Evolution of global contribution in multi-level threshold public goods games with insurance compensation

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Received 8 September 2017
Accepted for publication 18 November 2017
Published 22 January 2018

Online at stacks.iop.org/JSTAT/2018/013403
https://doi.org/10.1088/1742-5468/aa9bb6

Abstract. Understanding voluntary contribution in threshold public goods games has important practical implications. To improve contributions and provision frequency, free-rider problem and assurance problem should be solved. Insurance could play a significant, but largely unrecognized, role in facilitating a contribution to provision of public goods through providing insurance compensation against the losses. In this paper, we study how insurance compensation mechanism affects individuals' decision-making under risk environments. We propose a multi-level threshold public goods game model where two kinds of public goods games (local and global) are considered. Particularly, the global public goods game involves a threshold, which is related to the safety of all the players. We theoretically probe the evolution of contributions of different levels and free-riders, and focus on the influence of the insurance on the global contribution. We explore, in both the cases, the scenarios that only global contributors could buy insurance and all the players could. It is found that with greater insurance compensation, especially under high collective risks, players are more likely to contribute globally when
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only global contributors are insured. On the other hand, global contribution could be promoted if a premium discount is given to global contributors when everyone buys insurance.

**Keywords:** evolutionary game theory, evolution models, stochastic processes, inference in socio-economic system

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**Introduction**

Many collective action scenarios [1], such as a group of people hunting large prey, a community group fundraising for a shared resource, neighborhood residents donating money to construct a public project (a dam, a bridge, or a lighthouse) and investing in a national defense, can be represented as public goods games (PGG) [2], which involve the provision of a public good relying on voluntary contributions. Voluntary contributions (e.g. money, energy, or time) are beneficial for the group, but costly for individuals. It is fact that selfish individuals have an advantage over those who act cooperatively. How can the beneficiaries of collective action be persuaded to contribute the money necessary for the effort to succeed? Rational and selfish players will recognize they can free ride on the successful contributions of others. Why should one contribute when there is only a trivial chance that their contribution will make critical difference and when the only other possibilities are that the group effort will be realized without their contribution and that it will not be realized if they do contribute. In more formal terms, the problem is a social dilemma [3]. If individuals follow their self-interest, groups will not attain objectives that all members want. In a natural situation, however, individuals do not always appear to follow their self-interest. Charitable fundraising activity is widespread and substantial [4–7], and understanding it has important practical implications [8–11].

https://doi.org/10.1088/1742-5468/aa9bb6
Voluntary contribution to public goods is often threatened by the immediate advantage of free-riding, which can drive the population into the tragedy of the commons [12]. Research on this question has been conducted by economists [13–15], psychologists [3, 16], biologists [17, 18], and has received increasing interest from physicists [19–21]. In real situations, people are often faced with the option of a voluntary contribution to achieve a collective goal, where public goods are physical (e.g. dams, lighthouses, bridges, railway lines, etc) and cannot be provided in part, but only in whole after a certain cost, called a threshold or provision point, is covered. Threshold public goods game (TPGG) models nicely capture the main features of the above described social phenomena [22–25]. In the typical TPGG, the size of a proposed project and the associated total cost (threshold) are predetermined. The public good is provided if the total contributions meet or exceed the threshold; otherwise, no good is provided and all individuals suffer with nothing irrespective of whether they contributed or not.

Threshold public goods games have been intensively studied both theoretically [26, 27] and experimentally [15, 28]. It is well known that differing from PGG, Pareto-optimal outcomes are supportable as Nash equilibria [26, 27, 29]. Yet, in TPGG experiments, we still see significant under-provision of public goods [30, 31]. A number of factors have been shown to impact voluntary contributions towards the provision of public goods. Corresponding mechanisms that overcome the free or cheap-rider problem in TPGG have been studied by researchers of different disciplines. We give a brief overview of the relevant research as follows. The existence of a threshold in TPGG is positive, in general, for cooperation given that free-riding is no longer the dominant strategy due to the existence of multiple equilibria and the amount of cooperation is affected by the level of the threshold [32–35]. Uncertainty about the threshold level of contributions needed for successful action is one factor that potentially affects individuals’ decisions to participate in a collective action [36–38]. Making information (e.g. threshold level, incomes, and etc) available to players is positive for public goods provision [29, 39]. Experimental studies have shown that a sequential contribution mechanism, where real time adjustments of the voluntary contributions can be made based on other’s previous contributions, may improve public goods provision [40, 41]. The continuous contribution mechanism, where contributions are not restricted to all or nothing, increases the amount of cooperation [36, 42, 43]. The group size and excludability influence the contribution. For instance, designating a minimum contributing set is positive for public goods provision [41, 44, 45]. Selection of group members [46], value orientations [47], social preferences and beliefs about others’ giving [48, 49] are also in favor of cooperation. Economic and psychological studies find that activating the salience of a shared common social identity among individuals increases cooperative behavior [50–53]. Different forms of communication structures have been examined through experiments, e.g. face to face contact [54], free communication via unstructured discussion [44], and structured cheap talk [55], where higher levels of public goods provision have been found [56]. Full agreement [57] and positive framing are in favor of contributions [54]. Introducing a rebate treatment in TPGG is positive for cooperation [43, 58–60]. Other monetary incentives have been studied, such as seed money and refunds [61], matching donations [50], voluntary contribution mechanism (VCM) [42, 58, 62], step return mechanism or marginal per capita return (MPCR) [30, 54]. Researchers have also examined how punishments inhibit or foster successful public goods provision [63, 64]. Recently, many other economics experiments studying
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charitable contributions to public goods provision have been surveyed in review papers [28, 65–67].

