



ARTICLE



<https://doi.org/10.1057/s41599-022-01436-6>

OPEN

Economic experiments support Ostrom's polycentric approach to mitigating climate change

Manfred Milinski ¹✉ & Jochem Marotzke ²

The late Nobel laureate Elinor Ostrom envisioned a polycentric approach to mitigating climate change rather than a centralised solution. Debating about global efforts to solve climate-change problems has yet not led to an effective global treaty. Ostrom argued that instead of focusing only on global efforts, it is better to encourage polycentric efforts to reduce the risks associated with the emission of greenhouse gases. Many problems conceptualised as 'global problems' are the cumulative results of actions taken by individuals, families, small groups, private firms, and local, regional, and national governments. Ostrom and colleagues pointed to many examples of successfully managing a common good through interaction within a community. Energy-saving actions undertaken by individuals, families and actors at a small-scale pay off and, when multiplied, may reduce emissions globally. The incentive to achieve an individual net gain may trigger human investment decisions. Here we provide experimental support for Ostrom's basic ideas using methods of experimental economics. By subdividing experimental populations in subgroups that approach sub-goals of mitigating simulated dangerous climate change combined with incentives, the 'global' solution is achieved by combined subgroup contributions exceeding the 'global' threshold for averting simulated dangerous climate change. Incentives from refunded saved energy motivate reaching sub-goals, as Ostrom suggested. By contrast, coercing free-riding subgroups through sanctioning at a cost fails, because sanctioning also hits fair individuals who then reduce their contributions. However, the power of polycentricity with numerous successful units can help mitigate climate change.

¹Max-Planck-Institute of Evolutionary Biology, Plön, Germany. ²Max Planck Institute for Meteorology, Hamburg, Germany. ✉email: milinski@evolbio.mpg.de

Introduction

The global community of countries has entered the legally binding Paris Agreement (COP21) to limit global warming to well below 2 °C and to pursue efforts to limit warming to 1.5 °C. Achieving these two goals requires CO₂ emissions to reach net-zero by the middle of the century or during the second half of the century, respectively (IPCC, 2021). Nevertheless, global CO₂ emissions have kept rising even after the adoption of the Paris Agreement, apart from the dip caused by the COVID-19 pandemic (Friedlingstein et al., 2021). Current pledges by individual countries to reduce emissions are not putting the world on a path toward net-zero CO₂ emissions (Hausfather and Peters, 2020), and a recent comprehensive assessment concluded that the current social dynamics toward decarbonisation are not powerful enough for zero CO₂ emissions by 2050 (Stammer et al., 2021). A plausible explanation for the slow path toward decarbonisation is the tendency toward, and fear of, free-riding among the countries sending delegations to UN conferences (Milinski et al., 2016), ultimately an example of Hardin's tragedy of the commons (Hardin, 1968).

However, Ostrom criticised (Ostrom et al., 1999; Berkes et al., 1989; Dietz et al., 2003) Hardin's claimed inevitability that 'whenever people have free access to a public resource, the resource will be overused and collapse' (Hardin, 1968), and that resource users are trapped in a common's dilemma, unable to create solutions, and thus can be rescued only by a centralised government. Instead Ostrom propagated a decentralised, 'polycentric' approach to mitigating global climate change (Ostrom, 2009a, 2009b; Ostrom, 2012; Ostrom, 2014). She and her co-workers (Dietz et al., 2003; Berkes et al., 1989; Ostrom, 1990; Ostrom et al., 1992; Volland and Ostrom, 2010) referred to the many social groups that have struggled successfully against threats of resource degradation by developing and maintaining self-governing institutions. Many examples exist of long-term sustainable resource use in economically advanced communities with effective, local, self-governing rights, requiring that rules of resource use are generally followed based on trust but also by imposing modest sanctions (Dietz et al., 2003; Ostrom, 2009a; Ostrom, 1990). It is often true that relatively small groups in large societies, such as local communities, have enormous potential to organise and manage themselves in ways that promote cooperation and prevent them from depleting natural resources. These are important virtues of a local organisation, formal or informal, relative to a more global authority (Van Lange et al., 2013). Social bonding and social networks are favoured in small-scale societies (Boehm, 2019). By contrast, the efforts of an external authority to change the group behaviour in a certain direction can, counter-intuitively, have an opposite effect on individual behaviour (Gavrilets, 2021).

