

# The devil's dung? Money as a mechanism of generalized reciprocity in human societies

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## Abstract

St. Francis of Assisi (1181/82–1226) famously called money the devil's dung, and indeed money is often associated with greed, inequality, and corruption. Here, we argue that money can facilitate the formation of circuits of generalized reciprocity across human groups, a crucial mechanism for the evolution of cooperation when monitoring the actions and reputation of potential partners becomes difficult. Using an agent-based evolutionary tournament, we show that money exchange constitutes an evolutionarily stable strategy, promoting cooperation without the cognitive demands of traditional reciprocity mechanisms. In particular, we demonstrate how the monetary exchange strategy can take advantage of, and ultimately displace, reputation-based systems in mixed populations. However, we also find that

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excessive liquidity can be detrimental because it can distort the informational value of money as a signal of past cooperation, making defection more profitable. Our results suggest that, in addition to institutions that promoted trust and punishment, generalized reciprocity within and across human groups may also have depended on institutions regulating the money supply.

### Keywords

money, cooperation, reputation, generalized reciprocity, evolution

## Introduction

How can we reconcile the fact that humans engage in extensive cooperative behavior when a strictly rational pursuit of individual self-interest would predict free riding on the contribution of others? A wide range of explanations has been proposed in the social and biological sciences, including genetic relatedness, kinship, and interpersonal selection mechanisms (Axelrod and Hamilton, 1981; Bowles and Gintis, 2013; Dawkins, 1981; Gintis, 2003; Nowak, 2006; Okada, 2020; Redhead et al., 2024; Welser et al., 2007). This paper argues that the institution of money enables the formation of self-sustaining circuits of generalized reciprocity that are crucial for the evolution of human cooperation, by superseding more cognitively demanding interpersonal and social mechanisms.

Previous research has shown that direct and indirect reciprocity are key social norms that sustain cooperation (Okada, 2020; Rossetti and Hilbe, 2024; Schmid et al., 2021). Direct reciprocity relies on personal memory, which helps individuals to cooperate only with those who have cooperated with them in the past (Axelrod, 2006). When repeated encounters with the same individuals are likely, it becomes easier to remember past actions, reducing defection and enabling mutually beneficial relationships to prevail. Indirect reciprocity, in contrast, entails cooperating with individuals who have a good reputation as previous cooperators. This expands the range of cooperative actions: agents  $i$  can help other agents  $j$  at time  $t$  if they expect future benefits from agents  $k$  at time  $t + 1$ , who have directly observed or indirectly know about  $i$ 's cooperative efforts. This allows for the formation of broader cooperation circuits that do not depend on the individual memory of previous counterparts.

However, human cooperation also occurs beyond the reach of personal memory, reputation, or shared membership in the same networks and

groups (Robinson and Barker, 2017). Indeed, a remarkable feature of human societies is the extensive anonymous cooperation that takes place between complete strangers (Nowak, 2006; Bowles and Gintis, 2013; Simmel, 2011[1900]; Giddens, 1990; Powers et al., 2021). A prominent example is the economic division of labor (Giddens, 1990; Harwick, 2023; Hayek, 2000; Kocherlakota, 1998; Nirjhor and Nakamaru, 2023). Individual  $i$  would benefit from consuming good  $x$  (e.g., rice) but lacks the resources or the ability to produce it independently. Instead, individual  $i$  relies on the costly efforts of a producer, individual  $j$ , with  $i$ 's benefits typically exceeding  $j$ 's costs. Individual  $j$ , in turn, depends on the costly efforts of other producers — often unrelated to individual  $i$  — to benefit from the use or consumption of good  $y$  (e.g., a mechanical tool). The refusal to bear the costs of production for the benefit of unrelated individuals, while at the same time reaping the rewards of the productive efforts of others, constitutes a defection from the expected cooperation, as it would jeopardize the division of labor.

Since the capacity to produce goods that satisfy increasingly sophisticated needs is unlikely to be found within one's own genetic pool or social ties, cooperation among strangers is essential in order to gain access to goods and resources that would otherwise be inaccessible, leading to the emergence of more differentiated societies (Durkheim, 2023[1893]; Jaeggi et al., 2016; Robinson and Barker, 2017; Cooper and West, 2018; Shin et al., 2020; Powers et al., 2021; Fauvelle, 2025). However, this requires individuals to access information about unrelated others to assess their ability to engage in cooperative behavior (Pisor and Gurven, 2018; Shin et al., 2020).

We therefore propose that money can serve as a means of solving cooperation dilemmas among strangers, such as those observed in the context of the economic division of labor, by functioning as a “*token of delayed reciprocal altruism*” (Dawkins, 1981), thereby promoting the formation of circuits of generalized cooperation and reciprocity. Indeed, previous research has suggested that money functions as a public record-keeping device (Giddens, 1990; Ostroy, 1973; Ostroy, J. M. & Starr, R. M., 1990; Searle, 2005; Guala, 2020) or ‘*social memory*’ mechanism (Hart, 2000; Kocherlakota, 1998) that facilitates the exchange of information between individuals who lack direct or indirect means of monitoring each other's past behavior (Camera et al., 2013; Fauvelle, 2025; Kocherlakota, 1998). Receiving monetary compensation for a cooperative action creates a tangible record of efforts expended to produce benefits for others. Possession of money thus signals an individual's history of cooperative behavior and the ability to reciprocate the costly efforts of others. This creates a dynamic

circuit of cooperation in which individuals are incentivized to cooperate in exchange for money, which they can then use to incentivize further cooperation from unrelated others, such as the production of goods they need but cannot produce themselves.

Money can thus be understood as a key ‘*disembedding mechanism*’ (Giddens, 1990) that enables the expansion of coordinated social activities in time and space, without relying on the constraints of personal relationships, group communication, or long-term commitments (Fauvelle, 2025). Indeed, the use of money is well documented across different historical contexts and societies, as shown by both archaeological artifacts and abstract systems of value accounting and debt (e.g., tally sticks, paper, gold, salt, cowrie shells) (Demps and Winterhalder, 2019). Despite great variation in other aspects of culture such as beliefs, social norms, or material practices, money-mediated exchange appears to be universal across many different social formations, especially as their size increases (Fauvelle, 2025; Haour and Moffett, 2023; Hudson, 2020; Kuijpers and Popa, 2021; Shin et al., 2020). For instance, recent archaeological studies report evidence of monetary-like exchange mechanisms taking place as early as the Late Pleistocene, with evidence from regions such as China and the Levant (Richter et al., 2011; Ridout-Sharpe, 2015; Singh and Glowacki, 2022; Xie et al., 2025).

