How strategy environment and wealth shape altruistic behaviour:

Cooperation rules affecting wealth distribution in dynamic networks

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Abstract

All societies rely on individual contributions to sustain public goods that benefit the entire community. A variety of mechanisms, that specify how individuals change their decisions in response to past experiences and behavioral attributes of interacting partners, have been proposed to explain how altruists are not outcompeted by selfish counterparts. A key aspect of such strategy-update processes involves only a comparison of an individual's latest payoff with that of a randomly chosen neighbor. In reality, both the economic and social milieu often shapes cooperative behavior. We propose a new decision heuristic in social dilemmas, where the propensity of an individual to cooperate depends on the local strategy environment in which she is embedded as well as her wealth relative to that of her connected neighbors. Our decision-making model allows cooperation to be sustained and also explains the results of recent behavioral experiments on cooperation in dynamic social networks. Final cooperation levels depend only on the extent to which the strategy environment influences altruistic behaviour but is largely unaffected by network restructuring. However, the extent of wealth inequality in the community is affected by a subtle interplay between the environmental influence on a person's decision to contribute and the likelihood of reshaping community ties through breaking old and making new links, with wealth-inequality levels rising with increasing likelihood of network restructuring in some situations.

Introduction

Contemporary society faces many challenges like climate change, civil wars, pandemics and mass migration due to social conflicts that require concerted action not only from governments but also from individuals. Growing wealth inequality is another pressing problem that can undermine democratic norms leading to destabilization of society by increasing the number and intensity of social conflicts. A recent poll by Ipsos[1] reveals that the wealthiest 1% own more than 30% of the total household wealth in 17 of 29 countries surveyed with the disparities being greater than 40% in many major emerging economies. Individuals as well as nation states are often faced with the choice of contributing to the public good for the benefit of society. Such disparities in wealth can affect the quantum of contribution necessary for sustaining various public goods thereby lowering the quality of life and the environment. Hence, our actions as individuals as well as those of our government can potentially affect our ability to survive as a species[2]. In view of their significance, it is important to understand how the factors that affect individual choices shape collective outcomes.

Cooperation manifests itself in many forms and various mechanisms, like direct reciprocity[3,4], indirect reciprocity[5–8], kin selection[9–11] and structured populations[12–19], have been put forward to explain the evolution of cooperation[20]. All these mechanisms specify rules for updating strategies in response to past experiences of interactions and in some cases, reputation of interacting partners[7,21]. However, the effectiveness of these update rules in sustaining cooperative behaviour can depend on the structure of the underlying social network as well. Prior studies have also examined the effect of accounting for social diversity[22], resource heterogeneity[23] and wealth-based conditions for participation in a PGG[24] on cooperation levels in spatially structured populations.

Several studies have highlighted the usefulness of rewiring social ties[25,26,35,27–34] in promoting cooperation in the absence of punishment. While these papers differ in the details of the strategy update and rewiring processes, they all show that the fraction of the cooperators in the population can be enhanced by the coevolution of individual strategy and the underlying network structure. In all these models, strategy update occurs after a pair-wise comparison of payoffs between the focal player and a randomly chosen connected neighbor. A different approach to sustaining cooperation levels and social cohesion was adopted in a model proposed by Roca and Helbing[36]. Their low-information, learning-based model[37] proposed strategy-update rules depending on individual satisfaction levels that are oblivious to the payoffs or reputation of connected neighbors. Their results, recently extended to evolving complex networks[38], showed that cooperation and social cohesion can be sustained even at moderate levels of greediness despite lack of information about strategies of connected neighbors.