Vincent Ostrom (1999) defined 'a polycentric order as one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements.' 'Polycentricity is a useful analytical approach for understanding and improving efforts to reduce the threat of climate change' (Ostrom, 2010). Polycentric theory generally assumes that actors will mobilise against a problem when it is in their self-interest to do so (Jordan et al., 2018). Ostrom's hypothesis builds on the human habit of being cooperative if it pays off through individual gains (Ostrom, 2010; Milinski et al., 2002; Milinski et al., 2006). She identifies this opportunity when families and small firms can achieve benefits that offset costs at a household or neighbourhood level or by small firms that invest in better construction of a building, investment in solar panels, and many other investments in equipment that families as well as private firms can make that pay off in the long run. 'The

important point is that benefits can be achieved that offset costs at the household or neighbourhood level' (Ostrom, 2012). 'At least seventeen actions that can be taken within a home or a business facility can cumulatively have a major impact on carbon emissions and save the family or firm budget' (Dietz et al., 2009). The incentive to achieve this net gain, thereby reducing greenhouse gas emissions, may trigger human investment decisions. Even though each of these small units saves energy and thus CO₂ emissions at a small scale, it is the multitude of these units that can make polycentricity successful at the global level (Ostrom, 2010, 2012, 2014).

Interestingly, the minister of trade and commerce of a European country has just suggested that all households together each saving 10% energy could resolve the country's energy crisis—very close to Ostrom's ideas.

'The emergence of a polycentric system is argued to start the process of reducing greenhouse gas emissions and to act as a spur to international regimes to do their part' (Ostrom, 2012; Green et al., 2014; Jordan et al., 2015; Cole, 2015). Although Ostrom (2012) stresses that 'researchers need to understand the strength of polycentric systems where enterprises at multiple levels may complement each other', she always comes back to mention 'the importance of building a strong commitment to finding ways of reducing individual emissions for coping with climate change'. The familiar slogan 'Think globally but act locally' hits right at the dilemma facing all inhabitants of the world: 'To solve climate change in the long run, the day-to-day activities of individuals, families, firms, communities, and governments at multiple levels must change substantially' (Ostrom, 2010). 'It is obviously much easier to craft solutions for collective-action problems related to smaller scale common pool resources than for the global commons' (Ostrom, 2009a).

Jordan et al. (2018) provide a comprehensive state-of-the-art discussion of the polycentric approach to climate governance, its promise and potential limits. However, while both self-governed stable preservation of common goods and successful multiscale governance demonstrably exist, experimental evidence has been lacking so far that indeed Ostrom's polycentric approach is more successful at maintaining a global common good than relying on global agreements alone. It is this gap that we try to fill here. 'We use the design of the 'collective-risk social dilemma' that arises from attempts to avert simulated dangerous climate change in experimental games' (Milinski et al., 2008; Milinski et al., 2011; Tavoni et al., 2011; Jacquet et al., 2013; Milinski et al., 2016; Dannenberg et al., 2015; Skatova et al., 2016; Kline et al., 2018; Andrews et al., 2018; Marotzke et al., 2020; Andrews et al., 2021; Szekely et al., 2021): The essential features of the dangerous climate change game are simulated in a 'nutshell': 'Will a group of people reach a fixed target sum through successive individual monetary contributions, when they know they will lose all their remaining money with a certain probability if they fail to reach the target sum for averting simulated dangerous climate change?' (Milinski et al., 2008).

We test with student volunteers whether a polycentric approach helps mitigate simulated climate change better than an approach based solely on more 'global' cooperation (see Methods, instructions for participants in SI). In short, the approach compares the success of groups of 9 players each to assemble the 'global' target sum with that of such groups subdivided in three subgroups each assembling their subgroup target; the subgroup targets need to add up to the group target to pay off 'globally'. Further treatments test Ostrom's idea that incentives of refunded saved energy that subgroups are offered or sanctions of subgroups by other subgroups may help groups meeting the 'global' target. Although we follow the tradition of experimental economics (e.g.,

Smith, 1986) using small groups mimicking reality, results need to be discussed with caution when compared to reality. We provide a proof of principle, meaning that the principle is shown to be correct, although in reality it might be affected by many influences that have been controlled for in the laboratory. Vernon Smith discusses how economic experiments reflect reality (Smith, 2002).

