Behavioral dynamics under climate change dilemmas

Francisco C. Santos[a,c] and Jorge M. Pacheco[b,c]

[a] Departamento de Engenharia Informática & INESC-ID, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[b] Departamento de Matemática e Aplicações, Universidade do Minho, 4710 - 057 Braga, Portugal.

[c] ATP-group, CMAF, Instituto para a Investigação Interdisciplinar, P-1649-003 Lisboa Codex, Portugal.

Manuscript information:

The manuscript includes 4 figures (supplied in the separate files) and 3554 words. Figure captions are provided at the end of the document. For your convenience we also join the endnote file used to compile the list of references.

Authors' address:

Francisco C. Santos

Address:
GAIPS/INESC-ID, IST Tagusparque,
Av. Prof. Dr. Cavaco Silva,
2744-016 Porto Salvo,
Portugal
franciscocsantos@ist.utl.pt

tel: +351. 21. 7904891
fax: +351. 21. 7954288 / 89

Jorge M. Pacheco

Address:
Departamento de Matemática e Aplicações
Universidade do Minho, Campus de Gualtar, 4710-057
Braga,
Portugal
pacheco@cii.fc.ul.pt

tel: +351. 21. 7904891
fax: +351. 21. 7954288 / 89

Abstract

Preventing global warming is a public good requiring overall cooperation. Contributions will depend on the risk of future losses, which plays a key role in decision-making. Here, we discuss a theoretical model grounded on game theory and large-scale population dynamics. We show how decisions within small groups under high risk and stringent requirements toward success significantly raise the chances of coordinating to save the planet's climate, thus escaping the tragedy of the commons. In addition, our model predicts that, if one takes into consideration that groups of different sizes will be interwoven in complex networks of contacts, the chances for global coordination into an overall cooperating state are further enhanced.

1. Introduction

In a dance that repeats itself cyclically, countries and citizens raise significant expectations every time a new International Environmental Summit is settled. Unfortunately, few solutions have come out of these colossal and flashy meetings, challenging our current understanding and models on decision-making, such that more effective levels of discussion, agreements and coordination become accessible. From Montreal and Kyoto to Copenhagen and Durban summits, it is by now clear how difficult it is to coordinate efforts[1] . Often, individuals, regions or nations opt to be *free riders*, hoping to benefit from the efforts of others while choosing not to make any effort themselves. Cooperation problems faced by humans often share this setting, in which the immediate advantage of free riding drives the population into the Hardin's tragedy of the commons , the ultimate limit of widespread defection.

To address this and other cooperation conundrums ubiquitous at all scales and levels of complexity, the last decades have witnessed the discovery of several core mechanisms responsible to promote and maintain cooperation at different levels of organization . Most of these key principles have been studied within the framework of two-person dilemmas such as the Prisoner's Dilemma, which constitute a powerful metaphor to describe conflicting situations often encountered in the natural and social sciences. Many real-life situations, however, are associated with collective action based on joint decisions made by a group often involving more than two individuals . These types of problems are best dealt-with in the framework of N-person dilemmas and Public Goods games, involving a much larger complexity that only recently started to be unveiled . Arguably, the welfare of our planet accounts for the most important and paradigmatic example of a public good: a global good from which everyone profits, whether or not they contribute to maintain it.

One of the most distinctive features of this complex problem, only recently tested and confirmed by means of actual experiments[2] , is the role played by the perception of risk that accrues to all actors involved when taking a decision. Indeed, experiments confirm the intuition that the risk of collective failure plays a central role in dealing with climate change. Up to now, the role of risk has remained elusive . Additionally, it is also unclear what is the ideal scale or size of the population engaging in climate summits — whether game participants are world citizens, regions or country leaders — such that the chances of cooperation are maximized. Here we address these two issues in the context of game theory and population dynamics.

[1] See Barrett 2005, 2007
[2] See Milinski, et al. 2008, 2011

The conventional public goods game — the so-called N-person Prisoner's Dilemma — involve a group of *N* individuals, who can be either Cooperators (*C*) or Defectors (*D*). *C*s contribute a cost "*c*" to the public good, whereas *D*s refuse to do so. The accumulated contribution is multiplied by an enhancement factor the returns equally shared among all individuals of the group. This implies a collective return which increases linearly with the number of contributors, a situation that contrasts with many real situations in which performing a given task requires the cooperation of a minimum number of individuals of that group[3] . This is the case in international environmental agreements which demand a minimum number of ratifications to come into practice , but examples abound where a minimum number of individuals, which does not necessarily equal the entire group, must simultaneously cooperate before any outcome (or public good) is produced. Furthermore, it is by now clear that the N-person Prisoner's Dilemma fails short to encompass the role of risk, as much as the non-linear nature of most collective phenomena.