2

Behavioral experiments[39–41] have pointed out striking disparities between the "imitate the best" predictions of strategy update based on the pairwise comparison rule[42–44] and actual behaviour of human participants playing prisoners' dilemma games. Such studies underscore the need to come up with decision heuristics that more accurately reflects the evolution of human behaviour in social dilemmas. Behavioral economics experiments also indicate that individual decisions are affected by the economic milieu in which the members of the social network find themselves. High wealth inequality leads to more exploitation of poorer people by richer people while rich are more generous when wealth inequality is low[45]. Removing the anonymity of wealth accumulated by players in a dictator game can lead to increased donations by richer participants[46]. On the contrary, the visibility of wealth of connected neighbors was found to adversely affect equilibrium wealth distribution and cooperation levels in co-evolving social networks[47]. These results suggest the importance of the social[48] and economic environment in influencing individual strategy-updates.
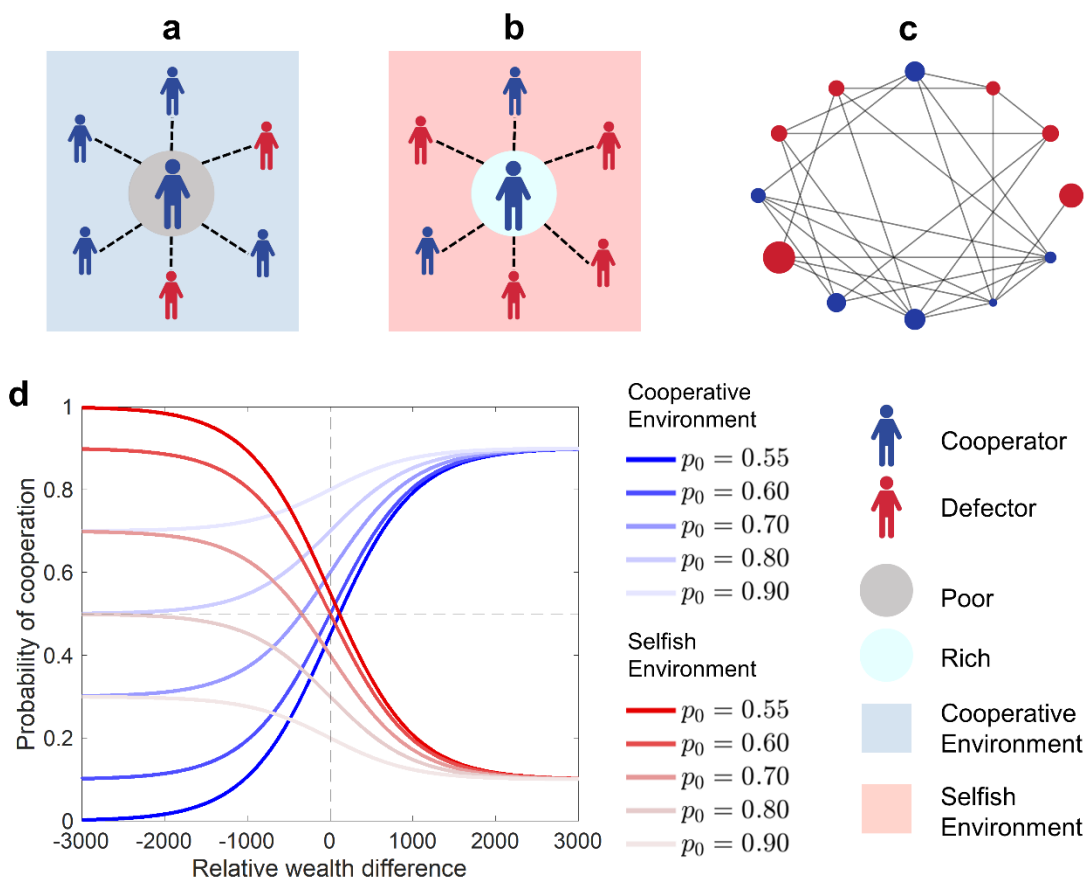

Figure 1. Salient features of the model: (a) A poor cooperator in a cooperative environment and (b) A rich cooperator in a selfish environment. (c) A snapshot of a network where the size of the

nodes represents the cumulative wealth of the individual and the colors represent the strategy adopted at a specific time-point. (d) The S-shaped function showing the impact of the wealth difference (relative to the average wealth of the neighbourhood) and the strategy environment (quantified by the parameter p_0) on the likelihood of cooperation.

In this paper, we use a variant of a public goods game to present a new model for cooperative strategy updating that depends on the nature of the local strategy environment in which the individual is embedded. If this environment is a cooperative one (i.e. >50% of the connected neighbors are cooperators), the focal player cooperates with a probability that is determined by the difference between her own wealth and the average wealth of all her connected neighbors. On the contrary, if the neighborhood is a selfish one (i.e. >50% of the connected neighbors are defectors), the focal individual is more likely to defect with the probability for defection being given by the same functional form as before. We find that such a decision heuristic can sustain cooperation with cooperation levels being determined by the impact of the local environment on individual decisions. An increasing likelihood for reorganizing social ties does not affect cooperation levels but does affect final wealth-inequality in a manner that depends on the role of the strategic environment on altruistic behaviour. Fig. 1 highlights the key features of our model. Supplementary material Movie M1 shows the evolution of individual strategy and wealth in a dynamic network.