Dangerous climate change (Schneider, 2001) might occur when a certain temperature threshold is passed (COP21, 2015; Meinshausen et al., 2009; Peters et al., 2013). Such threshold-passing is averted in our game if the nine participants of a group collectively reach the specified target sum of €180 after 10 rounds, through individual contributions per round to a climate account, from their personal account that carries an initial endowment of €40. All nine members of a group are paid out anonymously the money left in their personal account after the game. If they fail to meet the target, they lose all their money with a probability of 90%.

Though threshold variation occurs in reality (Barret and Dannenberg, 2012), we use a fixed threshold mimicking the 2 °C threshold (Randalls, 2010) in our experiments. This is what humans have been told and thus may have in mind when deciding to invest in mitigation in the real game. To increase external validity, we informed participants that all the money they paid into the climate account would be used to purchase an advertisement on ‘how to mitigate climate change’ in each of four German newspapers (see Supplementary Information).

We use groups of nine volunteers in a collective-risk social dilemma investing individually over 10 rounds towards a group target, either in a single group of nine (treatment T1), or the nine players are subdivided in three subgroups of three players each (treatment T2, T3, T4) (Fig. 1). In T2 each player has the incentive to gain an extra monetary reward if her subgroup of

three has approached the sub-target of €60 after ten rounds, starting refund at €52 reached and increasing it until €60 reached (Fig. 1, see Methods for procedure). The players are told that contributions simulate investment in an energy-saving block heat and power plant for the community that starts saving costs with a sub-target approached (Ostrom, 2009a, 2012). The extra monetary refund is paid out after the game irrespective of whether the final global target sum of €180 has been assembled by the nine players. The comparison between T1 and T2 tests Ostrom’s original idea—polycentricity combined with incentives. Will any of the subgroups in T2 reach the subgroup target of €60 with higher probability than *post-hoc* randomly formed subgroups in T1, and will the groups of nine players reach the ‘global’ target of €180 with higher probability in T2 than in T1?

With treatment T3 (see Methods, Fig. 1) we test the predictions of a dynamic evolutionary model (Vasconcelos et al., 2013; Pacheco et al., 2014) that sanctions boost mitigation by groups in a polycentric setting. Each of the three subgroups can, at a small cost to each member, sanction another subgroup by majority vote. Each member of the sanctioned subgroup has to pay a larger fine. Each subgroup is shown the contribution of each subgroup. One or two subgroups can decide, if at least two members of a subgroup happen to agree to sanction a specific other subgroup, that has, e.g., contributed below the fair share in the last round, to sanction that subgroup.

Our treatment differs from the model assumption in one important aspect. In the model (Vasconcelos et al., 2013; Pacheco et al., 2014) each subgroup can avert climate change and gain the payoff by exceeding only its subgroup threshold. Therefore, it makes sense if group members sanction free-riders within their own subgroup. In the present study, however, subgroups can gain the payoff only when subgroups jointly invest to reach the ‘global’ target, as in reality. Will any of the subgroups in T3 reach the subgroup target of €60 with higher probability than subgroups in T4, a control without the sanctioning opportunity, and will any of the groups of nine players reach the global target of €180 with higher probability in T3 than in T4?

Methods

Participants and procedure. Experiments were conducted in November, December 2014, and in April, May 2015 with a total of 396 undergraduate students from the universities of Kiel, Hamburg, Köln and Greifswald, Germany. The students received a show-up fee of €10 each and participated in 44 experimental sessions with nine participants each in a computerised experiment using the software z-Tree (Fischbacher, 2007). The participants were separated by opaque partitions and each had a computer on which they received the instructions for the experiment and with which they communicated their decisions.

Participants were randomly allocated to experimental groups, were anonymous throughout the whole experiment, and made their decisions under a neutral pseudonym. Pseudonyms were moons of our solar system: Ananke, Telesto, Despina, Japetus, Kallisto, Metis, Galatea, Vestia, Leda.