Besides the so-called ‘free-rider’ or ‘cheap-rider’ problem, however, there exists another potential incentive problem that makes the provision of public goods difficult. A potential provider can have an incentive to contribute if, and only if, she has a credible guarantee that others will also contribute. Absent such a guarantee, the provider may withhold. An environment exhibiting such incentives, but without a guarantee is said to exhibit the ‘assurance problem’ [68], where one stands to lose money in the event that total contributions fail to reach the threshold. If potential contributors fear the loss of money with no benefit, then the assurance problem can lead to failure in fundraising efforts. Researchers argued that the assurance problem is more serious than free riding in the TPGG [58]. Then, plenty of experimental results reveal that the assurance problem can be mitigated by using a ‘money-back guarantee’. For example, if all the contributions are refunded to contributors when the threshold is not met, then potential contributors do not risk paying for something and getting nothing in return [26]. Although experimental papers which test this prediction provide conflicting evidence [29, 58], money-back guarantee, step-return, refund and rebate rules in experiments have been found to improve contributions and provision frequency by providing insurance against the loss of contributions [30, 43, 45, 59].

Insurance could play a significant, but largely unrecognized, role in facilitating contribution to provision of public goods. For example, building a flood resistant dam requires a minimum amount of contributions for the project to be successfully built. If not, flood will annihilate human populations, physical structures, economic assets, and sensitive environments [69]. Insurance can deal with these losses by providing financial protection following a disaster and encouraging people to invest in cost-effective mitigation measures (public goods). For Hurricane Katrina, insurance companies had paid billions in claims due to financial losses, one of the costliest events in the history of insurance worldwide [70]. By helping households and businesses manage risks, insurance has become an emerging and vital tool in social economy. Property casualty insurance has a long history of combining insurance and risk management to reduce and control risks [71]. In order to witness an integration of risk and insurance issues into general economics, the theory of risk has been developed based on the foundations such as the theory of behavior under uncertainty [72, 73], the application to risk attitudes [74], the analysis of risk aversion [75], and furthermore, the model of general equilibrium under uncertainty [76, 77], the model of portfolio selection [78], and the model of equilibrium capital asset pricing (the CAPM) [79–81]. The purpose of insurance is to allow mitigation of future risks. An entity which provides insurance is usually known as an insurance company. An individual who buys insurance is known as an insured (policyholder). The insurance transaction involves the insured exchanging its risk of a large future loss for smaller payments (premium) paid to the insurance company [82]. The benefits of policyholders include receiving funds such as compensation when a disaster event of a covered loss occurs. The compensation is usually of considerably high value in comparison to the insurance premiums. However, if a catastrophe does not occur, the insurance premiums paid by the insured become burdens [83]. The risk insurance and compensation system is intended to shield property owners and communities from the full costs of living and also economic losses [84, 85]. Insurance is critical to risk
management, due to its financial viability and ability to influence behavioral changes towards more preventive behaviors [86]. However, there is only limited research on how buying insurance affects the decision-making on contribution to provision of public goods under risk environments. Herein we will focus on the issue in this paper.

Pure public goods are defined as being unrivalled in consumption and non-excludable [87]; however, impure public goods exist in reality. Geographic space, distance, occupational area, industrial category and personal interests often act as the possible factors that determine exclusion. Some classes of goods are globally public, and others are only locally public. Global public goods are available to the entire population (including those unable or unwilling to contribute globally) while local public goods may be available only to the residents of a very small neighborhood or a specific population community [65]. The construction of a dam is a typical example of global public goods. It requires a minimum number of contributors for the project to be successfully built. It would not make much sense to provide 1/3 or 2/3 of the dam needed. Thus, full funding is required to provide the public goods, since partial funding would result in no level of public goods provision. If the dam breaks, a flood will probably inundate the whole coastal region due to the unaccomplished and nonfunctional dam. Nearly all coastal inhabitants will be affected [88]. Most of the global public goods involve such a risk characteristics with threshold, such as spread of disease caused by inadequate vaccination [89] and collapse of regional defense system due to insufficient finance [90]. On the other hand, local public goods provide benefits that are much more excludable and only accrue to a specific population or social community. Some fundraising examples in local areas or groups are as follows. The Niagara Mohawk Power Corporation (NMPC) of New York proposed the Green Choice program in 1995 [91, 92], which collected fees from citizens in upstate New York to build an environmentally friendly power station and plant trees in its small service area [59, 60]. Similar green-pricing programs are proposed by Traverse City Light and Power in Michigan and The City of Fort Collins in Colorado [92, 93]. Other examples are: voluntary contributions to raise funds for a new stadium in Seattle [59, 94], for the removal of abandoned roads that continued to provide access to ecologically sensitive areas of Grand Canyon National Park [95], for volunteer water-quality monitoring on an individual water body in Rhode Island [96]. Therefore, individuals will choose among contributions to global or local public goods. It is common that individuals respond more quickly to aid disaster victims when the victims are local [97]. Such bias toward contributing to local needs can be widely noted. While our sympathies may be broad, our capacity to do good is limited and we will devote it to those closer at hand [98]. Thus, there exist different kinds of contributors. Some of them focus on their own local groups, which are divided by geographic scope or population attribution, and only contribute to local affairs, such as regional economics and leisure entertainment. However, the others show great foresight with a global view. They are concerned with the whole population’s sustainable development and devote themselves to global public goods collection. Each individual engages in not only the local PGG in her group, but also the global PGG played among distinct groups. Hence, individuals are simultaneously involved in multi-level PGGs (MPGG) on different hierarchical levels [99]. There exist experimental studies on MPGG [52, 65, 100], however, the theoretical discussion has seldom provided clear answers to the question of the relative propensity to give to the local or global public good.
Motivated by these, we propose a multi-level threshold public goods game model, where there are two kinds of public goods, global public goods and local public goods. In particular, the global public goods game involves a threshold, which is related to the safety of all participants. We clearly distinguish global and local contributions and investigate the role of preferences on individual willingness to contribute to the provision of a local group versus a global public good. We particularly introduce an insurance mechanism into the model, where global contributors could buy insurance for their cooperative activity and pay for insurance company the premium. In accordance with the contractually agreed conditions, such as the collective target fails and disaster strikes, the insured can get compensation from the insurance company; on the contrary, if no disaster occurs, all the premiums belong to the insurance company. Based on this model, we theoretically probe the evolution of contributions of different levels and free-riders under collective risks and focus on the influence of the insurance compensation mechanism on the global contribution. In addition, we explore the case that all the players could buy insurance. We further study how global contribution evolves if a premium discount is given to global contributors.