Results

Fig. 2 highlights how our decision rule, which relies on comparison between the focal player's wealth and the average wealth in her local strategy environment, leads to distinctly different outcomes compared to the standard pairwise comparison rule[42–44] used in evolutionary game theory. The Fermi function giving the probability of changing strategies according to the pairwise comparison rule is $P(S_x \rightarrow S_y) = \dfrac{1}{1 + e^{-\beta(\pi_y - \pi_x)}}$ where P(S$_x$➔S$_y$) is the probability that the focal player x adopts the strategy of a neighbor y and π_x, π_y are the respective payoffs. b is the inverse of the selection temperature which is a measure of the intensity of selection.

Fig. 2a and 2b shows the variation in the fraction of cooperators and the Gini coefficient starting from an initial Gini coefficient = 0.2. Our proposed environmentally-dependent decision heuristic ensures that the fraction of cooperators stabilizes to around 0.5 in contrast to the pairwise comparison rule modelled using a Fermi function where the fraction quickly decays to zero. This fraction depends on the minimum and maximum cooperation levels for relatively richer and poorer individuals and is controlled by the environmental parameters p_0 and *b*. Wealth inequality as measured by the Gini coefficient also reduces in our model in contrast to the standard decision-update rule where wealth-inequality saturates to a higher value. A change in initial Gini coefficient does not change the qualitative behaviour in these cases. A greater reduction in wealth inequality

4

observed in our model can primarily be attributed to the higher fraction of cooperators and a large number of local cooperative environments at equilibrium, as well as an increase in average degree of the network (Fig. 2c) in comparison to the standard case. These three features ensure more efficient accumulation and redistribution of wealth generated from each PGG, consequently leading to lesser wealth-inequality.
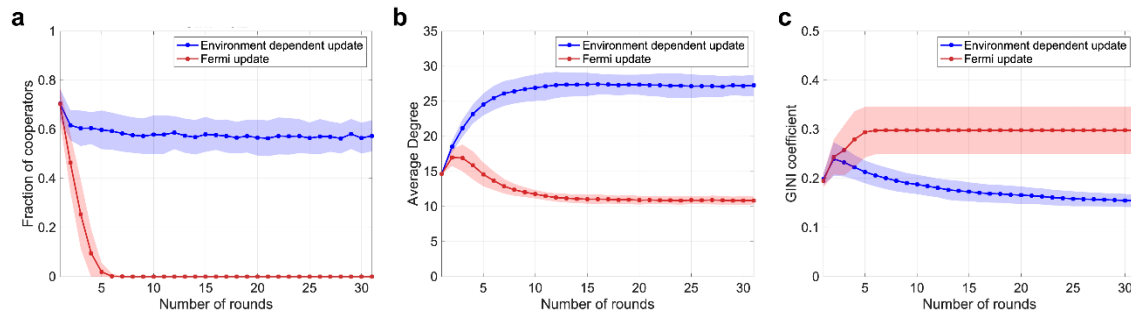

Figure 2. Comparison between the environment and wealth-dependent decision heuristic and the pairwise comparison rule: (a) The fraction of cooperators and (b) the average degree saturate to a comparatively higher value while (c) the wealth inequality reduces significantly, in the former case. These results are independent of the initial wealth-inequality levels. Each data point has been averaged over 100 trials. The shaded regions represent one sigma variation from the mean. Parameters used: N=50, β=0.01, b=0.1, p_0=0.7, λ=0.001, initial Gini=0.2, re=0.3, r=2.

Fig. 3a,b shows heat maps depicting the equilibrated fraction of cooperators in the population and extent of wealth inequality in the population (quantified by the final Gini) when the influence of the local strategy environment and the rewiring fraction are varied. Once the impact of the strategy environment on decision making is fixed (by specifying p_0), an increase in the probability of changing network structure by rewiring of social ties does not have much of an impact on the frequency of cooperators. However, the extent to which wealth-inequality is affected by changing this rewiring fraction depends on the impact of the strategy environment. These results can be understood by carefully analyzing how the strategy update dynamics affects network topology manifest through the connectedness of rich and poor cooperators and defectors as well as the nature (C or D) of the dominant strategy environments.