Treatments. We use groups of nine volunteers to simulate a ‘country’, either in a single group of nine (T1)—10 groups, or the nine players are subdivided in three subgroups of three players each (T2—12 groups, T3—12 groups, T4—10 groups) (Fig. 1). We use groups of 9 volunteers, to be divided in subgroups of equal size. The participants interacted in a variant of the ‘collective-risk social dilemma’ game (Milinski et al., 2008). They received an initial endowment of €40 and were asked, in each of ten rounds, to contribute €0, €2 or €4 from this endowment into a ‘climate account’. After ten rounds, the game

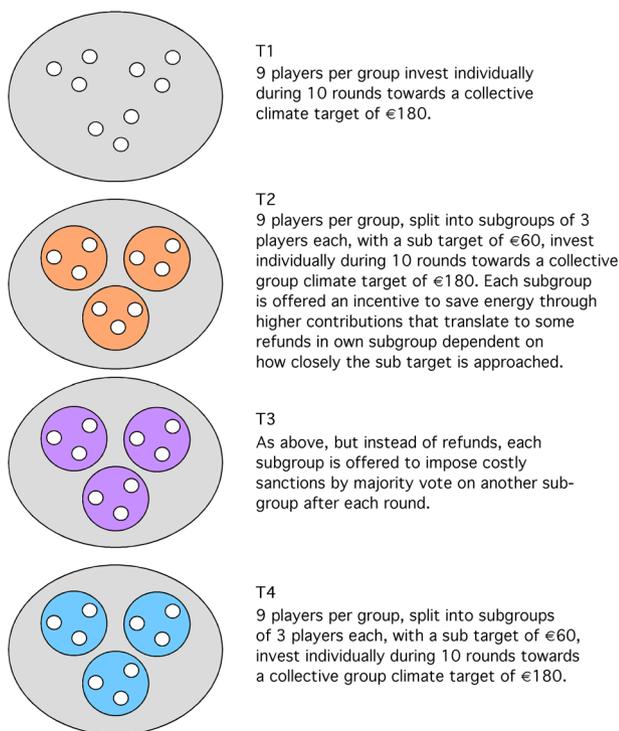


Fig. 1 Description of experimental treatments. T1: 9 players of a group invest individually. T2: groups are split into subgroups of 3 players each, offered an incentive to save energy. T3: each subgroup is offered to impose costly sanctions on another subgroup. T4: groups are split into subgroups of 3 players each, no incentive is offered, no opportunity to impose costly sanctions is offered.

software checked whether total contributions of all group members matched (or exceeded) the target sum of €180. If that was the case, that is each group member had paid €2 per round on average, participants received the money in their account in cash in a way that maintained the participants' anonymity. If the collective target was not reached, participants lost their remaining money with 90% probability. All money contributed to the climate account, regardless of country success was used to publish a newspaper advertisement on 'how to mitigate climate change' composed by the Max Planck Institute for Meteorology (see Supplementary Information). To gain external validity, all money invested in mitigation is lost by the players, as in reality, and is now invested in the advertisements, irrespective of the success of mitigation.

In treatment T2, the nine players are subdivided in three subgroups of three players each and each player has the incentive to gain an increasing extra monetary reward of €0.50 if her subgroup of three has reached a sub-target starting at €52. Rewards increase with higher sub-targets reached after ten rounds, paid out anonymously after the game, irrespective of whether the final global target sum of €180 has been assembled by the nine players, sub-target reached after 10 rounds: €52—reward per player: €0.50 €, sub-target reached after 10 rounds: €54—reward per player: €1.00 €, sub-target reached after 10 rounds: €56—reward per player: €2.00 €, sub-target reached after 10 rounds: €58—reward per player: €4.00 €, sub-target reached after 10 rounds: €60 and more—reward per player—€8.00.

Treatment T3 is as T2 without incentives, but each of the three subgroups can costly sanction another subgroup by majority vote. Simulated dangerous climate change is averted only when the group target, not the subgroup, target is reached. If at least 2 of the 3 players of a subgroup have anonymously voted to sanction another specific subgroup, each player of the active subgroup pays €0.50 and each of the sanctioned

subgroup €2.00 from his/her account 'extra expenses', €15 per player. Only in T3 does each player receive an additional funds called 'extra expenses', from which costs of sanctioning and being sanctioned are covered. Each player receives the money that has not been spent from his/her 'extra expenses' anonymously after ten rounds irrespective of whether the collective target of €180 has been reached. Treatment T4 is the same as T3 but without the sanctioning opportunity (Instructions to participants, see Supplementary Information).