The debate about the importance of generalized reciprocity for the evolution of human societies, and the evidence of the prehistoric, widespread diffusion of money calls for a deeper analysis of the role that money may have played in shaping the evolution of cooperation. To study this, we implemented a mechanism of money exchange for cooperative actions in an evolutionary game-theoretic simulation model (Guth and Kliemt, 1998; Welser et al., 2007; Back and Flache, 2008; bin Oslan, 2024) where we assumed that agents hold an initial number of tokens — goods or marks recorded in a reliable ledger — that have no intrinsic value and confer no evolutionary advantage by themselves. These collections constitute an agent’s personal balance: countable, privately held, and nonperishable. We assumed that some agents would prefer to cooperate on the condition that they receive units of these balances in immediate exchange. These agents will expend the costly effort associated with cooperation only if their partner has a token and is willing to transfer that token in exchange for help. Specifically, they would be motivated to cooperate at a cost ( $c$ ) at time  $t$  in exchange for a token that they can later use to obtain cooperation from other agents — e.g., to secure their desired goods — at  $t + 1$ , thereby receiving a benefit  $b > c > 0$ . The ratio between benefits and costs of cooperation,  $\frac{b}{c}$ , is a key parameter of our model. Note that without receiving

tokens, agents following this monetary exchange strategy would have no incentive to cooperate at all and would therefore defect.

We expect this strategy to maintain a population-level cooperation equilibrium when becoming widely adopted (Bigoni et al., 2020; Camera et al., 2013). To test this hypothesis, we embedded agents following this monetary exchange strategy in a heterogeneous population under selective pressure similar to an evolutionary tournament (Axelrod, 2006; Back and Flache, 2008; Nowak and Sigmund, 1992), which included four other types of competing strategies in a indefinitely repeated helping game with random-matching (Axelrod and Hamilton, 1981; Bigoni et al., 2019; Camera et al., 2013; Nowak and Sigmund, 1998; Tkadlec et al., 2023). We initialized a balanced population of size  $N = 500$  (Hauert and Doebeli, 2004; Nowak and Sigmund, 1992; Riolo et al., 2001), consisting of unconditional cooperators (always help, i.e., produce goods at cost  $c$ ) defectors (never help, i.e., benefit only by receiving help from others), and both direct (helping only those who have not defected against the agent in previous encounters) and indirect reciprocators (helping only agents with a good reputation), in addition to agents following the monetary exchange strategy.

We implemented a relatively robust version of standard reciprocity strategies, in which direct reciprocators had no memory constraints, reputation was fully visible and noise-free, and agents could not make mistakes (Hilbe et al., 2017; Nowak and Sigmund, 1998; Panchanathan and Boyd, 2003, 2004). At each iteration of the tournament, agent strategies were probabilistically adjusted based on the in-round fitness of the surviving alternatives, following a roulette wheel selection process (Nowak and Sigmund, 1998; Tkadlec et al., 2023). As main results, we evaluated the evolutionary stability of each strategy and the overall cooperation rate at the population level.

This design served three purposes. First, it allowed us to test whether, and under what conditions, the monetary exchange strategy could be widely adopted even in a population where other conditional cooperation strategies were initially present. This ensured that the eventual success of the monetary exchange strategy was not driven by a lack of plausible alternatives.

Second, it allowed us to identify the specific aspects of the monetary exchange strategy that distinguish it from reciprocity-based strategies and directly influence the evolutionary trajectories of the population. For instance, the so-called *second-order defection problem* (Nowak and Sigmund, 1998; Okada, 2020) poses significant challenges to the ability of reputation-based mechanisms to sustain cooperation in the long run. Even relatively complex indirect reciprocity strategies that successfully eliminate defectors can become vulnerable to invasion by unconditional

cooperators, which ultimately reintroduces an evolutionary advantage for mutations that promote defection. This determines recurrent cycles of defection and cooperation. For cooperation to be evolutionarily stable, strategies are needed that, unlike most reciprocity strategies, eliminate both unconditional defectors *and* cooperators from mixed populations. Money fulfills exactly this function.

Finally, our design allows us to precisely identify the evolutionary mechanism through which the monetary exchange strategy exploits and ultimately displaces reputation-based reciprocity as the dominant strategy for promoting cooperation. This could open up new avenues for research into whether, and under what conditions, such a transition may have occurred during specific periods of human history when alternative mechanisms were needed to sustain cooperation as social groups grew in size.

## The model

We consider a population of  $N$  agents ( $N = 500$ ) playing an indefinitely repeated helping game with random matching. At each time step  $t$ , each agent is paired with a randomly selected partner and must choose an action, either to cooperate ( $a_i^t = \text{Coop}$ ) or defect ( $a_i^t = D$ ). Cooperation involves providing a benefit  $b$  to the partner (referred to as ‘help’ in the game) and incurring a cost  $c$  (with  $b > c > 0$ ), while defection involves withholding help, providing no benefit and incurring no cost (Nowak, 2006). We define an agent’s fitness,  $f_i^t$ , as the difference between benefits received and costs paid in a given round. For most agents, in-round fitness will simply be either  $b - c$  (if they provide and receive help),  $b$  (if they only receive help),  $-c$  (if they only provide help), or zero (if no help is provided or received). Because partner assignment is stochastic, multiple agents may occasionally face the decision of whether to help the same counterpart. In such cases, if these multiple agents provide help, the recipient’s fitness may exceed  $b$ . Let  $h^t$  denote the number of agents assigned to help  $i$  in the current round, if  $h^t > 1$ , and all of them cooperate and the recipient does not provide help to its counterpart, then recipient’s fitness can reach  $h^t \times b$ . For simplicity, we fixed  $c$ , and we determined  $\frac{b}{c}$  by exploring a wide range of benefit-cost ratios, going from exceptionally low ( $\frac{b}{c} = 1.25$ ) to extremely high ( $\frac{b}{c} = 100$ ). Equation (1) summarizes these relationships:

$$f_i^t = \mathbf{1}_{\{a_i^t = \text{Coop}\}}(-c) + \sum_{j=1}^{h^t} \mathbf{1}_{\{a_j^t = \text{Coop}\}} b \quad (1)$$

where  $\mathbf{1}_{\{a'_i=Coop\}}$  is an indicator equal to one if agent  $i$  helps the randomly matched partner,  $h^t$  denotes the number of agents assigned to help  $i$  in the current round, and  $\mathbf{1}_{\{a'_j=Coop\}}$  is an indicator equal to one if agent  $j$ , assigned to help agent  $i$ , actually does so.