Impact of the strategy environment: A greater influence of the local strategy environment in modulating cooperative behaviour increases the likelihood of cooperators to dominate over defectors. For any rewiring fraction, a higher value of p_0 increases the propensity of rich individuals to cooperate in a cooperative environment and decreases their propensity to cooperate in a selfish environment (see Fig. 1d). The fraction of cooperators and the cumulative number of cooperative environments increase with p_0 (Fig. 3c); this increases the number of poor as well as rich cooperators (especially at large p_0). Since, lower wealth-inequality depends especially on the contributions of highly connected rich nodes in cooperative environments, high p_0 (≥0.8) leads to a

5

decrease in wealth-inequality as evident from Fig. 3b. Supplementary Fig. S1 shows how the strategies, strategy environments and relative wealth of each member in the network evolves with time. The influence of the strategy environment on the equilibrium fraction of cooperators is also evident by comparing panels with different values of p_0.
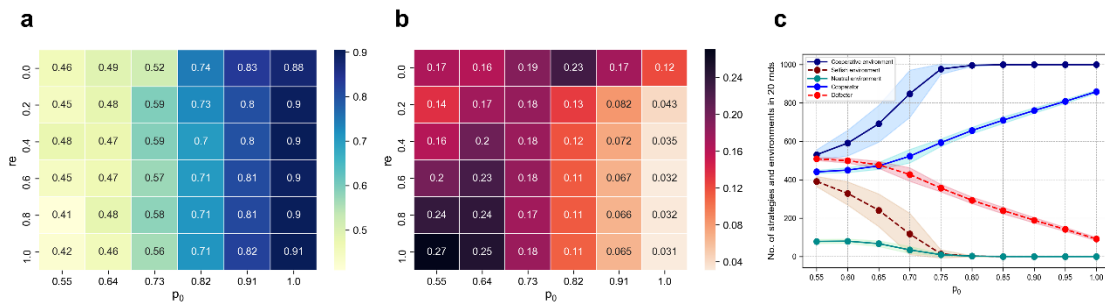

Figure 3: Effect of changing the strategy environmental influence on altruistic behaviour: (a) Equilibrated fraction of cooperators (b) Final Gini coefficient at the end of 20 rounds as the influence of the strategy environment (p_0) and network rewiring fraction (re) are varied. (c) Variation of the cumulative number of strategies and strategy environments of each type computed over all rounds of the game, with the strategy environment factor (p_0). For all panels, data points were obtained after averaging over 30 trials. The shaded regions in the last panel represent one sigma variation from the mean. Parameters: N=50, b=0.1, re=0.3, λ=0.001, r=2, initial G=0.2.

Impact of remaking social ties: In a static network, poor individuals (of both C & D types) outnumber rich individuals (Fig. 4a). For moderate environmental influence ($0.55 \leq p_0 \leq 0.73$), increasing the network rewiring fraction (*re*) increases the number of rich defectors (RD) (Fig. 4a, also see Supplementary Fig.S2(a)) while at the same time increasing the number of cooperative environments (Fig. 4b). This results in a situation where a rich defector in a cooperative environment can exploit cooperator neighbors thereby reducing contributions to the common pool leading to lower wealth redistribution and consequently a higher level of wealth inequality (Fig. 3b).

As the influence of the strategy environment increases, cooperators of either wealth categories dominate over defectors irrespective of the rewiring fraction (supplementary material Fig.S2(c)) which increases the contribution to the common pool and facilitates efficient redistribution of wealth leading to lowering of wealth inequality. Since the average number of poor cooperators (PC) and rich cooperators (RC), who are the primary drivers for lowering wealth inequality, changes substantially only when the network changes from static to dynamic (supplementary material Fig.S2) but is not affected by increase in rewiring fraction, we do not observe a significant reduction in wealth inequality with further increase in network rewiring fraction (Fig. 3b).

A highly dynamic network characterized by an increase in rewiring of nodes leads to an increase in the number of RD primarily at the expense of poor defectors (PD) (Fig. 4a). However, these