Here we address these problems resorting to a simple mathematical model, adopting unusual concepts within political and sustainability science research, such as peer influence and evolutionary game theory . As a result, we encompass several of the key elements stated before regarding the climate change conundrum in a single dynamical model.

In the following we show how small groups under high risk and stringent requirements toward collective success significantly raise the chances of coordinating to save the planet's climate, thus escaping the tragedy of the commons. In other words, global cooperation is dependent on how aware individuals are concerning the risks of collective failure and on the pre-defined premises needed to accomplish a climate agreement. Moreover, we will show that to achieve stable levels of cooperation, an initial critical mass of cooperators is needed, which will then be seen as role models and foster cooperation.

We will start by presenting the model in Section 2. In Section 3 we discuss the situation in which evolution is deterministic and proceeds in very large populations. In Section 4 we analyze the evolutionary dynamics of the same dilemma in finite populations under errors and behavioral mutations. Finally, in Section 5 we provide a summary and concluding remarks.

2. Model

Let us consider a population of size *Z*, in which individuals engage in a N-person dilemma, where each individual is able to contribute or not to a common good, i.e., to cooperate or to defect, respectively. Game participants have each an initial endowment *b*. Cooperators (*C*s) contribute a fraction *c* of their endowment, while defectors (*D*s) do not contribute. As previously stated, irrespectively of the scale at which agreements are tried, most demand a minimum number of contributors to come into practice . Hence, whenever parties fail to achieve a previously defined minimum of contributions, they may fail to achieve the goals of such agreement (which can also be understood as the benefit "*b*"), being this outcome, in the worst possible case, associated with an appalling doomsday scenario.

To encompass this feature in the model we require a minimum collective investment to ensure success: If the group of size *N* does not contain at least *M* *C*s (or, equivalently, a collective effort of *Mcb*), all members will lose their remaining endowments with a probability *r* (the *risk*); otherwise everyone will keep whatever they have. Hence, $M<N$ represents a coordination threshold, necessary to achieve a collective benefit.

[3] E.g., see Alvard, Boesch, Creel, Stander and others.

As a result, the payoff of a D in a group of size N and k Cs can be written as $\Pi_D(k) = b\{\theta(k-M) + (1-r)[1-\theta(k-M)]\}$, where $\theta(x)$ is the Heaviside step function ($\theta(x<0)=0$ and $\theta(x \geq 0)=1$). Similarly, the payoff of a ***C*** is given by $\Pi_C(k) = \Pi_D(k) - cb$. The risk r is here introduced as a probability, such that with probability *(1-r)* the benefit will be collected independent of the number of contributors in a group.

This collective-risk dilemma represents a simplified version of the game used in the experiments performed by Milinski et al (2008) on the issue of the mitigation of the effects of climate change, a framework which is by no means the standard approach to deal with International Environmental Agreements and other problems of the same kind . The present formalism has the virtue of depicting black on white the importance of risk and its assessment in dealing with climate change, something that Heal et al have been conjecturing for quite a while. At the same time, and unlike Milinski's experiments , our analysis is general and not restricted to a given group size.

Additionally, and unlike most of the canonical treatments , our analysis will not rely on individual or collective rationality. Instead, our model relies on evolutionary game theory combined with one-shot public goods games, in which errors are allowed. In fact, our model includes what we believe are key factors in any real setting, such as bounded rational individual behavior and the importance of risk assessment in meeting the goals defined from the outset.

We assume that individuals tend to copy others whenever these appear to be more successful. Contrary to strategies defined by a contingency plan which, as argued by McGinty before , are unlikely to be maintained for a long time scale, this social learning (or evolutionary) approach allows policies to change as time goes by, and likely these policies will be influenced by the behavior (and achievements) of others, as previously shown in the context of donations to public goods . This also accounts to the fact that agreements may be vulnerable to renegotiation, as individuals may agree on intermediate goals or assess actual and future consequences of their choices to revise their position .