Statistics. All *P*-values are two-tailed. Except for regression analysis we use non-parametric statistics throughout.

Results

The polycentric approach and Ostrom's incentive. In T1 individual contributions are mostly below the fair share of €2 on average except for the last two rounds (Fig. 2a), and the target sum of €180 is not reached on average (Fig. 2d, $P=0.83$, $z=-0.205$, $N=10$ groups, Wilcoxon one-sample test). In T2 the groups assembled significantly more than €180 on average (Fig. 2d, $P=0.0074$, $z=-2.68$, $N=12$ groups, Wilcoxon one-sample test) and more than groups in T1 ($P=0.045$, $z=-2.005$, $N_1=10$, $N_2=12$, Mann-Whitney *U*-test). A higher percentage of subgroups in T2 reached their sub-target of €60 than randomly formed subgroups of three players in T1 (Fig. 2c, $P=0.0196$, $z=-2.334$, $N_1=12$, $N_2=10$, Mann-Whitney *U*-test).

Thus, incentives for reaching a subgroup goal repaid eventually through savings of energy produced the 'global' solution in the experiment, supporting Ostrom's (Ostrom, 2009b) hypothesis. Depending on how closely subgroups approached the subgroup target of €60, repaid investments ranged from 0 to €8 per player (see Methods). In this way players in this treatment gained $€6.40 \pm €0.24$ per player, which is much