6

defectors have lower average degree than cooperators (Fig. 4c) and are typically embedded in a cooperative environment especially at higher p_0 values where cooperative environments dominate over selfish ones (Fig. 4b, also see supplementary material Fig.S3). This is also reflected in the increase in number of CC links with increase in rewiring fraction (see supplementary material Fig.S4). This leads to a network where cooperators are more connected than defectors even though the local strategy environments of both strategy types are more likely to be cooperative in nature. Remarkably, the reorganization of the network topology due to the rewiring process happens in a manner that keeps the fraction of cooperators invariant since that only depends on the degree of influence of the local strategy environment. In a cooperative environment, rich individuals are likely to cooperate with a higher probability for larger values of p0. Hence, as p0 increases, both PC and RC increase in number, primarily at the expense of RD, thereby increasing the total fraction of cooperators in the population (see supplementary material Fig.S5).
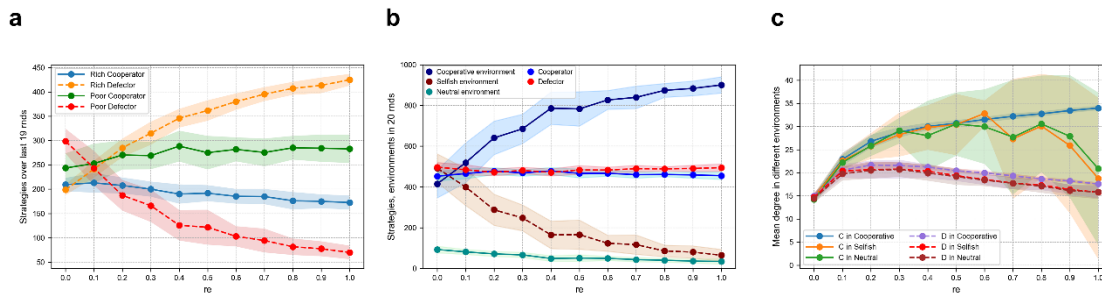

Figure 4: Effect of giving more nodes the option of restructuring their connections. Variation of the (a) Cumulative number of cooperators and defectors in each wealth category (b) Cumulative number of strategies (C or D) and strategy environments, computed over all rounds of the game and averaged over 30 trials, with rewiring fraction. (c) Variation of the average degree of players in different types of strategy environments, averaged over 50 trials. The shaded regions represent one sigma variation from the mean. With increase in rewiring rate, the degree of relatively rare C in selfish and neutral environments fluctuates wildly across different trials, which accounts for the increase in width of the shaded regions for large *re*. Parameters: N=50, b=0.1, λ=0.001, p0=0.7, r=2, initial G=0.2.

Effect of wealth categories on behaviour: An individual's propensity to cooperate in the PGG can be affected not only by her local strategy environment but also by the wealth category (rich or poor) she belongs to. Even though this dependence of cooperative decision-making on relative wealth difference is weaker than its dependence on strategy environment, it reveals intriguing features of strategy update dynamics and their consequent impact on wealth inequality within the community. For example, the number of cooperators and cooperative environments remain nearly unchanged as the impact of relative wealth difference on altruistic behaviour is enhanced through increasing λ. However, the average number of strategy shifts (C➜D, D➜C) show a marked transition (Fig. 5a) from visible wealth (moderate and high λ) regime to the invisible wealth (very

7

low $\lambda < 10^{-4}$) regime where the probability of cooperation is effectively independent of one's wealth. In the invisible wealth scenario characterized by $\lambda \rightarrow 0$ as, the probability of cooperation for both relatively richer and poorer individuals converge to the same value in a cooperative environment. In a selfish environment, they converge to a different and lower value (see equation (3) & (4)). This makes it more likely for relatively richer individuals and less likely for relatively poorer individuals to cooperate in a cooperative environment. Since cooperative environments dominate, the former amounts to an increase in number of RC and decrease in number of RD (Fig. 5b) facilitated through increasing D to C transitions. In contrast, the latter amounts to an increase in number of PD at the expense of PC (Fig. 5b) brought about by an increase in C to D transitions. These features also explain why the final Gini increases significantly (Fig. 5c) when the visibility of wealth makes altruistic behaviour dependent on wealth categories. The decrease in RC accompanied by increase in PC and RD, even though number of cooperative environments remain roughly constant, leads to poorer cooperators giving up some of their wealth even as a larger fraction of richer individuals increase their wealth through defection. Moreover, as the decrease in C to D and D to C transition shows, RD's and PC's are more likely to retain their strategies. All these factors suppress redistribution of wealth to relatively poor individuals while favoring accumulation of wealth by richer individuals, leading to higher levels of wealth inequality. These results are consistent with the outcome of behavioral experiments regarding wealth visibility being detrimental to reduction in wealth inequality[47].
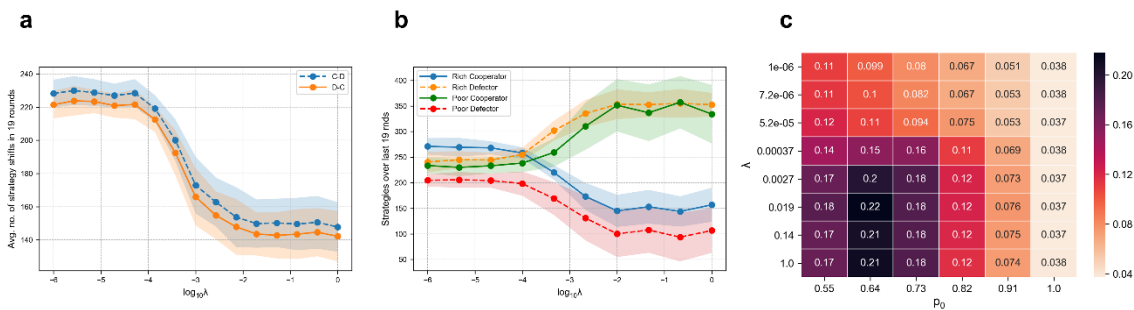