3. Behavioral dynamics in large populations

In the framework of evolutionary game theory, the evolution or social learning dynamics of the fraction x of Cs (and *1-x* of Ds) in a large population ($Z \to \infty$) is governed by the gradient of selection *g(x)* associated with the replicator dynamics equation $g(x) \equiv \dot{x} = x(1-x)(f_C - f_D)$, which characterizes the behavioral dynamics of the population, where f_C (f_D) is the fitness of Cs (Ds), here associated with the game payoffs. According to the replicator equation, Cs (Ds) will increase in the population whenever *g(x)>0* (*g(x)>0*). If one assumes an unstructured population, where every individual can potentially interact with everyone else, the fitness (or social success) of each individual can be obtained from a random sampling of groups. The latter leads to groups whose composition follows a binomial distribution[4] .

<Please insert Fig. 1 here>

Fig. 1 shows the behavior of *g(x)* as a function of the fraction of cooperators (x) for different risk intensities. In the absence of risk (r=0.0), $\dot{x}$ is always negative, leading to the extinction of ***C***s (x=0) irrespectively of the initial fraction of cooperators. The presence of risk, in turn, leads to the emergence of two mixed internal *equilibria,* rendering cooperation viable: For

[4] For details, see Santos and Pacheco, 2011.

finite risk r, both ***C****s* (below x_L) and ***D***s (above x_R) become disadvantageous when rare. Co-existence between ***C***s and ***D***s becomes stable at a fraction x_R which increases with r. Hence, collective coordination becomes easier to achieve under high-risk, and once the coordination barrier is overcome (x_L), high levels of cooperation will be reached.

<Please insert Fig. 2 here>

The appearance of two internal *equilibria* under risk can be studied analytically[5] . In a nutshell (see also Fig. 2a), it can be shown that the location of these *equilibria* can be written down as a function of the *cost-to-risk ratio* γ, defined as $\gamma=c/r$, and coordination threshold M. Scenarios with none, one and two interior fixed points are possible depending if γ is smaller, larger or equal, respectively, to a critical value $\bar{\gamma}$. Hence, the *cost-to-risk ratio* γ plays a central role in dictating the viability of an overall cooperative state:

Intuitively, the smaller the contribution required, the easier it will be to reach such a globally cooperative state. Moreover, the higher the perception of the risk at stake, the more likely individuals react to overcome such a cooperation dilemma.

Fig. 2b also shows the role played by the threshold M: for fixed (and low) γ, increasing M will maximize cooperation (increase of x_R) at the expense of making it more difficult to emerge (increase of x_L).

4. Behavioral dynamics in small populations

In reality, however, populations are finite and, in some cases, may be small, as in many collective endeavors, from animal group hunting and warfare, to numerous Human affairs, such as small community collective projects, macroeconomic relations and the famous world summits on climate change, where group and population sizes are comparable and of the order of the hundreds.

For such population sizes, stochastic effects play an important role. Stochastic effects are amplified in the presence of errors of different sorts (inducing behavioral *"mutations"*, including errors of imitation. Consequently, they may play an important role in the collective behavior at a population level.

Formally, the population dynamics becomes discrete, whereas the replicator dynamics is no longer valid. Alternatively, we adopt a stochastic process where each individual i imitates the strategy of a randomly selected member of the population j with probability which increases with the fitness difference . Under these circumstances, the behavioral dynamics is best described by a finite population gradient of selection $G(k/Z)$ — defined as the difference of the probabilities to increase and decrease the number k of ***C***s in the population by one individual — and by the respective stationary distribution of the population, which characterizes the (average) pervasiveness in time of a given fraction of cooperators (k/Z) of the population. Additionally, we consider that, with a small ("mutation") probability, an individual may explore a randomly chosen strategy.

<Please insert Fig. 3 here>

In Fig. 3a we show the stationary distributions for different values of risk, for a population of size Z=50 where N=2M=6. While the finite population gradient of selection $G(k/Z)$ exhibits a behavior qualitatively similar to $\dot{x}$ in Fig. 1, Fig. 3a shows that the population spends most of the time in configurations where ***C***s prevail, irrespectively of the initial condition. This is a direct consequence of stochastic effects, which allow the "tunneling" through the coordination

[5] For details, see Santos and Pacheco, 2011.

barrier associated with x_L, rendering such coordination barrier (x_L) irrelevant and turning cooperation into the prevalent strategy. In short, stochastic effects are able to promote cooperation under collective-risk dilemmas.