Model

We assume that all the $N$ players are in a structured population where individuals are divided into $M$ local groups with $m = N/M$ players in each group [101]. Each individual $k$ is assigned a strategy $S_k \in \{S, L, G\}$. Here $S$, $L$ and $G$ represent selfishness, local contribution and global contribution, respectively. There are three accounts, namely, a personal account, a local account and a global account. At the beginning of the game, each individual is given a single unit of money. The option is to decide into which account they put their money. The money put into the personal account is saved without multiplication, which leads to a single unit eventually to the individual. All the units put into the local account are added together. Then, the total amount is multiplied by a local gain-factor $r_1$ ($1 < r_1 < m$), and equally distributed to the individuals within the group. Likewise, the money donated into the global account are summed, and multiplied by a global gain-factor $r_2$. From a social dilemma perspective, we assume $r_1 < r_2 < N$. For the global contributor, their donation is divided into two parts. Most of the money (with a proportion of $c$) is collected for the global public goods. While, the other part of the money is used to buy insurance from insurance company. Then the treasures in the global account are redistributed to all the individuals in the whole population irrespective of whether they are global contributors or not. Denote $\pi^1_G(i)$, $\pi^1_L(l)$ and $\pi^1_S(m - i - l)$ as the payoff of each $G$, $L$ and $S$ player, respectively, when there are $i$ $G$ players, $l$ $L$ players in the local group and the other $N - i - l$ players all hold $S$ strategy in the whole population [102]:

$$\pi^1_S(m - i - l) = \frac{i \times c \times r_2}{N} + \frac{l \times r_1}{m} + 1$$

(1)

$$\pi^1_G(i) = \frac{i \times c \times r_2}{N} + \frac{l \times r_1}{m}$$

(2)
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\[ \pi_L^1(l) = \frac{i \times c \times r_2}{N} + \frac{l \times r_1}{m}. \] (3)

The payoff of each player is threatened by the global risks. Here, we denote a threshold \( s \). If the amount of collected global public goods is less than \( s \), a potential danger is on the way with a probability \( q \). We introduce a threshold function \( \theta \):

\[ \theta(i) = \begin{cases} q & \text{for } i \times c \times r_2 < s \\ 0 & \text{for } i \times c \times r_2 \geq s \end{cases} \] (4)

where \( i \) is the number of global contributors. If the amount of public goods in the global account is greater than \( s \), the collective target achieves and disasters are not going to happen. In this case, all the players will get their payoffs in the public goods games. Specifically, we assume that the global crisis can not be afforded by any single group. Thus, we restrict \( s > mcr_2 \).

Once a danger strikes, the payoffs of individuals are zero. However, the insurance will take effect under such circumstance. The insured can get some compensation from the insurance company. Here, we denote \( \phi \) (\( 0 < \phi < 1 \)) as the insured amount (insurance compensation). The insured amount should be related to the insurance premium by the individuals in advance. Thus, we introduce a function \( F(\cdot) \) to depict the relation between insurance compensation and premium. Without loss of generality, we denote \( \phi = F(\xi) \), which is a monotone increasing function, where \( \xi \) is the insurance premium. It indicates that with the increase in premiums, individuals will receive more insurance compensation once disaster occurs. On the other hand, this kind of safeguard for participants’ cooperative behavior is based on the fact that individuals need to spend on insurance. It will affect the contribution and payoffs of global cooperators when they participate in the TPGG. The more money individuals spend on insurance, the less money they spend on public goods. For the form of function \( F(\cdot) \), it can be linear or exponential growth function. We take a linear function as a simple example, \( \phi = \xi \times \Delta \), where \( \Delta \) is the premium rate (\( \Delta > 1 \)). Noting that \( \xi = 1 - c \), where \( c \) is the proportion of money that is contributed to the global account by global contributors.