In the evolutionary tournament, agents decide whether to play  $a'_i = Coop$  or  $a'_i = D$  according to one of five exogenously assigned strategies (Back and Flache, 2008), which are initially equally distributed in the population: (i) *unconditional cooperation*, whereby agents always play  $a'_i = Coop$  and help their randomly matched partners; (ii) *defection*, whereby they never help their current partners; (iii) *direct reciprocity*, whereby they help their current partners provided those have not defected against them in previous interactions; (iv) *indirect reciprocity*, whereby they help provided partners hold a good reputation as cooperators; and (v) *monetary-exchange*, whereby they help their partners as long as those can transfer one unit of their token balances in exchange for help. We assume that agents follow these predefined scripts, which specify their behavior in the cooperation dilemma (Back and Flache, 2008; bin Oslan, 2024). However, under environmental pressure, agents may revise their strategies by adopting alternatives that currently yield higher fitness in the population.

We implemented robust versions of each reciprocity strategy. All agents maintain a memory “blacklist” that records previous defectors. Direct reciprocators cooperate only with partners who are not on their list. Otherwise, they punish those who have previously failed to help them by defecting. The punished partner is then removed from memory, allowing cooperation to resume (Hilbe et al., 2017). Each agent also has a personal reputation score, or *standing* (Panchanathan and Boyd, 2003). Indirect reciprocators cooperate only if their partner has “good” standing; otherwise, they defect (Panchanathan and Boyd, 2003). Cooperation sets an agent’s standing to “good”, while defection can be *justified* or *unjustified*. Justified defection, against a partner with “bad” standing, leaves the defector’s standing unchanged. This is the case, for instance, of an indirect reciprocator refusing to help a defector. Unjustified defection against a partner with “good” standing sets the defector’s standing to “bad”. This applies to defectors in general and may also apply to money users who refuse to cooperate with a partner who has “good” standing but no tokens. All agents start with “good” standing (Panchanathan and Boyd, 2003). We assume perfect memory and fully observable, noise-free reputation scores.

Rather than the famous image-score model of Nowak and Sigmund (1998), we adopt the standing-based indirect reciprocity model of Panchanathan and Boyd (2003) because standing prevents defection

cascades triggered by punishing defectors among indirect reciprocators. However, we also present results using image scores in the Supplementary Information (SI) file.

The initial amount of money held by each agent is derived from a *liquidity* parameter as follows: For a liquidity value of 1, each agent is initialized with one unit of money; for values greater than 1, each agent receives the corresponding units of money; for values lower than 1 (e.g., 0.5), only the corresponding percentage of agents (e.g., 50%) are randomly given one unit of money.

The relevance of memory, standing, and monetary balances depends on the strategy an agent follows. For example, monetary-exchange agents maintain a memory list, but they do not use it to guide their cooperation decisions. Similarly, direct reciprocators may hold money balances, yet their actions are unaffected by the monetary holdings of others. In short, agents’ attention to personal characteristics or resources of others depends on their strategy.

Figure 1 visually summarizes the main endogenous effects of cooperation and defection on fitness and other important agent-level variables. Regardless of the strategy an agent follows, cooperative actions always reduce the fitness of the helping agent by  $c = 1$ . At the same time, cooperation establishes the agent’s standing as “good”. The recipient receives a fitness

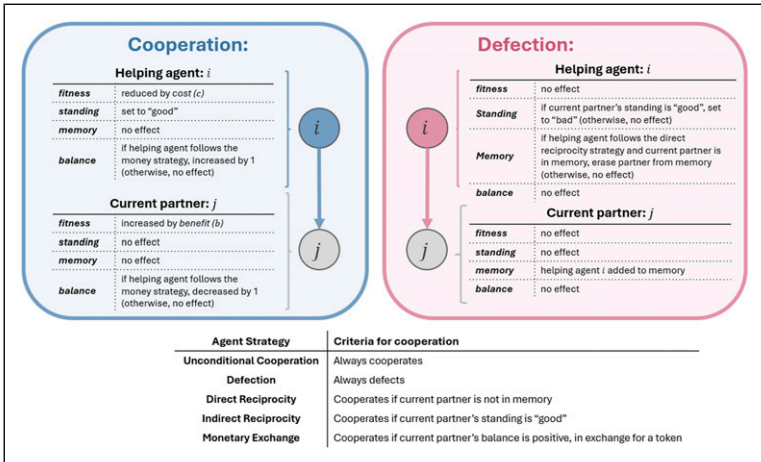


Figure 1. Summary of the endogenous effects of cooperation and defection on key agent-level variables, along with a brief description of the conditions under which each strategy chooses to cooperate.

increase of  $+b$ , where  $b$  is determined by the benefit-to-cost ratio as follows:  $\frac{b}{c} \times c = b$ . If the helping agent follows the monetary exchange strategy, their token balance increases by one unit and the recipient's token balance decreases by one unit. As previously discussed and summarized in the table in the middle of [Figure 1](#), this monetary exchange can only occur if the recipient has at least one token in their balance at the time of the interaction.

Defection does not affect the fitness of either the helping agent or the recipient. It does, however, affect the agents' memory. When an agent defects, the partner adds the defector to their memory list (if they were not already present). Conversely, if the defecting agent follows a direct reciprocity strategy, this action may 'free' a previously stored agent from the list, effectively removing them from memory. Thus, direct reciprocators do not follow a grim trigger strategy, such as 'if you defect once, I will defect forever' ([Friedman, 1971](#)).

Defection also has no effect on token balances. If an agent following the monetary exchange strategy refuses to help a recipient who lacks tokens to exchange, the agent's token holdings remain unchanged. Here, we assume that there is no retaliation, as recipients who do not receive help do not steal or damage the wealth of the agent who refused to help. Finally, defection results in a loss of reputation, setting an agent's standing to "bad" when the defection is unjustified, that is, when an agent withholds help from a "good" standing partner.