Besides perception of risk, group size must also be considered when maximizing the likelihood of reaching overall cooperation, as it defines the scale at which global warming should be tackled. Cooperation for climate control can be achieved at different scales, from regional to global agreements. Hence, even if the problem is certainly global, its solution may be achieved via the combination of several local agreements. So far, attempts have concentrated in a single, global group, although it remains unclear at which scale collective agreements are more easily achieved, as also discussed by Ascheim et al. . As shown by the stationary distributions of Fig. 3b, cooperation is better dealt with within small groups, even if, for higher *M/N* values, coordination is harder to attain (see Fig. 2).

Fig. 3b confirms that with increasing group size cooperation is inhibited, in both scenarios. Given that current policies favor world summits, the present results suggest a reappraisal of such policies regarding the promotion of public endeavors: Instead of world summits, decentralized agreements between smaller groups (small *N*), possibly focused on region-specific issues, where risk is high and goal achievement involves tough requirements (large relative *M*), are prone to significantly raise the probability of success in coordinating to tame the planet's climate.

5. Behavioral dynamics in structured populations

The success in self-organizing cooperative behavior within small groups when compared with global dilemmas, naturally begs the question of how these groups should be organized to maximize the chances of cooperation. So far, all groups and individuals have been assumed as identical. Yet, socio-political dynamics is often grounded on a strong diversity in roles and positions . As previously discussed in the context of international agreements , countries are part of intricate networks of overlapping and interrelated alliances or agreements, many of regional nature, involving also geographical neighbors, and others with a global character which transcends geography (see randomly assembled example in Fig. 4a). Similarly, diversity in geographical positions, or in social or political configurations, means that some *players* may play a pivotal role in a global outcome, as they may participate in a larger number of 'collective dilemmas' than others.

<Please insert Fig. 4 here>

The overall number and size of the dilemmas faced by each individual may be seen as a result of a complex interaction network, where nodes represent individuals, and links represent exchanges, collective investments or shared interests . As exemplified in Fig. 4a, each neighborhood of such structure may represent a group with a size given, e.g., by the connectivity of the focal individual. In Fig. 4b we show the effect of such heterogeneity or diversity of group sizes in the problem at stake, comparing the finite gradients of selection in a homogeneous setting — taking the well-mixed population as reference — with a heterogeneous case. For the latter, we adopt the ubiquitous power law distribution of connectivities, resulting from a s*cale-free* interaction network and a constant *M*. This leads to distributions of group sizes and number of games played by each player that also follow a power-law.

As shown in Fig. 4b, a heterogeneous contact network changes the location of the internal *equilibria*, without changing either the nature of the effective game or the nature of the internal *equilibria*. However, the impact of such a diversity on the type of game played in each local group is sizeable: In large groups coordination is easier to achieve (*M/N* is small) but co-existence occurs for a lower fraction of cooperators; in small groups, coordination faces stern requirements (*M/N* increases) but, once surpassed, most group members will actually cooperate. Whenever the risk of failure is high, introducing group diversity primarily enlarges the stable fraction x_R at equilibrium, also determining a slight increase of the size of the cooperative basin of attraction. Because coordination is easily achieved in large groups, highly connected players at the group centers will acquire a larger fitness. Whenever such *hubs* happen to be occupied by cooperators (as shown in), they will influence the participants of small groups (the majority) to cooperate, hence enabling small groups to overcome their stringent coordination requirements. Overall, this will act to reduce the average x_L of the population. Once this coordination barrier is surpassed, co-existence will be determined by the small size of the majority of the groups, leading to the dominance of cooperators at x_R.

6. Conclusion

Dealing with environmental sustainability cannot overlook the uncertainty associated with a collective investment. Here we propose a simple form to describe this problem and study its impact in behavioral evolution, obtaining an unambiguous agreement with recent experiments together with several concrete predictions. We do so in the framework of non-cooperative N-person evolutionary game theory, an unusual theoretical tool within the framework of modeling of political decision-making. We propose a new N-person game where the risk of collective failure is explicitly introduced by means of a simple collective dilemma. Moreover, instead of resorting to complex and rational planning or rules, individuals revise their behavior by peer-influence, creating a complex dynamics akin to many evolutionary systems. This framework allowed us to address the impact of risk in several configurations, from large to small groups, from deterministic towards stochastic behavioral dynamics.