The evolution of strategy is described by the imitation process where individuals are likely to adopt strategies of more successful opponents’. Firstly, we randomly choose an individual, namely \( A \), from the entire population of size \( N \). Then, we choose another individual, namely \( B \). With a probability \( p \), \( B \) is chosen from the entire population with the exception of the local group where \( A \) is in. While with probability \( 1 - p \), \( B \) is chosen only from the local group where \( A \) is in. In other words, the larger \( p \) is, the more likely it is that individuals interact with each other globally. In our daily life, the interaction within a group is much more frequent than that between groups, thus we assume that \( p \to 0 \). Subsequently, \( A \) adopts \( B \)'s strategy with probability \( 1/[1 + e^{-\omega(\pi_B - \pi_A)}] \) [103, 104], where \( \pi_k \) is the payoff of individual \( k \). \( \omega \) denotes the rational degree of individuals, measuring the dependence of decision making on the payoff comparison. For \( \omega \to 0 \), individual \( A \) imitates the strategy of \( B \) almost randomly, which is referred as ‘irrationality’ [105–107]. For \( \omega \to \infty \), a more successful player is always imitated, which is referred as ‘rationality’. Here, we define two different rational degrees. We denote \( \omega_1 \) as the rational degree within a group and \( \omega_2 \) as the rational degree between groups. During the evolutionary process of strategies, each player has the chance of
switching its strategy to a different one with a probability $\mu$. In this paper, we assume the mutation rate $\mu \to 0$.

We are interested in how global contribution evolves. To this end, we study the stationary distribution and the fixation time. We assume that the interaction within a group is much more frequent than that between groups [108, 109], which coincides with the phenomena in daily life. Thus, the fixation process of a single mutant in the population goes through two steps: the fixation of this mutant in its local group and the fixation of such group in the whole global group.

Results and discussion

Insurance is a means of protection from financial loss in human societies, which can insure people’s benefits against the risk of accident or some risks. We explore how insurance and risk influence the evolution of global contribution in multi-level TPGG. The stationary distribution of three strategies in different models are compared in figure 1. We investigate PGG, TPGG and the TPGG model with insurance (the detailed analysis please see the appendix). It is found that the behaviors of individuals are affected by collective risk and insurance compensation. In PGG model, the Nash equilibrium predicts zero provision. Thus, the selfishness is the dominant strategy, while global contribution is inferior. When public goods can only be provided if the global contributions reach a minimum threshold, this creates an advantage in that the Pareto efficient outcomes can be Nash equilibria. Compared with PGG, the existence of a threshold is beneficial for global contribution as well as local contribution. In TPGG, however, we still see significant under-provision of the global public goods. Since whether others will also contribute is uncertain, the player may lack confidence in successful collection. Once the collective target fails, as a global contributor, the total loss of property is too disappointing. There exists the assurance problem. Thus, we introduce the insurance compensation. When the player contributes globally, their donation is insured. The mechanism changes in comparison between different strategies, which makes the global contribution no longer the most inferior strategy especially under the high risk circumstance. Once disaster occurs, the global contributors will obtain certain compensation from the insurance company, where global contribution become both collectively optimal and a Nash equilibrium (if the collective target is so large that it requires almost all the players to contribute). As shown in figure 1, the global cooperative behavior is further promoted by introducing the insurance compensation. Here, we assume $\Delta = 5$ and $\xi = 0.1$, then the insurance compensation amount, which global contributors could acquire if disaster happens, is $\phi = \xi \times \Delta = 0.5$. Players are more apt to contribute globally in the case that even if their donation may be lost due to the failure of public goods collection, they do not lose everything. In such case, with the increase of a global contribution, the selfishness and local contribution are both inhibited.

We then probe the effects of the premium rate on the evolution of different strategies in the TPGG model with insurance compensation. As is illustrated in figure 2, the stationary distribution of $G (X_G)$ shows an ascending trend while $X_S$ and $X_L$ descend. Differing from PGG and TPGG, the payoff of $G$ is added as an implicit benefit in this model. This benefit will come true when disaster strikes, and makes it possible that
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Figure 1. Comparison of three strategies in different models. The stationary distribution of selfishness, local contribution and global contribution \((X_S, X_L \text{ and } X_G)\) in PGG, TPGG and the TPGG model with insurance are calculated according to the methods in appendix. \(X_G\) is promoted by introducing the threshold and further the insurance into the PGG model. For TPGG models, the threshold \(s = 200\). For the TPGG model with insurance, \(c = 0.9, \xi = 0.1\) and \(\Delta = 5\). Other common parameters are \(m = 5, M = 20, N = 100, q = 0.8, r_1 = 2, r_2 = 3, \omega_1 = 0.005\) and \(\omega_2 = 0.001\).