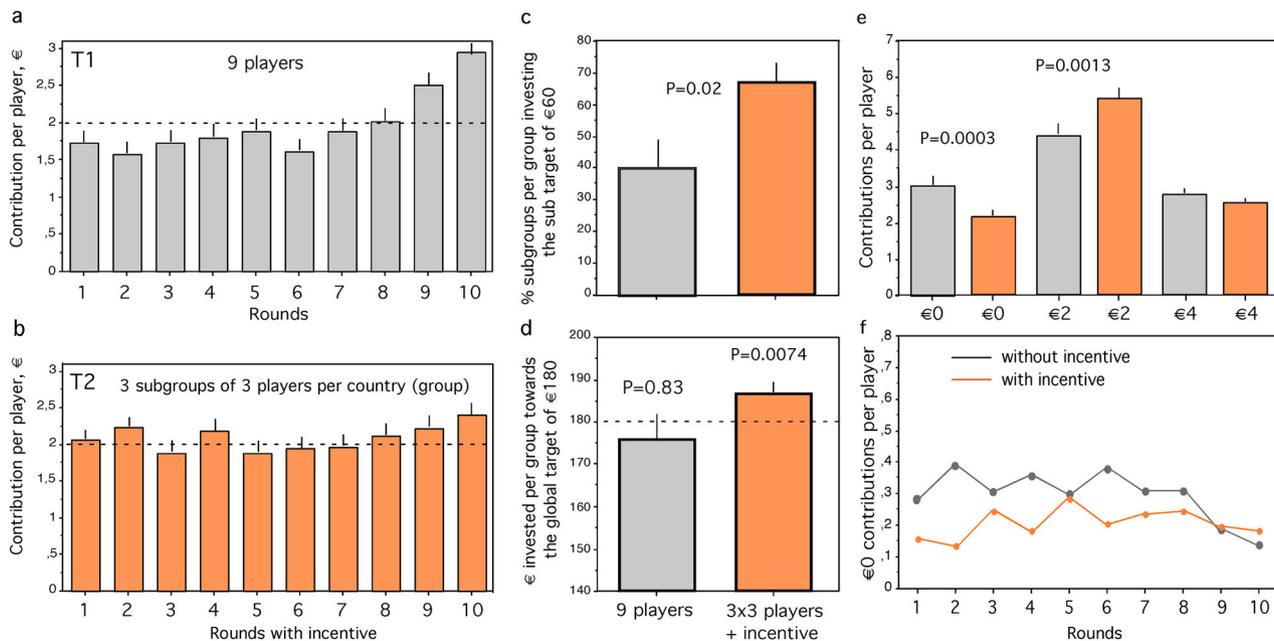


Fig. 2 Investment into climate change mitigation. **a** Contribution per player of 9 players per group investing individually during each of 10 rounds (T1). Stippled line shows fair share of €2. **b** Contribution per player of 9 players per group subdivided into 3 fixed subgroups of 3 players investing individually in mitigation during each of 10 rounds with an incentive to save energy, benefiting own subgroup (T2). **c** Percentage of subgroups per group investing the sub-target of €60, for randomly simulated subgroups of 3 players in T1 (grey) and in T2 (orange). **d** Euros invested per group towards the global collective target of €180 (stippled line), for T1 (grey) and T2 (orange). **e** Selfish (€0), fair (€2) and generous (€4) contributions per player per round for randomly simulated subgroups investing without incentive (grey), and for fixed subgroups with incentive (orange). **f** Selfish (0€) contributions per player in each round for randomly simulated subgroups in T1 (grey) and for the fixed subgroups in T2 (orange). See text for statistics, bars indicate standard errors.

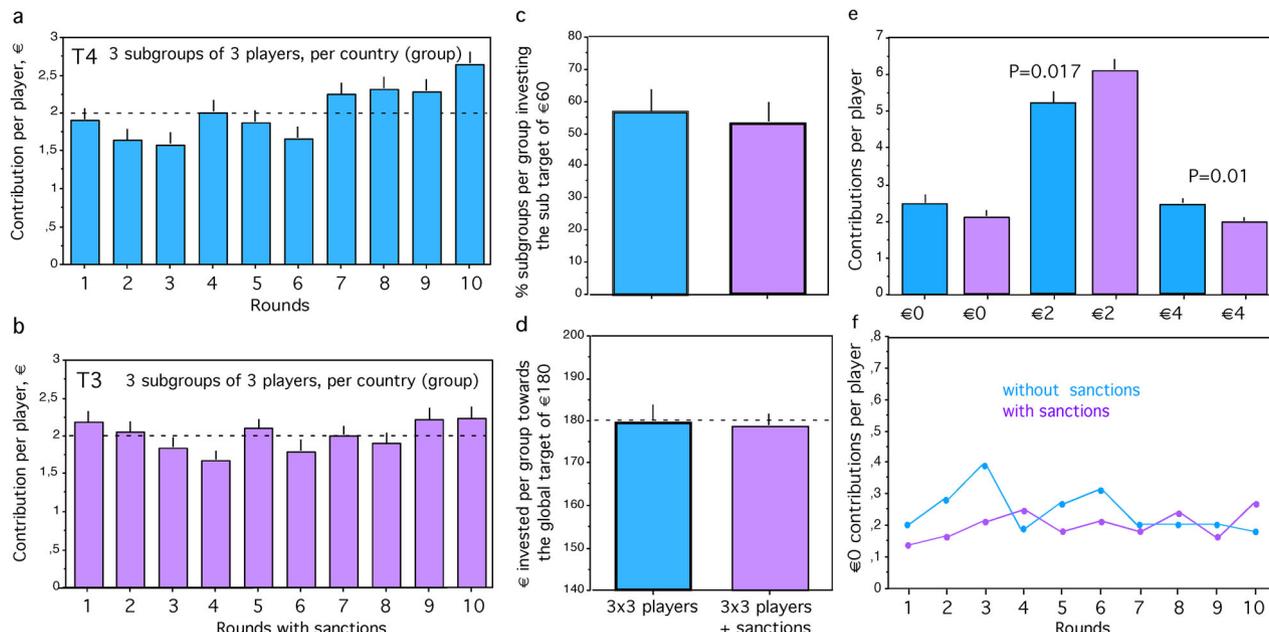


Fig. 3 Sanctions and climate change mitigation. **a** Contribution per player of 9 players per group each subdivided into 3 fixed subgroups of 3 players investing individually in mitigation during each of 10 rounds (T4). Stippled line shows fair share of €2. **b** Contribution per player when each subgroup is offered to impose costly sanctions on another subgroup after each round (T3). **c** Percentage of subgroups per group investing the sub-target of €60, for fixed subgroups (blue) and for fixed subgroups with the opportunity to impose costly sanctions (pink) **d** Euros invested per group towards the global collective target of €180, see stippled line. **e** Selfish (€0), fair (€2) and generous (€4) contributions per player per round with fixed subgroups investing without sanction opportunity (blue), and with sanction opportunity (pink). **f** Selfish (0€) contributions per player in each round with fixed subgroups investing without sanction opportunity (blue), and with sanction opportunity (pink). See text for statistics, bars indicate standard errors.

less than €20 per player to be gained on average when the overall target of €180 was contributed.

