperation increasingly difficult to sustain even in structured populations with repeated interactions.

4. CONCLUSION

This study addresses a critical gap in evolutionary game theory by examining how power asymmetry, conceptualized as benefit inequality in reciprocal interactions, influences the evolution of cooperation in structured populations. By developing an asymmetric iterated Prisoner's Dilemma model embedded within assortative networks, we isolate the effects of unequal benefit structures while controlling for other variables such as cost and interaction probability.

Our key finding is that power asymmetry systematically destabilizes cooperative strategies, even in settings with repeated interactions and positive assortment conditions traditionally believed to be conducive to cooperation. As asymmetry increases, the parameter space in which cooperative equilibria remain evolutionarily stable shrinks significantly. When power disparities are sufficiently high, cooperation collapses altogether, regardless of the continuation probability or network structure. This occurs because high-power individuals face diminished incentives to reciprocate cooperative behavior from low-power partners, as their asymmetric benefits reduce the relative value of maintaining cooperation. The destabilizing effect is particularly pronounced when the benefit ratio exceeds critical thresholds, beyond which even the most favorable network configurations cannot sustain cooperative equilibria.

These results are strongly aligned with the recent theoretical work by Colnaghi et al. [13], who also demonstrate that reciprocal cooperation becomes evolutionarily unstable in the presence of power differences. They show that in both asymmetric Prisoner's Dilemma and Snowdrift games, high-power individuals have less incentive to reciprocate, thereby undermining the mutual reinforcement that sustains cooperation. Our findings corroborate and extend this result by situating it within a structured population framework, emphasizing that positive assortment alone cannot rescue cooperation under substantial power imbalance. The convergence between our network-based analysis and their game-theoretic approach strengthens the evidence that power asymmetry represents a fundamental constraint on cooperative evolution across different modeling frameworks.

The robustness of our findings across different network structures and asymmetry levels reveals important insights about the limits of structural solutions to cooperation problems. While previous research has demonstrated that network effects can promote cooperation through mechanisms such as clustering and assortment, our results show that these beneficial effects are systematically eroded by increasing power disparities. This erosion occurs because power asymmetry fundamentally alters the strategic landscape, making cooperation less attractive for high-power players regardless of network topology. The implication is that structural interventions must be coupled with mechanisms that address underlying power imbalances to be effective.

Together, these results challenge the traditional optimism surrounding reciprocity and structure as universally robust mechanisms for sustaining cooperation. They underscore the need for future models and institutional designs to consider power, hierarchy, and inequality as core parameters, not peripheral complications. More broadly, our findings resonate with growing empirical evidence from economics and social psychology that fairness and equity are critical not only for ethical reasons but also for maintaining stable cooperative dynamics [13], [15], [18]. Recent work by Gächter and others has shown that perceived fairness in distribution mechanisms significantly affects cooperation rates in experimental settings, supporting our theoretical prediction that power asymmetries undermine cooperative behavior.

Future research should explore the robustness of these findings across different game structures, investigate potential mechanisms for mitigating asymmetry effects [20-23], and examine empirical validation in real-world cooperative systems [24-27]. Additionally, extending the analysis to finite populations [28-31] and incorporating evolutionary dynamics beyond equilibrium analysis [32-36] would provide valuable insights into the transient behavior of asymmetric cooperative systems. Particularly promising avenues include investigating how institutional mechanisms such as redistribution schemes, graduated sanctions, or democratic governance structures might counteract the destabilizing effects of power asymmetry.

5. ACKNOWLEDGMENT

We are grateful to the grant-in-Aid for Scientific Research from JSPS, Japan, KAKENHI (grant No. JP 23H03499) for the support.

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