Figure 2. The influence of the premium rate on the stationary distribution of strategies. The tendency of stationary distribution of selfishness, local contribution and global contribution \((X_S, X_L \text{ and } X_G)\) with respect to the increase of premium rate \(\Delta\) is shown. \(X_G\) is promoted with the increasing \(\Delta\), while \(X_L\) and \(X_S\) decrease. It means that the effect of insurance on promoting global contribution becomes remarkably obvious with the increase of compensation. With more guarantees, players are more apt to contribute globally. Parameters are \(m = 5, M = 20, N = 100, q = 0.8, r_1 = 2, r_2 = 3, s = 200, \xi = 0.1, c = 0.9, \omega_1 = 0.005\) and \(\omega_2 = 0.001\).
the payoff of $G$ is larger than those of $S$ and $L$. Since we consider $\phi = \xi \times \Delta$, thus the larger the premium rate $\Delta$, the larger the hidden payoff $\phi$ (compensation) under the same premium $\xi$, which affects the payoff expectation of global contributors. Especially under the high risk of danger, more potential compensation will make the global contributive behavior more competitive among strategies. In such case, the effect of insurance becomes remarkably obvious. With more guarantees, players are more apt to contribute globally, which matches the real situation [110].

In the following, we study how long the population fixates at each state. We focus on the fixation time of each strategy, especially that of $G$ strategy. With the increase of insurance compensation, the changes of average time that a mutant of each strategy invades population full of the other two respectively are shown in figure 3. After introducing an insurance compensation into the TPGG model, the time for $G$ invading the other two strategies are obviously shortened. The larger the compensation amount, the more likely that global contribution will be learned and adopted by other strategies’ holders. Then $G$ strategy could occupy the entire population more quickly. The change of the fixation time of $S$ is on the contrary. Without the insurance compensation,
the time for $G$ invading $S$ is the longest; while, with a large insurance compensation, the time for $G$ invading $S$ is shorter than that $S$ invading $G$. It is known that the fixation time of $L$ is shortened in TPGG compared with PGG, however, it slightly rises after introducing an insurance compensation. Compared with the promotion of global contribution and the inhibition of selfishness owing to insurance, to a certain extent, it only has little impact on local contribution.

We further investigate how decision-making is affected by the change of the threshold. As shown in figure 4, the global contributive behavior is promoted with the increasing threshold. By adding a threshold in PGG, the game is turned from a social dilemma into a sort of coordination game. In particular, with a large threshold, players are facing a sufficiently severe potential crisis. Such risk indicates that all the players probably lose their wealth. Higher threshold means a bigger target that has to be reached to avoid the risk. Global contribution is necessary for public safety, and becomes more and more important with the increasing threshold. Because global contributors can gain a foothold owing to the insurance compensation in high risk cases. This paves the way for them to dominate the population. Under high threshold, the proportion of global contribution and local contribution is successively larger than selfishness with the increase of insurance compensation. In comparison, the growth of global contribution is more obvious. It hints that individuals are inclined to cooperate with others for the collecting of global public goods to resist the disaster, since any single one cannot afford the huge expense.
Based on the above model, subsequently, we consider an extended case, where all the players are allowed to buy insurance, regardless of whether they contribute to the global public goods. We assume that global contributors still follow the aforementioned insurance mechanism. When they contribute to the global public goods, they are insured automatically. Non-G players (local contributors and selfish ones), however, participate in insurance with a probability \( v (0 \leq v \leq 1) \). Noting that \( v = 0 \) corresponds to the case that has already been discussed in previous paragraphs; while \( v = 1 \) means all the people take out an insurance policy. We explore how the probability \( v \) affects the decision-making. As shown in figure 5, allowing full insurance coverage is detrimental to global contribution. With the increase of the probability for non-G players to insure, the average proportion of \( G \) decreases while other strategies are promoted. It may be because that such a money-back guarantee for all the players (including non-G players) creates inefficient Nash equilibria below the provision threshold. Thus, given the decisions of others, an individual does not incline to contribute globally. Since all the players could be compensated by the insurance company, the comparison between \( G \) and non-G players degenerates to the case of classical TPGG. All the players have the same payoff if global public goods fail to reach the threshold and disaster happens. Intuitively, with more guarantee for not losing all, the individuals (especially potential non-G players) show little willingness to invest to global public goods which leads to less payoff than other strategies. The influence of the amount of insurance premium on

\[ \text{Figure 5.} \text{ The influence of allowing full insurance coverage on the evolution of strategies. With the increase of the probability } v, \text{ the average proportion of } G \text{ decreases while those of } S \text{ and } L \text{ increase. It means that allowing full insurance coverage is detrimental to global contribution. Results under different amounts of insurance premium are shown. (a) The case of lower premium, where } c = 0.9, \text{ i.e. premium } \xi = 0.1. \text{ (b) The case of higher premium, where } c = 0.6, \text{ i.e. premium } \xi = 0.4. \text{ It is shown that higher premium is in favor of global contribution. Other parameters are } m = 5, M = 20, N = 100, q = 0.8, r_1 = 2, r_2 = 3, s = 200, \Delta = 5, \omega_1 = 0.005 \text{ and } \omega_2 = 0.001. \]
the decision-making is also demonstrated in figure 5. It is found that a higher premium is in favor of global contribution. When the premium is high, less money is used for public goods, which incurs higher risks. Thus, more global contributors are needed to prevent the risks.