At each step  $t$ , each agent is randomly paired with a partner and decides whether to provide help based on their current strategy and relevant variables, such as personal memory, token balance, or standing, either theirs or their partner's. After all interactions, the fitness of the agents is evaluated following equation (1). Then, a randomly selected agent may revise its strategy with a probability proportional to the relative fitness of the surviving alternatives observed in that round, following a roulette wheel selection process ([Nowak and Sigmund, 1998](#); [Tkadlec et al., 2023](#)). In practice, this means that agents are more likely to adopt strategies that have been most successful in the current round, while those already playing successful strategies are unlikely to switch. Barriers to strategy change thus emerge endogenously and are continuously updated as new outcomes are introduced into the population.

Since  $c = 1$ , we increase the fitness of all agents by  $+1$  to ensure non-negative values when calculating reproduction probabilities, particularly in cases where an agent cooperates but receives no help in return ([Nowak and Sigmund, 1998](#)). The roulette wheel selection process allows us to keep the population size constant while introducing random noise into the selection

mechanism. For simplicity and without loss of generality, the fitness values of the agents are reset at the end of each step.

We rely on two output metrics to evaluate the success of each strategy and its consequences. First, we track the number of agents adopting each of the five strategies over time. Second, we evaluate the overall cooperation rate, defined as the number of helping actions (i.e., a cooperation counter) divided by the total number of interactions taking place during each time step (Riolo et al., 2001; Hilbe et al., 2017; Schmid et al., 2021). The cooperation counter is reset at the end of each time step, after saving the previous value. To optimize memory usage without losing essential information, simulation data were stored locally at intervals of 250 time steps.

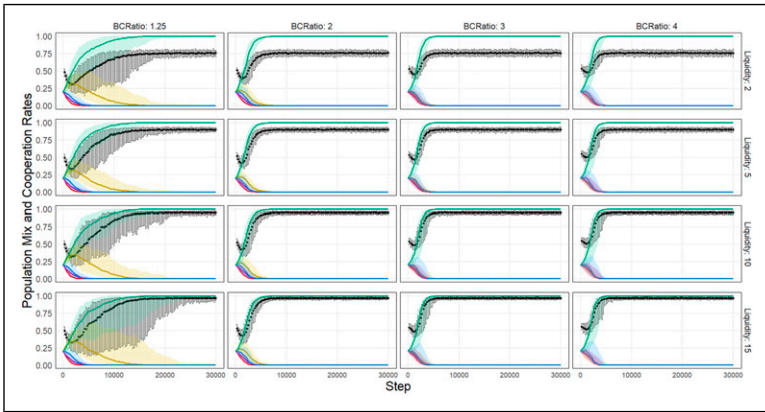
We examined the following 10 parameter values for  $\frac{b}{c}$  ratios: {1.25, 1.5, 2, 3, 4, 5, 10, 20, 50, 100}. We also varied the liquidity parameter across 14 possible values: {0.25, 0.5, 1, 2, 3, 5, 10, 15, 20, 25, 35, 50, 75, 100}, generating 140 possible parameter combinations that could influence evolutionary selection and overall cooperation rates. For each parameter combination in each scenario, we ran 100 parallel repetitions. All simulations were run for 30,000 steps to ensure sufficient duration to capture the long-term equilibrium effects of agent interactions. For instance, this means that each agent is selected on average 60 times to potentially update its strategy. The SI file presents a benchmark scenario without the monetary strategy (evaluating the evolutionary performance of reciprocity-based strategies when competing exclusively with unconditional cooperators and defectors), as well as further robustness checks for selected parameter combinations.

## Results

### *The success of money: Representative trajectories*

Figure 2 shows representative evolutionary trajectories of populations starting with an even distribution of strategies. The monetary exchange strategy consistently thrives in this region of the parameter space. This pattern remains robust across a wide range of liquidity values: even modest initial liquidity (for example, when agents are endowed with only two tokens) enables the monetary exchange strategy to outperform all others and eventually dominate the population across various benefit-cost ratios.

When the monetary exchange strategy is widely adopted, population-level cooperation rates tend to show low variability, as indicated by the increasingly narrow interquartile ranges, thereby stabilizing cooperation around a particular equilibrium cooperation level. However, an equilibrium of full cooperation in the population does not always emerge when the

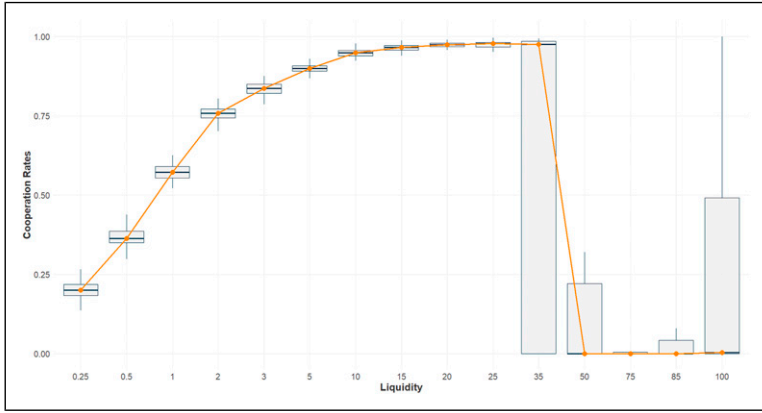


**Figure 2.** Evolutionary dynamics of population composition and cooperation in the tournament model under selected benefit-to-cost ratios and liquidity levels. Lines show the median population share of each surviving strategy over time, with shaded ribbons indicating interquartile ranges (IQR). In the online color version, green, yellow, red, light blue, and purple denote agents following the monetary exchange strategy, defectors, unconditional cooperators, indirect reciprocators, and direct reciprocators, respectively. In the printed (black-and-white) version, these strategies are distinguished by unique markers: stars, triangles, circles, diamonds, and squares. The black line and associated error bars indicate the median and IQR of the overall cooperation rate.

monetary exchange strategy proliferates because, depending on the initial liquidity levels, agents may lack sufficient balances to compensate their randomly matched partners for cooperation. Consequently, the stabilization of cooperation through the money mechanism only generates higher payoffs for the entire population when liquidity levels are sufficiently high (Figure 2).

### The excess liquidity effect

Figure 3 more clearly shows how initial liquidity levels affect overall cooperation rates when the returns to cooperation are low, as a selected case ( $\frac{b}{c} = 1.25$ ). Under these conditions, the monetary exchange strategy tends to dominate all others, even when initial liquidity is scarce (Figure 2). In such cases, final cooperation rates are low because there are few money units in circulation, and cooperative actions occur only when a money user meets a counterpart with positive balances. As liquidity increases, cooperation rates rise according to a non-linear relationship, reaching a saturation point at



**Figure 3.** Cooperation rates across different levels of initial liquidity at the 30000th simulation step. The line connects the medians of the distributions of cooperation rates across liquidity levels, highlighting the overall trend and the excess liquidity effect. Here, the benefit-cost ratio was held constant at 1.25.