Figure 5: Impact of relative wealth difference on cooperative decision-making. Variation of the (a) cumulative number of C➔D and D➔C strategy shifts over the entire duration of the game, averaged over 50 trials and (b) cumulative number of cooperators and defectors in each wealth category computed over all rounds of the game, with λ. (c) Heat map showing how the final wealth-inequality level at the end of 20 rounds depends on factors determining the role of the strategy environment (p_0) as well as the relative wealth difference. All data points in (b) and (c) are averaged over 50 trials. The shaded regions in the first two panels represent one sigma variation from the mean. Parameters: N=50, b=0.1, p_0=0.7, r_e=0.3, r=2, initial G=0.2.

Discussion

Our inclinations to be altruistic are often strongly influenced by the behaviour of the people we associate with as well as our wealth relative to that of our acquaintances. Our individual response in such situations can shape collective outcomes leading to profound consequences for our own prosperity as well as on the viability of sustaining public goods that rely on our contributions. Our strategy environment and wealth-dependent decision heuristic ensures that altruists are never eliminated from the population. The key aspect of our decision heuristic that ensures sustenance of cooperation is the anti-correlated nature of the propensities to cooperate in cooperative and in selfish environments. This ensures that even under unfavourable conditions characterized by relatively low probabilities of cooperation of poor individuals in either cooperative or selfish environments and of rich individuals in cooperative environments, cooperators are always sustained in the population although their mean fraction decreases slightly. The wealth inequality predicted by our model under different scenarios is consistent (see supplementary material Fig.S6a-c) with the results of behavioral experiments described in Nishi et al.[47] Since our decision heuristic imposes distinctly different propensities to cooperate for rich and poor members of the community in different strategy environments, we also compared the outcomes of alternative decision heuristics to examine the impacts of each on cooperation levels and wealth inequality. One such alternative makes richer individuals more likely to cooperate in a cooperative environment and poorer individuals more likely to cooperate in selfish environments. Then, populations with higher initial Gini saturate to lower and unrealistic final wealth inequality levels not supported by experiments[47] (see supplementary material Fig.S6d), than those with lower initial Gini. In the invisible wealth scenario (I=0), even though the likelihood of cooperation becomes independent of wealth and only dependent on strategy environments, relatively richer individuals cooperate with a higher probability in cooperative environments (which outnumber selfish environments) compared to the visible wealth scenario. This leads to more contributions on an average, which when redistributed benefits more people thereby reducing wealth-inequality. When more people get the option of rewiring their social ties to punish selfish interacting partners, the change in wealth inequality levels depend on the influence of the local strategy environment on decisions to contribute in a PGG. If a cooperative strategy environment induces high propensities for cooperation from individuals regardless of their relative wealth difference, reorganization of social ties (irrespective of the rewiring fraction) can further aid in reducing wealth inequality. However, as the impact of the strategy environment on altruistic behaviour reduces, reorganization of social ties increases wealth inequality primarily because it allows RD embedded in cooperative environments to more frequently exploit their altruistic neighbors.