Overall, we have shown how the emerging behavioral dynamics depends heavily on the perception of risk. The impact of risk is enhanced in the presence of small behavioral mutations and errors and whenever global coordination is attempted in a majority of small groups under stringent requirements to meet coactive goals. This result calls for a reassessment of policies towards the promotion of public endeavors: Instead of world summits, decentralized agreements between smaller groups (small *N*), possibly focused on region-specific issues, where risk is high and goal achievement involves tough requirements (large relative *M*), are prone to significantly raise the probability of success in coordinating to tame the planet's climate. Our model provides a "bottom-up" approach to the problem, in which collective cooperation is easier to achieve in a distributed way, eventually involving regions, cities, *NGO*s and, ultimately, all citizens. Moreover, by promoting regional or sectorial agreements, we are opening the door to the diversity of economic and political structure of all parties, which, as showed before can be beneficial to cooperation.

Naturally, we are aware of the many limitations of a bare model such as ours, in which the complexity of Human interactions has been overlooked. From higher levels of information, to non-binary investments, additional layers of realism can be introduced in the model. On the other hand, the simplicity of the dilemma introduced here, makes it generally applicable to other problems of collective cooperative action, which will emerge when the risks for the community are high, something that repeatedly happened throughout Human history, from ancient group hunting to voluntary adoption of public health measures. Similarly, other cooperation mechanisms, known to encourage collective action, may further enlarge the window of opportunity for cooperation to thrive. The existence of collective risks is pervasive in nature, in particular in many dilemmas faced by Humans. Hence, we believe the impact of these results go well beyond decision-making towards global warming.

References

Alvard, M.S., and D.A. Nolin. "Rousseau's Whale Hunt?: Coordination among Big-Game Hunters." *Current Anthropology* 43, no. 4 (2002): 533-59.

Asheim, GB, CB Froyn, J Hovi, and FC Menz. "Regional Versus Global Cooperation for Climate Control." *Journal of Environmental Economics and Management* 51, no. 1 (2006): 93-109.

Barabási, A. L., and R. Albert. "Emergence of Scaling in Random Networks." *Science* 286, no. 5439 (Oct 15 1999): 509-12.

Barrett, S. *Environment and Statecraft: The Strategy of Environmental Treaty-Making*. Oxford University Press, USA, 2005.

———. *Why Cooperate?: The Incentive to Supply Global Public Goods*. Oxford University Press, USA, 2007.

Black, J, MD Levi, and D De Meza. "Creating a Good Atmosphere: Minimum Participation for Tackling The'greenhouse Effect'." *Economica* 60, no. 239 (1993): 281-93.

Boehm, C. *Hierarchy in the Forest: The Evolution of Egalitarian Behavior*. Harvard University Press, 1999.

Brewer, N. T., G. B. Chapman, F. X. Gibbons, M. Gerrard, K. D. McCaul, and N. D. Weinstein. "Meta-Analysis of the Relationship between Risk Perception and Health Behavior: The Example of Vaccination." *Health Psychol* 26, no. 2 (Mar 2007): 136-45.

Fowler, J. H., and N. A. Christakis. "Cooperative Behavior Cascades in Human Social Networks." *Proc Natl Acad Sci U S A* 107, no. 12 (Mar 23 2010): 5334-8.

Hardin, G. "The Tragedy of the Commons." *Science* 162, no. 5364 (Dec 13 1968): 1243-8.

Heal, G. "Formation in International Environmental Agreements." In *Trade, Innovation, Environment*, edited by C. Carraro. Dordrecht: Kluwer, 1993.

Heal, G, and B Kristrom. "Uncertainty and Climate Change." *Environmental and Resource Economics* 22, no. 1 (2002): 3-39.

Kollock, P. "Social Dilemmas: The Anatomy of Cooperation." *Annu. Rev. Sociol.* 24 (1998): 183-214.

Lazer, D., A. Pentland, L. Adamic, S. Aral, A. L. Barabasi, D. Brewer, N. Christakis*, et al.* "Computational Social Science." *Science* 323, no. 5915 (Feb 6 2009): 721-3.

McGinty, M. "International Environmental Agreements as Evolutionary Games." *Environmental and Resource Economics* 45, no. 2 (2010): 251-69.

Milinski, M., T. Röhl, and J. Marotzke. "Cooperative Interaction of Rich and Poor Can Be Catalyzed by Intermediate Climate Targets." *Climatic Change* (2011): 1-8.

Milinski, M., D. Semmann, and H. J. Krambeck. "Reputation Helps Solve the 'Tragedy of the Commons'." *Nature* 415, no. 6870 (Jan 24 2002): 424-6.