Particularly, since buying insurance is good for non-G players, it is possible that all the players are inclined to take out an insurance policy. In this case, if global contribution should be further promoted, there needs to be some incentive to adapt. For example, global contributive behaviors could earn a discount on the insurance premium. We attempt to explore the effect of premium discount on global contribution (please see figure 6). It is found that, for the same insurance transaction, if the premium paid by a global contributor is less than non-G players, the proportion of G strategy is promoted, especially when global contributors could get a bigger discount. If the insurance cost is more expensive, the promoting effect will be more obvious. Individuals in high-risk areas (e.g. low-lying regions or a coastal community) should definitely buy insurance so as to avoid the more likely loss of property. The high insurance costs may affect the decision and behavior of the individuals. Rather than personal consumption (selfishness) or contributing to the construction of a stadium or park for fun (local contribution), the players may contribute to build a barrier such as sea wall or levee (global contribution) to reduce risk as well as gain a discount in the insurance bill.

Therefore, the cost of insurance can be a powerful communicator of risk. The insurance compensation given by insurance companies comes from insurance premiums paid by insured and also the company’s other profitable revenue. Insurance companies do not take part in the public goods games, but assess the impact of behaviors of all the individuals on their companies’ own earnings. For example, if a large number of individuals choose non-G strategies, the insurance company will face a large amount of risk.

Figure 6. The proportion of global contribution changes with insurance premium discount. With the rise of discount, global contribution is promoted, especially when the premium is high. Parameters are $m = 5$, $M = 20$, $N = 100$, $q = 0.8$, $r_1 = 2$, $r_2 = 3$, $s = 200$, $\xi = 0.4$, $c = 0.6$, $\Delta = 5$, $\omega_1 = 0.02$ and $\omega_2 = 0.001$. 

https://doi.org/10.1088/1742-5468/aa9bb6
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claims, because there is not enough public goods to effectively prevent the risk. On the contrary, more global contributions can ensure that the threshold would be satisfied, so that the individual’s property is not lost, then the payment of insurance claims will be greatly reduced. Thus, insurance companies may give $G$ players a discount in order to stimulate the global contributive behaviors. Furthermore, with the dynamic changes of the market, insurance companies can adjust their premiums in real-time according to the current amount of global contributions. For instance, the more global public goods in the global account, the greater the discount for global contributors. As a result, insurance can be used as a direct economic indicator of the risk of the probability of damage to property. That is, it hints that the higher the insurance premium, the less the global contributions and the greater the risks.

Conclusion

In this paper, we have studied the evolution of strategies in the multi-level threshold public goods games, where global and local contributions are clearly distinguished. By introducing insurance compensation mechanism, we investigate how insurance (premium rate) and risk (threshold) influence the average abundance of strategies and fixation time. It is shown that with more guarantees (compensation), players are more apt to contribute globally, especially under high collective risks. We further explore the influences of the amount of insurance premium, the probability of buying insurance (for selfish ones and local contributors) and the premium discount (for global contributors) on the global contributions. We find that the increase of the probability for non-$G$ players to insure has an unfavorable effect on global contribution. However, if a premium discount is given to global contributors, the global contributive behavior could be promoted. In particular, a higher premium is in favor of global contributions. Our results imply that allowing global contributors to buy insurance or giving them a discount when everyone buys insurance may be helpful for solving global social dilemmas. Such an insurance compensation mechanism makes the global contributor’s behavior no longer be enslaved to other players’ choice. It also offers global contributors more psychological guarantee for their possession, because their donation for preventing risks will prospectively reduce their potential loss to a certain extent. It thus might heighten their confidence in global contributive behaviors. Our model is relatively simple compared with the actual situations, but it characterizes some main features of the money-back guarantee, and shows results that the frequency of global contribution may be promoted in some cases. This study may provide some useful implications for investors, insurance participants, fundraisers and also government officials.

Acknowledgments

This research was supported by the National Key Research and Development Program of China (2016YFB0901900), the National Natural Science Foundation of China (NSFC) (Grant No. 61703082, 61374203), the Fundamental Research Funds for the Central Universities (Grant No. N160403001), the Fund for Innovative Research Groups of
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the National Natural Science Foundation of China (Grant No. 71621061), the Major
International Joint Research Project of the National Natural Science Foundation of
China (Grant No. 71520107004), and the 111 Project (B16009).

Appendix

A.1. Fixation probability

The fixation is the process that a single invader strategy takes over a group full of
another strategy. Thus, under the limit of small exploration rates, only two strategies
exist during the fixation process. We consider a single local group in which there are $i$
$G$ players and $m - i$ $S$ players, and assume that all the other groups are full of $S$
players. Based on equations (1) and (2), the payoffs of each $G$ player and each $S$
player in the focal group are:

$$
\pi^1_{G}(i) = \frac{i \times c \times r_2}{N} \quad \text{(A.1)}
$$

$$
\pi^1_{S}(m - i) = \frac{i \times c \times r_2}{N} + 1. \quad \text{(A.2)}
$$

The probability that the number of $G$ individuals changes from $i$ to $i \pm 1$ in one time
step is:

$$
T^\pm(i) = (1 - p) \frac{i}{m} \frac{m - i}{m} \frac{1}{1 + e^{\pm \omega_1 [\pi^1_{S}(m - i) - \pi^1_{G}(i)]}}. \quad \text{(A.3)}
$$

where $\omega_1$ is the rational degree within a group. We assume $p \to 0$, which indicates that
the player is apt to choose counterpart from its local group.