To check the robustness of our results, we have verified the effect of variation in other parameters like synergy coefficient, likelihoods of making, breaking and retaining links and population size. An increase in synergy factor increases average wealth and reduces wealth inequality, without

affecting the fraction of cooperators or average degree of the network, since a larger multiple of the altruist's contribution is redistributed to each connected neighbor. Changes in network restructuring probabilities can change the system metrics with the extent of change being dependent on the fraction of links given the option of rewiring. If rigid rules for network restructuring are imposed, with existing links retained and new links made only if both connecting partners are cooperators, a more dynamic network (larger *re*) is counter-productive for sustaining cooperation and even maintaining social cohesion due to breakdown of social ties (see supplementary material Fig.S7).

Despite being valid for larger population sizes, our decision heuristic is likely to be useful in populations where members possess relatively smaller average number of connected neighbors who can influence their decisions. This would make it possible for each person to gather information about the strategy environment and average wealth of such neighbors. For very large network neighborhoods, such information would be more difficult to acquire, process and utilize due to cognitive limitations as well as individual cognitive biases. The population sizes we have chosen are therefore of the order typically sampled in behavioral experiments[40,41,47]. Such a choice seems reasonable since a lot of social interactions occur within relatively small communities where individual behaviour is shaped by a few influential interacting partners. Even though we have not explicitly included punishing strategies[49], the effect of punishment is indirectly accounted for through rewiring of social ties. Such a process can be thought of as a cost-free mechanism of penalizing selfish behaviour; whose effect is manifest through the lower average degree of defectors in comparison to the cooperators. It will be interesting to see how explicit incorporation of punishing strategies in our decision-making framework affects the strategy distribution and wealth inequality levels in the population. Introducing heterogeneity in contributions for the upkeep of the public good, which is akin to imposing wealth-dependent tax brackets, may also constitute a fairer mechanism for encouraging altruistic behaviour. It is quite likely that such conditions will not only affect cooperation levels but also result in reshaping the underlying structure of the social network.

Altruistic behaviour in humans can depend on a variety of motivating factors such as empathy, personal values and aspirations, social environment and cultural norms. The relative importance of these diverse factors can not only vary from one person to another but also depend on the nature of the social dilemma encountered. While no single decision rule can fully capture the behavioral complexities of individuals, by studying emergent patterns in human behaviour in different situations, it might be possible discover general principles of decision-making that can then be encapsulated in a heuristic. The decision-making heuristic proposed and explored in this paper provides a simple, yet powerful framework for understanding how the co-evolution of individual choices and social network ties can work in tandem to sustain cooperation levels and consequently affect wealth inequality in the population.

Materials and Methods

Individuals are distributed across an Erdős–Rényi random, dynamic social network that can change over time due to breaking of existing links and creation of new links. Initially, any two members in the network are connected with a probability $q=0.3$. Each member is initially assigned one of two possible wealth levels (rich and poor) and provided with an amount of money to match the appropriate wealth level and wealth distribution. Our results are independent of initial random network topology and wealth assignments. The initial wealth distribution across the population is fixed by specifying an initial Gini coefficient (G) defined as

$$G = \frac{\dfrac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} |\, y_i - y_j \,|}{2\mu} \tag{1}$$

where y_i is the wealth of the i'th individual and μ is the mean of the wealth distribution. G=0 implies perfect equality with every member having the same wealth and $G=1$ corresponds to perfect inequality with one member possessing the entire wealth. The wealth of each individual is visible to only her connected neighbors but not the entire population. Each round consists of two steps, a decision step followed by a rewiring step where a certain fraction of the population is given the option to break an existing link and create a new link. In the decision step, following [47], each individual plays a modified public-goods game (PGG) with all of her connected neighbors. Each individual 'i' participates in (k_i+1) PGG, once as a focal player and remaining times as a connected neighbor of another focal player, where k_i is the degree of the i'th node. During each such game, the individual can choose to either cooperate (C) by pledging a fixed amount of money (m units) to each connected neighbor or defect (D) by refusing to donate. The amount pledged to each connected neighbor is multiplied by a synergy factor (r) and redistributed to all the connected neighbors regardless of their choice to cooperate or defect as focal players. If the focal individual chooses to defect, none of her connected neighbors get anything. In the first round, every individual has a fixed probability ($p_{C=}p_0>0.5$) of cooperating which reflects a collection of people who choose to be mostly cooperative initially on the basis of trust, although cultural differences may affect the way in which different people behave[50] even in the first round. The payoff to the i'th individual, connected to n_c cooperators and ($i-n_c$) defectors, is given by

$$\begin{aligned} \pi_{iC} &= rmn_C - k_i m \\ \pi_{iD} &= rmn_C \end{aligned} \tag{2}$$