Milinski, M., R. D. Sommerfeld, H. J. Krambeck, F. A. Reed, and J. Marotzke. "The Collective-Risk Social Dilemma and the Prevention of Simulated Dangerous Climate Change." *Proc Natl Acad Sci U S A* 105, no. 7 (2008): 2291–94.

Ostrom, E. *Governing the Commons: The Evolution of Instituitions for Collective Action*. Cambridge Univ. Press, 1990.

Pacheco, J. M., F. C. Santos, M. O. Souza, and B. Skyrms. "Evolutionary Dynamics of Collective Action in N-Person Stag Hunt Dilemmas." *Proc Biol Sci* 276, no. 1655 (Jan 22 2009): 315-21.

Santos, F. C., M. D. Santos, and J. M. Pacheco. "Social Diversity Promotes the Emergence of Cooperation in Public Goods Games." *Nature* 454, no. 7201 (Jul 10 2008): 213-6.

Santos, F.C., and J.M. Pacheco. "Risk of Collective Failure Provides an Escape from the Tragedy of the Commons." *Proc Natl Acad Sci U S A* 108, no. 26 (2011): 10421.

Sigmund, K. *The Calculus of Selfishness*. Princeton University Press, 2010.

Skyrms, B. *Evolution of the Social Contract*. Cambridge Univ Pr, 1996.

———. *Signals: Evolution, Learning, & Information*. Oxford Univ Pr, 2010.

———. *The Stag Hunt and the Evolution of Social Structure*. Cambridge University Press, 2004.

Souza, M. O., J. M. Pacheco, and F. C. Santos. "Evolution of Cooperation under N-Person Snowdrift Games." *J Theo Bio* 260, no. 4 (2009): 581-88.

Van Segbreck, S., F. C. Santos, and J. M. Pacheco. "Adaptive Contact Networks Change Effective Disease Infectiousness and Dynamics.". *Plos Comput Bio* 6, no. 8 (2010): e1000895.

Figure captions

Fig. 1. For each fraction of *C*s, if the gradient *g(x)* is positive (negative) the fraction of *C*s will increase (decrease). Increasing risk (*r*) modifies the population dynamics rendering cooperation viable depending on the initial fraction of *C*s (N=6, *M=3* and *c=0.1*).

Fig. 2. a) Classification of all possible dynamical scenarios when evolving an infinitely large population of *C*s and *D*s as a function of *γ*, *M* and N. A fraction *x* of an infinitely large population adopts the strategy *C*; the remaining fraction *1-x* adopts *D*. The replicator equation describes the evolution of *x* over time. Solid (open) circles represent stable (unstable) *equilibria* of the evolutionary dynamics; arrows indicate the direction of selection. b) Internal roots x^* of *g(x)* for different values of the cost-to-risk ratio *γ=c/r*, at fixed group size (N=6) and different coordination thresholds (*M*). For each value of *γ* one draws a horizontal line; the intersection of this line with each curve gives the value(s) of x^*, defining the internal *equilibria* of the replicator dynamics. The empty circle represents an unstable fixed point (x_L) and the full circle a stable fixed point (x_R) (*M=4* and *γ=0.15* in example).

Fig. 3 a) Stationary distribution describing the prevalence of each fraction (*k/Z*) of cooperators in finite populations (*Z*=50 in the presence of mutations and imitation errors). Whenever risk is high, stochastic effects *i*) turn collective cooperation into a pervasive behavior and *ii*) favor the overcome of coordination barriers, rendering cooperation viable, irrespective of the initial configuration (*N=6*, *M=3* and *c=0.1*). **b)** Stationary distributions for different group sizes and constant threshold *M=2*. Cooperation will be maximized when risk is high and groups are small (small *N*), as goal achievement involves stringent requirements.

Figure 4. Evolutionary dynamics in heterogeneous populations. a) Given an interaction network of size *Z* and average degree $<\zeta>$, where nodes represent individuals, and links represent exchanges or shared goals, *collective-risk dilemmas* may be associated with neighborhoods in this network. As an example, the central individual participates in 6 groups, hence participating in 6 public goods games, each with a given group size. The individual fitness derives from the payoff accumulated from all games she/he participates. **a)** Gradients of selection *G* for a homogeneous (well-mixed) population (dashed lines) and for heterogeneous (scale-free) networks (solid lines), for different values of risk, a population size of *Z=500* and an average group size of $<N>=7=<\zeta>+1$. In the heterogeneous cases, both size and number of the *N*-person games each individual participates follow a power-law distribution.