Denote the fixation probability of a single $G$ mutant invading a group of $S$ players
by $P^1_{SG}$. This fixation probability is given by [104, 109]:

$$
P^1_{SG} = \frac{1}{1 + \sum_{j=1}^{m-1} \prod_{i=1}^{j} \frac{T^-(i)}{T^+(i)}} = \frac{1}{1 + \sum_{j=1}^{m-1} e^{\omega_1 \sum_{i=1}^{j}[\pi^1_{S}(m - i) - \pi^1_{G}(i)]}}. \quad \text{(A.4)}
$$

Denote the fixation probability of a local group full of $G$ players invading the global
group of only $S$ individuals by $P^2_{SG}$. Suppose there are $i$ local groups consisting of only
$G$ players and $M - i$ local groups of only $S$ players. In the global group, the payoff of
each $G$ player is denoted by $\pi^2_{G}(i)$ and that of each $S$ player is $\pi^2_{S}(M - i)$:

$$
\pi^2_{G}(i) = \frac{i \times c \times r_2}{M} \quad \text{(A.5)}
$$

$$
\pi^2_{S}(M - i) = \frac{i \times c \times r_2}{M} + 1. \quad \text{(A.6)}
$$

Since the interaction within a group is much more frequent than that between
groups, the time in which this mutant takes over the focal group to which it belongs or
disappears is shorter than the time taken by two individuals from different local groups
to meet. The time scales of fixation in a local group and imitation between two individu-
als from different groups are separated. A new group full of $G$ players arises when
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two players with different strategies from different local groups are chosen, and the \( S \) player alters its strategy through imitation, then it takes over its local group. Thus, the probability to increase the number of local groups full of \( G \) players by one is given by:

\[
\Gamma^+(i) = p \frac{i}{M} \frac{M - i}{M} \frac{P_{SG}^1}{1 + e^{\omega_2 [\pi^G_1(M-i) - \pi^G_S(i)]}},
\]

where \( \omega_2 \) is the rational degree between groups. Similarly, the probability to decrease the number of \( G \) groups by one is:

\[
\Gamma^-(i) = p \frac{i}{M} \frac{M - i}{M} \frac{P_{GS}^1}{1 + e^{\omega_2 [\pi^G_1(M-i) - \pi^G_S(i)]}}.
\]

Hence, the fixation probability of a \( G \) group in the whole population is obtained as follows:

\[
P^2_{SG} = \frac{1}{1 + \sum_{j=1}^{M-1} e^{\omega_2 [\pi^G_1(M-i) - \pi^G_S(i)]} \left( \frac{P_{GS}^1}{P_{SG}^1} \right)^j}.
\]

We aim to analyze the multi-level threshold PGG. Thus, the payoffs above are conditional. Once danger happens, all the individuals will lose their wealth. Since we have introduced the insurance compensation mechanism, the global cooperator’s payoff should be superadded an additional part. By utilizing the threshold function, equation (4), the revised payoffs are as follows:

\[
\pi^1_G(i) = \phi \theta(i) + \left( \frac{i \times c \times r_2}{N} \right) [1 - \theta(i)]
\]

\[
\pi^1_S(m - i) = \left( \frac{i \times c \times r_2}{N} + 1 \right) [1 - \theta(i)]
\]

\[
\pi^2_G(i) = \phi \theta(m \times i) + \left( \frac{i \times c \times r_2}{M} \right) [1 - \theta(m \times i)]
\]

\[
\pi^2_S(M - i) = \left( \frac{i \times c \times r_2}{M} + 1 \right) [1 - \theta(m \times i)].
\]

Inserting equations (A.10) and (A.11) into (A.4), and equations (A.12) and (A.13) into (A.9), we can get:

\[
P^1_{SG}(k) = \left\{ 1 + \sum_{j=1}^{m-1} e^{\omega_1 \sum_{i=1}^{j} [1 - \theta(i + m k)]} \right\}^{-1}
\]

\[
P^2_{SG} = \left( 1 + \sum_{j=1}^{M-1} \left\{ \frac{e^{\omega_2 \sum_{i=1}^{j} [1 - \theta(m i)]}}{\prod_{i=1}^{j} \left[ \frac{P_{GS}^1(i)}{P_{SG}^1(i)} \right]} \right\} \right)^{-1}
\]

Denote the fixation probability of a single \( G \) mutant invading the whole global group consisting of only \( S \) players by \( \rho_{SG} \). Here, we have:

\[
\rho_{SG} \approx P^1_{SG}(0) \times P^2_{SG}.
\]
Similarly, we can get the fixation probability \( \rho_{GS}, \rho_{SL}, \rho_{LS}, \rho_{LG}, \) and \( \rho_{GL}. \)

### A.2. Stationary distribution

In the evolutionary process of strategies, each individual has the chance of randomly switching its strategy to a different one with a probability \( \mu. \) We suppose the mutation rate \( \mu \to 0, \) since sufficiently small \( \mu \) assures that a single mutant vanishes or fixates in a population before the next mutant appears [111, 112]. In this limit, the evolutionary process can be approximated by a Markov chain where the state space is composed of homogeneous states full of each type of players (\( S, L \) or \( G \)). The corresponding transition probability matrix \( T \) is:

\[
T = \begin{pmatrix}
T_{SS} & \frac{\mu}{2} \rho_{SL} & \frac{\mu}{2} \rho_{SG} \\
\frac{\mu}{2} \rho_{LS} & T_{LL} & \frac{\mu}{2} \rho_{LG} \\
\frac{\mu}{2} \rho_{GS} & \frac{\mu}{2} \rho_{GL} & T_{GG}
\end{pmatrix}. \tag{A.17}
\]