Do incentives reduce selfish contributions and/or increase generous contributions? Players could contribute either €0, €2 or €4 in each round. Selfish contributions (0€) were more frequent in T1 than in T2 (Fig. 2e, f; T1: 2.978 ± 0.211 , mean \pm SE; T2: 2.12 ± 0.158 , $P = 0.0013$, $N_1 = 30$, $N_2 = 36$ subgroups, $z = -3.205$, Mann-Whitney *U*-test). Fair contributions per player (€2) were less frequent in T1 than in T2 (Fig. 2e; T1: 4.211 ± 0.243 ; T2: 5.343 ± 0.216 ; $P = 0.0013$, $z = -3.225$, $N_1 = 30$, $N_2 = 36$ subgroups, Mann-Whitney *U*-test). Generous contributions per player (4€), however, did not significantly differ between T1 (2.711 ± 0.164) and T2 (2.5 ± 0.156 ; $P = 0.3182$, $N_1 = 30$, $N_2 = 36$ subgroups, Mann-Whitney *U*-test; Fig. 2e). Thus, polycentricity combined with incentives reduces selfish contributions, increases fair contributions but hardly affects generous contributions.

Sanctioning does not help reach the target. When subgroups have the opportunity to impose sanctions on another subgroup (T3), at least two players of a subgroup have to select the same subgroup to be disciplined. Each player of the active subgroup has a cost of €0.50 and each player of the sanctioned subgroup has a cost of €2.00. Sanctioning was used extensively, 9.0 ± 0.937 per group during the 10 rounds, almost once per round. Sanctioning had, however, almost no effect on contributions per round as compared to T4 (Fig. 3a, b). Contributions per group towards the target of €180 were on average close to the target sum in T3 but not different from T4 (Fig. 3d, $P = 0.5529$, $N_1 = 10$, $N_2 = 12$, $z = -0.596$, Mann-Whitney *U*-test). Similarly, the percentage of subgroups per group investing the subgroup target of €60 averaged over all groups was slightly higher than 50% in T3 but not different from T4 (Fig. 3c, $P = 0.6608$, $N_1 = 10$, $N_2 = 12$,

$z = -0.439$, Mann-Whitney *U*-test). Contributions per player increased from the first half to the second half in T4 (Fig. 3a, $P = 0.0005$, $N = 30$ subgroups, $z = -3.463$, Wilcoxon-signed-rank test) but not in T3 (Fig. 3b, $P = 0.2939$, $N = 36$ subgroups, $z = -1.05$, Wilcoxon-signed-rank test).

Selfish contributions per player (0€) did not differ significantly between T3 (2.00 ± 0.163) and T4 (2.367 ± 0.212 ; $P = 0.16$, $z = -1.398$, $N_1 = 30$ subgroups, $N_2 = 36$ subgroups, Mann-Whitney *U*-test; Fig. 3e). Fair contributions per player (€2) were more frequent in T3 (6.00 ± 0.245) than in T4 (5.178 ± 0.246 ; $P = 0.0166$, $z = -2.395$, Mann-Whitney *U*-test; Fig. 3e).

Generous contributions per player (4€) were significantly less frequent in T3 (1.898 ± 0.158) than in T4 (2.367 ± 0.212 ; $P = 0.0091$, $z = -2.606$, Mann-Whitney *U*-test; Fig. 3e). Thus, overall contributions were similar with and without sanction opportunity. Polycentricity combined with a sanction opportunity hardly affects selfish contributions, increases fair contributions but decreases generous contributions compared to polycentricity without a sanction opportunity.

The puzzle of sanctioning without disciplining. Figure 4a shows a strong correlation between the number of sanctions received by a subgroup and its contribution toward the target sum ($P = 0.0001$, $N = 36$, r -squared = 0.466, F -test = 29.723): subgroups that have contributed least have been sanctioned most. Thus, sanctioning does not equalise contributions among subgroups. The number of sanctions received is highest in the subgroups with the lowest contribution rank in a group (Fig. 4b). Average number of sanctions received differs among the three subgroup-contribution ranks per group (Fig. 4b) ($P = 0.0258$, Chi-squared = 7.316, Friedman-test).