In subsequent rounds, individuals take cues from their strategy environment while deciding whether to cooperate. The probability of a focal player to cooperate depends on the fraction of cooperators present in her local neighborhood and on the comparison between her wealth and the average wealth of her connected neighbors. Previous work[45] suggest that rich and poor people behave differently with richer people being less generous especially in high wealth-inequality scenarios. A poorer player (relative to the average wealth of the local neighborhood) has a higher incentive to cooperate with her neighbors since doing so increases the likelihood of her receiving favours from them in return. On the other hand, a richer player has a higher incentive to exploit her neighbors by defecting, since her higher wealth ensures that she pays a relatively lower cost when a link with her is broken in response to her selfish behaviour. Hence a poorer player is influenced by the wisdom of the majority and is likely to cooperate with a higher probability ($p_C>0.5$) if her local environment is mostly cooperative (>50% C neighbors) and more likely to defect if her local environment is mostly selfish (<50% C neighbors). By contrast, a richer player has more to gain by defecting in a cooperative environment and a greater likelihood of cooperating in a predominantly selfish environment to reduce the chances of being isolated due to breaking of her existing links. We therefore propose the following stochastic decision-making rule that gives the probability of cooperation (p_C) for a focal player that is dependent on her local strategy environment and relative wealth difference.

$$p_C = p_0 - b + (1 - p_0)\tanh(\lambda \Delta w) \tag{3}$$

when the focal player is in a cooperative environment and

$$p_C = (1 - p_0 + b) - (1 - p_0)\tanh(\lambda \Delta w) \tag{4}$$

when the focal player is in a selfish environment. $\Delta w = E_{LC}(w) - w_F$ is the relative wealth difference; where $E_{LC}(w)$ is the average cumulative wealth of connected neighbors of the focal player and w_F is the focal player's cumulative wealth accumulated over past rounds. λ is a parameter that determines the extent to which the wealth of the local environment affects the focal player's likelihood of cooperation. $\lambda=0$ implies that focal player's decision is insensitive to the wealth of the local neighborhood. b is a bias term which ensures that a considerably poorer player, whose wealth is very small compared to that of her neighbors, does not always cooperate. p_0 is an index that determines the influence of the strategy environment on an individual's likelihood to cooperate, irrespective of her wealth relative to the average wealth of the neighborhood.

12

There is a key difference between our decision rule and the pairwise comparison rule[42–44] that is typically used in evolutionary game theory literature. In the latter case, the decision to cooperate is made after a comparison of payoffs with a randomly chosen neighbor and the local environment plays no role contrary to our case where the local strategy environment influences cooperative behaviour.

We consider a dynamic network, reflecting the reality of social network restructuring, due to breaking of existing ties and creation of new ones at the end of every round. During the network rewiring step that follows the decision step, a fraction *re* (henceforth called the rewiring fraction) of all possible pairs of individuals chosen randomly are given the *option* to break a link with the partner and create a link with another player. If the pair of selected nodes is already connected via a link, then one of the pairs is selected at random to take the decision about retaining or breaking the link. If the partner of the randomly chosen decision-maker had cooperated in the previous round, the link is retained with probability p_r, otherwise the link is broken with a certain probability p_b. If the selected pair of nodes are not connected by a link, both are given a choice to establish a new connection. A link is established with a high probability p_m if *both* had cooperated in the previous round. If either or both of the nodes had defected in the last round, a new link can still be established with probability p_e and p_s respectively. To calculate the average degree of a C or D in different strategy environments, we use the following formula. $<k_X^Y> = \frac{1}{N_T}\sum_{i=1}^{N_T}\left[\frac{\sum_{j=1}^{M}\sum_{l=1}^{S}k_{X_l}^Y(j)}{\sum_{j=1}^{M}n_X^Y(j)}\right]$ where

X=C or D and Y=C- or D- or neutral-environment. $k_{X_l}^Y(j)$ is the degree of the l'th X in Y-environment in the j'th round and $S = n_X^Y(j)$ is the number of X's in Y-environments in the j'th round, M is the total number of rounds and N_T denotes the number of trials. Unless specified otherwise, we used p_r=0.87, p_b=0.7, p_m=0.93, p_e=0.3, p_s=0.2 for the network restructuring probabilities. Changes in these values within reasonable bounds do not affect our conclusions; the impact of significant changes in these parameters has been discussed in the previous section. An algorithmic view of the model can be found in the supplementary material.

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