100%. At moderately high liquidity levels, the monetary exchange strategy outperforms other strategies while maintaining very high cooperation rates, as most agents have sufficient money balances to exchange in most encounters (Figure 3). However, at extremely high initial liquidity levels, cooperation is fragile: the stability of the monetary exchange strategy may be compromised, and defectors may proliferate.

To better understand these dynamics, consider two extremes. With zero initial liquidity, agents following the monetary exchange strategy always defect: there is no incentive for them to cooperate since no agent in the population holds money. On the other hand, with infinite liquidity, these agents behave as unconditional cooperators: they cooperate in every interaction, since each partner always has sufficient balances to exchange for help. In this case, even defectors continuously benefit from the cooperation of these agents at no cost.

At intermediate levels of liquidity, the use of money becomes a discriminator strategy, similar to the famous ‘green beard’ effect (Dawkins, 1981; Hamilton, 1964). Through multiple transactions, tokens eventually become concentrated among agents who follow the monetary exchange strategy because they are the only ones who demand them. As a result, these agents end up cooperating exclusively with each other, creating a money-induced cooperative circuit that expands as the monetary exchange strategy spreads. At these intermediary liquidity levels, cooperation actions within the

circuit increase nonlinearly with liquidity: as tokens become more widely available, agents are more likely to have sufficient balances to exchange for help, leading to higher cooperation rates. However, when liquidity is extremely high, a tipping point is reached where the discriminatory effect ceases to work, and defectors may manage to stay in the money-induced cooperation circuit. With excessive liquidity, token ownership no longer reflects previous cooperative actions, allowing defectors to continuously obtain cooperation without reciprocating. Consequently, the monetary exchange strategy loses its evolutionary advantage in favor of costless defection.

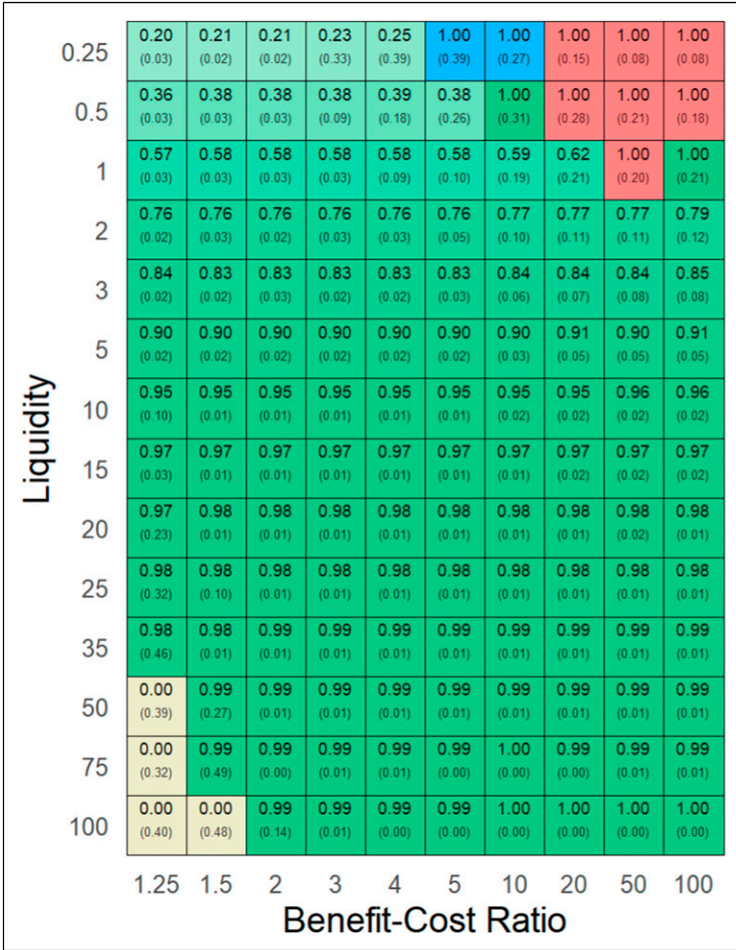
### *Exploring the parameters space: The money-induced cooperation circuit*

Figure 4 provides a comprehensive overview of how different combinations of benefit-cost ratios and liquidity levels affect equilibrium cooperation rates and population composition. The results show that the monetary exchange strategy emerges as an evolutionary stable strategy supporting cooperation across a broad ‘goldilocks zone’ within the parameter space. However, at the edges of this space, alternative strategies can dominate.

One notable exception is provided by the previously discussed ‘excess liquidity effect’, which we now delimit more precisely: it occurs when liquidity is high *and* the returns to cooperation (i.e., the  $\frac{b}{c}$  ratio) are low. Indeed, at high benefit-cost ratios, even substantial levels of liquidity do not undermine cooperation (Figure 4). Conversely, at low benefit-cost ratios, high levels of liquidity are detrimental to cooperation (Figures 3 and 4), as defectors proliferate. This highlights the need to ensure an adequate supply of tokens in the system to sustain cooperation when its benefits are minimal.

When the benefits of cooperation are very high, but liquidity is extremely low, cooperation remains strong (see Figure 4) but is instead supported by the indirect reciprocity ‘standing’ strategy of Panchanathan and Boyd (2003), or by a mix of such indirect reciprocators and unconditional cooperators. In these cases, although cooperation persists, it is no longer driven by money-mediated interactions.

The success of the monetary exchange strategy depends on the emergence of the money-induced exchange circuit, which expands over time as tokens become increasingly concentrated within and circulate exclusively among agents who condition their cooperation on receiving a token in return. Access to this circuit is therefore restricted: agents outside it can participate only by adopting the monetary strategy themselves. In doing so, they reinforce and extend the circuit, generating a self-reinforcing lock-in effect. By adhering to



**Figure 4.** Cooperation rates and dominant strategy in the population at the end of the simulation (30000th step) for broader combinations of benefit-to-cost ratios and liquidity values. Larger numbers indicate the median cooperation rate for each combination of benefit-to-cost ratio and liquidity level, with smaller numbers in parentheses indicating the standard deviations over 100 independent runs. The dominant strategy is indicated by color in the online version and by cell pattern in the printed version: money (green; no pattern), defection (yellow; oblique lines), indirect reciprocators (light blue; sparse, large dots), and a mix of indirect reciprocators and unconditional cooperators (red; dense, small dots). A transparency gradient illustrates median cooperation rates across the parameter space, with darker shades indicating higher cooperation.