Here, \( T_{ii} = 1 - \sum_{k \neq i} (\frac{\mu}{2} \rho_{ik}) \), where \( i, k \in \{S, L, G\}. \)

Stationary distribution describes the percentage of time spent by the population in each homogeneous state in the long run, which is determined by the normalized left eigenvector corresponding to the eigenvalue 1 of the transition matrix. The stationary distribution for equation (A.17) can be calculated as follows:

\[
X_S = \frac{\rho_{GS} \rho_{LG} + \rho_{GS} \rho_{LS} + \rho_{LS} \rho_{GL}}{\Delta} \tag{A.18}
\]

\[
X_L = \frac{\rho_{GS} \rho_{SL} + \rho_{SL} \rho_{GL} + \rho_{SG} \rho_{GL}}{\Delta} \tag{A.19}
\]

\[
X_G = \frac{\rho_{SG} \rho_{LS} + \rho_{SL} \rho_{LG} + \rho_{SG} \rho_{LG}}{\Delta}, \tag{A.20}
\]

where \( X_S, X_L, \) and \( X_G \) represent the probability to find the population in the homogeneous state consisting entirely of selfish ones, local cooperators, and global cooperators, respectively. The normalization factor \( \Delta \) assures \( X_S + X_L + X_G = 1. \)

### A.3. Fixation time

On the other hand, the average time to reach a certain state for the first time can be derived analytically in the limit of rare mutations. For example, we denote fixation time \( \tau_{GS} \) as the average time starting in pure state of \( G \) to reach \( S. \) This fixation time satisfies:

\[
\tau_{GS} = 1 + r_{GL} \tau_{LS} + r_{GG} \tau_{GS}, \tag{A.21}
\]

where \( r_{ij} = \delta_{ij} + \frac{\mu N}{2} (\rho_{ij} - \delta_{ij}) \). It represents the transition probability from the homogeneous state \( i \) to the homogeneous state \( j. \) \( \rho_{ij} \) expresses the fixation probability. \( \delta_{ij} \) denotes the Kronecker delta. \( \frac{\mu N}{2} \) means the rate at which mutants of type \( j \) are born (as only two types of mutants can be produced with equal probability), since on average it takes the time of \( \frac{1}{\mu N} \) for per mutation.

Then, we can get the average time of reaching the homogeneous state \( S \) from the initial pure states \( G \) and \( L: \)

\[\text{https://doi.org/10.1088/1742-5468/aa9bb6} \]

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\[ \tau_{GS} = 1 + \frac{\mu N}{2} \rho_{GL} \tau_{LS} + [1 - \frac{\mu N}{2} (\rho_{GS} + \rho_{GL})] \tau_{GS} \quad (A.22) \]

\[ \tau_{LS} = 1 + \frac{\mu N}{2} \rho_{LG} \tau_{GS} + [1 - \frac{\mu N}{2} (\rho_{LS} + \rho_{LG})] \tau_{LS}. \quad (A.23) \]

Solving equations (A.22) and (A.23), we have:

\[ \tau_{GS} = \frac{2 (\rho_{GL} + \rho_{LG} + \rho_{LS})}{\mu N (\rho_{GS} \rho_{LG} + \rho_{GL} \rho_{LS} + \rho_{GS} \rho_{LS})} \quad (A.24) \]

\[ \tau_{LS} = \frac{2 (\rho_{GL} + \rho_{GS} + \rho_{LG})}{\mu N (\rho_{GS} \rho_{LG} + \rho_{GL} \rho_{LS} + \rho_{GS} \rho_{LS})}. \quad (A.25) \]

Similarly, expressions for other fixation time can be shown as follows:

\[ \tau_{SL} = \frac{2 (\rho_{GL} + \rho_{GS} + \rho_{SG})}{\mu N (\rho_{GL} \rho_{SG} + \rho_{GL} \rho_{SL} + \rho_{GS} \rho_{SL})} \quad (A.26) \]

\[ \tau_{GL} = \frac{2 (\rho_{GS} + \rho_{SG} + \rho_{SL})}{\mu N (\rho_{GL} \rho_{SG} + \rho_{GL} \rho_{SL} + \rho_{GS} \rho_{SL})} \quad (A.27) \]

\[ \tau_{SG} = \frac{2 (\rho_{LG} + \rho_{GS} + \rho_{SL})}{\mu N (\rho_{LG} \rho_{SG} + \rho_{LS} \rho_{SG} + \rho_{LG} \rho_{SL})} \quad (A.28) \]

\[ \tau_{LG} = \frac{2 (\rho_{LS} + \rho_{SG} + \rho_{SL})}{\mu N (\rho_{LG} \rho_{SG} + \rho_{LS} \rho_{SG} + \rho_{LG} \rho_{SL})}. \quad (A.29) \]

Based on the solved fixation probabilities, we can deduce all the fixation times with a complete form.

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https://doi.org/10.1088/1742-5468/aa9bb6