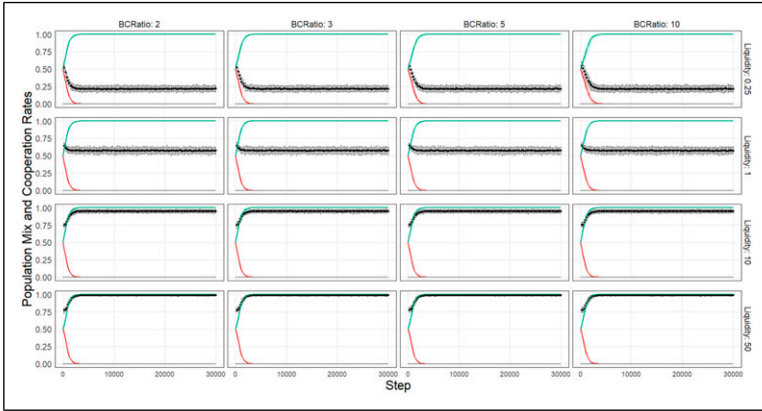
this simple conditional cooperation rule, agents avoid the costs of cooperating with those outside the circuit and pay a fitness cost only to help and support fellow circuit members.

This results in strong *positive assortativity* (Iyer and Killingback, 2020; Nax and Rigos, 2016), creating an impermeable boundary between a non-money user outgroup and a money user ingroup, where cooperative interactions occur. Interestingly, this separation emerges even without requiring agents to actively recognize their fellow members or signal their affiliation through costly or covert actions (e.g. Gambetta, 2011; Smaldino et al., 2018). Instead, a simple litmus test suffices: whether the recipient of one's costly cooperative action possesses a token that can later be used to incentivize others to cooperate. This litmus test not only excludes defectors but also unconditional cooperators and other conditional cooperation strategies from the circuit.

This implies that unconditional cooperators are not 'neutral mutants' of money users (Okada, 2020). In a population consisting only of unconditional cooperators and money users, the latter will eventually stop helping the former while continuing to receive their help, leading to the negative selection of unconditional cooperators (Figure 5). This prevents 'defection cascades' (Nowak and Sigmund, 1998; Okada, 2020) and ensures that a population composed entirely of agents following the monetary exchange strategy remains resistant to late-stage invasions by defectors or defection-promoting mutations. In the SI, we show that forcibly converting half of the population of agents following the monetary exchange strategy into defectors, once it has become dominant, has no long-term consequences for the system (see Figure S3 in the SI). The cooperation rate quickly returns to its pre-invasion level, demonstrating the resilience of the monetary exchange circuit in sustaining cooperation. Moreover, the SI shows that the money-induced circuit remains robust even when invaded by unconditional cooperators or a mix of unconditional cooperators and defectors (Figures S4 and S5 of the SI file).

### *Money exploiting reciprocity strategies*

More nuanced interaction effects reveal how the monetary circuit can emerge and persist even in the presence of competing conditional cooperation strategies, such as those based on reciprocity in our evolutionary tournament. These effects also help explain why indirect reciprocity, or a mix of indirect reciprocators and unconditional cooperators, prevails in situations of low liquidity and extremely high benefit-cost ratios.



**Figure 5.** Evolutionary dynamics of population composition and cooperation in the tournament model under selected benefit-to-cost ratios and liquidity levels, starting from a population of unconditional cooperators (red online, circle marker printed) and agents following the monetary exchange strategy (green online, star marker printed). Lines show the median population share of each surviving strategy over time, with shaded ribbons indicating interquartile ranges (IQRs). Ribbons are barely visible due to minimal variability, as the monetary exchange strategy quickly outcompetes and eliminates unconditional cooperators. The black line and error bands indicate the median and IQR of the overall cooperation rate.

Conditioning cooperation on the reputation of partners creates a cooperative circuit in parallel with the circuit formed by agents who follow the monetary exchange strategy. Defectors acquire a “bad” standing immediately after initialization, and are excluded from the “reputation circuit”, whereas unconditional cooperators always maintain a “good” standing and are included.

Even at low levels of liquidity, agents following the monetary exchange strategy initially behave like unconditional cooperators. This allows them to maintain a “good” standing with indirect reciprocators, giving them access to the reputation circuit. At the same time, they avoid “blacklisting” by direct reciprocators. Consequently, they receive help from unconditional cooperators, direct reciprocators, and indirect reciprocators.

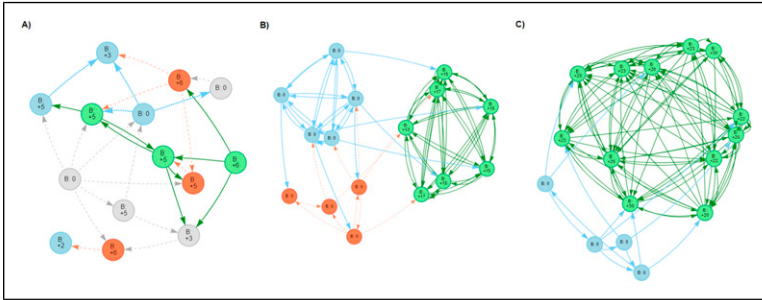
However, this equilibrium is temporary. It collapses once the token balances of competing strategies are completely exhausted. The rate at which this happens is inversely proportional to total liquidity. When depletion occurs, agents following the monetary exchange strategy stop cooperating with reciprocity-based strategies altogether, though they continue to receive

help from direct and indirect reciprocators. Focusing specifically on indirect reciprocators, money users continue to help one another within the money-induced circuit. This allows most agents to maintain a “good” standing and thus continue receiving help from indirect reciprocators. In other words, money users never completely lose access to the reputation-based circuit. Indirect reciprocators permanently lose access to the monetary circuit once their tokens are depleted. Only under conditions of very low liquidity ( $< 1$ ; [Figure 4](#)), does cooperation within the monetary circuit become too infrequent to sustain a “good” standing for most money users. When combined with very high benefit-to-cost ratios, which generally benefit unconditional cooperators (see SI), indirect reciprocators eliminate the monetary exchange strategy in these exceptional settings.

Apart from these extreme corner cases, money users generally exploit reciprocity-based strategies in ways that resemble defectors. Unlike defectors, however, they continue to cooperate with one another within the monetary circuit. This dual behavior provides a strong evolutionary advantage to the monetary exchange strategy, enabling it to “piggyback” on other conditional cooperation strategies and ultimately crowding them out. The key lies in the asymmetric permeability of the two cooperation circuits: while monetary users can access reputation-based circuits, reciprocity-based strategies cannot penetrate the monetary circuit.

As a robustness check, [Figures S6-S9](#) in the SI include alternative versions of [Figures 2](#) and [4](#), where the initial population exclusively consists of unconditional cooperators, defectors, and agents following the monetary exchange strategy. These tests confirm that the mechanisms and results described here remain consistent, even when the monetary exchange strategy does not piggyback on reciprocity strategies. In short, the monetary exchange strategy has a strong evolutionary advantage due to its ability to establish and maintain an expanding circuit in which cooperation occurs exclusively among participating agents.

[Figure 6](#) provides a distilled visualization of this mechanism in a simplified setting. In panel A, we observe the early stages of the tournament. Cooperation between agents is shown as directed links: solid arrows for monetary exchange users, thicker dotted arrows for indirect reciprocators, and thinner dashed arrows for the remaining strategies. Initially, money users can cooperate with all other strategies, provided that those agents have a positive token balance  $B$ . Indirect reciprocators cooperate with others if partners have a “good” standing (thicker dotted arrows), while the remaining strategies — direct reciprocators, unconditional cooperators, and defectors — may or may not cooperate, as indicated by dashed arrows. Over time (panel B), token balances concentrate among



**Figure 6.** Simplified representation of the evolution of the money-induced cooperation circuit across the initial (a), intermediate (b), and final (c) stages. Cooperation is depicted as directed links. Agents adopting the monetary exchange strategy are identified by solid outgoing links (highlighted in green in the online version), and their number increases over time due to their evolutionary success. Indirect reciprocators are represented by thicker dotted outgoing links (highlighted in light blue online), while all other strategies are shown with thinner dashed links. Unconditional cooperators are highlighted in coral in the online version and in a darker shade of gray in the printed version. Token balance is denoted by B.

money users, who begin forming a cooperative circuit encompassing an increasing number of agents adopting this strategy. Simultaneously, a parallel circuit emerges, primarily composed of indirect reciprocators and unconditional cooperators, whereas most defectors and direct reciprocators become marginalized or eliminated.

Crucially, as money users begin to cooperate exclusively among themselves once other agents have depleted their tokens, they continue to receive help from unconditional cooperators and indirect reciprocators. This is because most money users maintain a “good” standing by cooperating within their own circuit. In effect, they create an asymmetrically semi-permeable group boundary: they receive cooperation from others without reciprocating outside the monetary circuit. This gives the monetary exchange strategy an evolutionary advantage, allowing the circuit to expand through self-reinforcing dynamics (panel C) until, at equilibrium, all agents adopt the strategy.

As discussed above, the system’s stability faces two potential threats. First, an excessively high initial token supply combined with low returns to cooperation enables defectors to retain access to the monetary circuit and eventually undermine it from within. Second, very low liquidity can render the monetary circuit sparse — money users cooperate infrequently, and thus most agents have a “bad” standing — allowing the circuit of indirect

reciprocators and unconditional cooperators to expand and dominate the population. This, however, occurs only when returns to cooperation are extremely high.

## Discussion

Our results indicate that the monetary exchange strategy can evolve into a stable, dominant equilibrium within an initially heterogeneous population by establishing a self-sustaining circuit of money-contingent cooperation. This occurs even in the presence of other conditional cooperation strategies, while also enhancing and stabilizing population-level cooperation across a wide range of benefit-cost ratios and liquidity levels. At the same time, we also find that the stability of this mechanism depends critically on liquidity: excessive liquidity can destabilize monetary cooperation when the benefits of cooperation are low, whereas insufficient liquidity undermines it when benefits are very high. The role of liquidity in the success of the monetary exchange strategy is thus analogous to key parameters in other evolutionary models of cooperation, such as genetic relatedness, the likelihood of repeated interactions, or the visibility of reputation (Nowak, 2006).

In “Five Rules for the Evolution of Cooperation”, Nowak writes: “[...] Direct reciprocity is like a barter economy based on the immediate exchange of goods, whereas indirect reciprocity resembles the invention of money. The money that fuels the engines of indirect reciprocity is reputation” (Nowak, 2006, p. 3). Our model suggests that money *itself* should be seen as a generalized reciprocity mechanism: a special form of token-mediated reciprocity providing a kind of *sixth rule* for the evolution of cooperation. This simple rule consists of *cooperating with agents who have positive money balances, not cooperating otherwise, and cooperating only in exchange for a transfer of money*. This guarantees the formation of the self-policing circuits necessary to promote generalized reciprocity. Provided that liquidity remains within reasonable limits, agents will only cooperate with those who have previously cooperated with others and can prove it by exchanging a money token.

Unlike the individual links in direct reciprocity, or the within-group cycles of cooperation sustained by reputation in indirect reciprocity, money creates a stable, self-sustaining circuit of cooperation. This does not require individuals to keep track of personal interactions or rely on any form of group-level communication or gossip (Nowak, 2006). Notably, this advantage arises even when these cognitive, informational or social costs are not explicitly included in the fitness functions for direct and indirect reciprocators. Each transfer of money between pairs of agents corresponds to a cooperative action in the opposite direction, linking individuals in a long

chain of decentralized, anonymous cooperation. In this sense, money functions as a form of ‘social memory’ (Hart, 2000; Kocherlakota, 1998), providing information about past cooperative actions within a given population.

This seems to reflect the way reputation facilitates the generalization of cooperation in indirect reciprocity. However, unlike in reputation-based systems, the monetary circuit can police itself. As tokens held by other agents migrate to agents following the monetary exchange strategy through multiple transactions, both unconditional cooperators and defectors are gradually excluded from the circuit of money-induced cooperation as their token supply is depleted. This dynamic provides a novel solution to the first and second-order free-rider problems (Okada, 2020), making the monetary exchange strategy resilient to defection cascades that typically weaken reciprocity-based mechanisms.

The success of the monetary mechanism is also driven by two key differences between money and indirect reciprocity. The first is *interdependence*. In reputation-based systems, only the reputation of the agent in the helping role is updated after cooperation or defection, while the recipient’s reputation remains unaffected (Nowak and Sigmund, 1998; Panchanathan and Boyd, 2003). This is because reputation ultimately exists in the ‘eyes of the beholder’ (Nowak and Sigmund, 2005) and subsequently reaches other agents through gossip or other forms of nonverbal communication. In contrast, in a monetary exchange, both agents’ balances are updated simultaneously: a positive change in the cooperator’s balance is accompanied by an immediate and opposite change in the counterpart’s balance (see Figure 1). This reflects the tangible transfer of money that is contingent upon the completion of a cooperative action and binds both agents involved in the exchange.

The second difference is *control*. Reputation is largely beyond personal control, as it is determined by the judgments of others, whereas in a monetary mechanism agents voluntarily agree to an exchange (Freen and Marsland, 2023). This translates into a key difference when agents defect: in the monetary mechanism, agents’ balances remain unchanged and do not affect their ability to secure future cooperation from others who value money. In addition, the actions of agents following other strategies do not affect money balances — only agents following the monetary exchange strategy affect their distribution within the population. In contrast, reputation is dynamically updated after each action taken by each agent, reflecting a more passive and latent system of judgment over which individuals have little to no control.

Our model also shows that the stability of the monetary circuit depends on a delicate balance between the total number of tokens in circulation and the

frequency of cooperative actions taken by agents. The main threat to this stability arises when defectors have a significant stock of tokens. Such a stock of tokens allows them to masquerade as a trustworthy party with a history of extensive cooperation and thus continuously benefit from the cooperative actions of agents following the monetary exchange strategy without reciprocating. In other words, an oversupply of money in the system disrupts the information signal that tokens carry about past cooperative behavior. These findings are consistent with empirical observations of money oversupply (Friedman, 1994) and recent experimental studies on the relationship between tokens and cooperation (Bigoni et al., 2020). Moreover, they shift the issue of free-riding and defection from interpersonal dynamics to higher-order institutional concerns such as inflation, counterfeiting, and inequality. While the monetary strategy can effectively solve interpersonal cooperation problems by excluding defectors from the circuit, it simultaneously shifts the locus of trust to the institutional framework that must support the proper functioning of the monetary circuit itself (Giddens, 1990), especially in situations where the returns to cooperation are relatively low.

Our model necessarily relies on simplifying assumptions that could be relaxed in future extensions. First, we assumed that agents who do not care about money are always willing to give it away to obtain cooperation, regardless of their remaining token balance. In other words, agents begin to value money only once they adopt the monetary exchange strategy themselves. One possible extension would be to allow non-money users to act more strategically. For example, refraining from requesting help from money users when their token balance is low, knowing that once it reaches zero, they will no longer receive help. Another modification could introduce a stochastic mechanism that increases token holdings even among agents who do not condition their cooperation on monetary exchange. For instance, if tokens were cowry shells, such agents might occasionally find them on the shore or while fishing, without engaging in monetary transactions.

Second, we assumed that all agents have the same preference for receiving a single type of token in exchange for cooperation. Future research could investigate how a population in which agents initially prefer different token types might converge on a single, socially accepted medium of exchange that facilitates generalized cooperation. Additionally, the model endogenously generates an unequal distribution of token holdings, opening the door to explore the effects of wealth inequality. For instance, wealthier agents might stop investing effort to acquire additional tokens and instead engage in unproductive activities and leisure, effectively becoming defectors. Modifications could also allow agents' cooperation decisions to depend on the amount of token holdings of their partners, creating the potential to introduce

a price system and explore bargaining processes in which money users choose to engage in exchanges based on the expected gains from trade.

Having said this, our modeling framework also raises intriguing questions for research on cultural evolution. We have argued that the monetary exchange mechanism allows agents to offload the cognitive effort required to track past interactions, either via personal memory or in-group reputation, onto tokens, which function as synthetic indicators of prior cooperation. In this sense, money, whether in the form of tangible objects or virtual records, can be viewed as a distinctive numerical correlating device (Bowles and Gintis, 2013; Guala, 2020) or social cognitive artifact (Aoki, 2011) that facilitates cooperation through the shared social value attributed to tokens. Put differently, money provides a means to “unburden” (Guala, 2020) individuals from the cognitive demands of monitoring multiple personal interactions.

At the same time, while the monetary strategy is cognitively simple for individual agents—it only requires checking whether a partner has a token—it is relationally complex. Successful exchanges depend on both parties agreeing on the token’s value, verifying its authenticity, counting it, and ensuring that cooperators receive what they are due through enforceable arrangements. This necessitates symbolic abstractions that are likely to emerge only within a supportive social environment, including predictable rules and trust. In effect, the cognitive burden that money alleviates at the individual level is shifted to high-level cognitive demands associated with social norms, rules, and cultural learning.

Furthermore, by directly comparing the evolutionary success of money with that of reciprocity strategies, our model identifies areas for future research into how monetary exchange may have evolved from, or alongside, social mechanisms such as direct and indirect reciprocity. As societies became more complex and differentiated, impersonal interactions with strangers probably increased, putting pressure on social mechanisms that depend on personal memory or reputation. This, in turn, could have generated selective pressure for alternative conditional cooperation technologies capable of bypassing these limitations. Building on our framework, future research could also investigate interconnected issues related to scale and the prevalence of impersonal social and economic interactions. This could include possible evolutionary explanations for the human tendency to assign value to tokens (Harwick, 2023; Simmel, 2011[1900]), the dependence of money and other impersonal institutions on pre-existing psychological and neurological mechanisms that support social exchange (Herrmann-Pillath, 2016, 387), and the differing evolutionary prevalence of biological and cultural mechanisms that sustain human cooperation.

Concurrently, research on cultural evolution, which links the successful trajectory of human societies to the co-evolution of cognition, learning, and complex symbolic artifacts that foster sophisticated cooperation (Creanza et al., 2017), should also consider the role of money and its institutional regulation (Dodd, 2014; Ganßmann, 2013; Ingham, 2004; Maurer, 2020; Orléan, 2020).

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The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Data Availability Statement

The model was implemented in both NetLogo (version 6.4.0) (Wilensky, 1999) and C++ (C++17 standard). To ensure full reproducibility, the SI file includes the model pseudocode and a detailed execution flowchart. The simulated data were analyzed using R (version 4.3.3). The Supplementary Information file, the open-source code for both implementations, the data used to generate the figures, and the data analysis scripts are all available at: <https://github.com/ceco51/money-generalized-cooperation-reciprocity/tree/main>.

### Supplemental material

Supplemental material for this article is available online.

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