Do subgroups react to being sanctioned? Contributions of subgroups that are sanctioned by one subgroup are unfair—

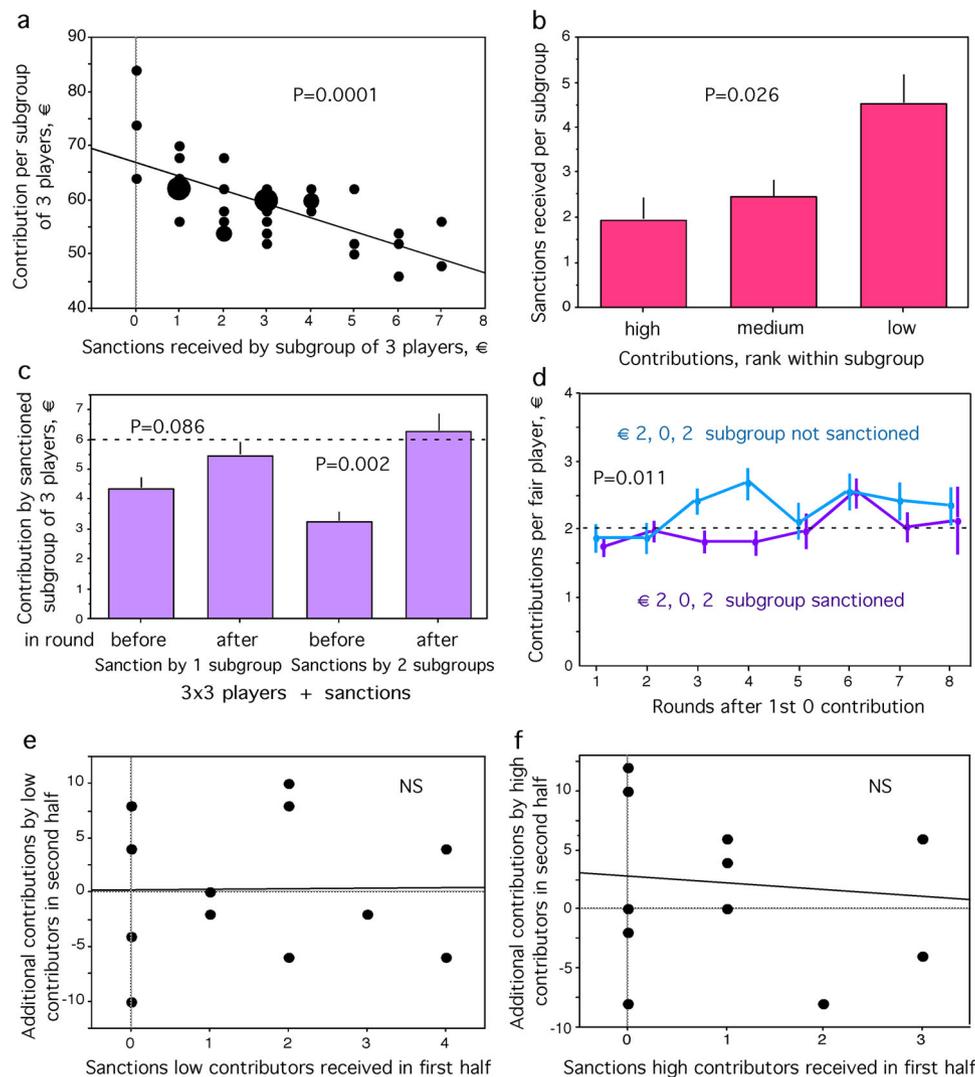


Fig. 4 The effect of sanctions. **a** Regression of sanctions received by subgroups of 3 players on the total contribution of subgroup. Bigger dots indicate overlay. **b** Sanctions received per subgroup whose total contribution ranks either high, medium or low within its group. **c** Mean contribution by sanctioned subgroup in round before and after sanctioning by one or two subgroups, respectively. Bars indicate standard errors. Stippled line indicates the fair contribution per subgroup. **d** Contribution per player that had contributed €2 when the subgroup was sanctioned because another player had contributed €0, during rounds after the sanctioning was received (T3, pink); only first instance of sanctioning per subgroup analysed. The same analysis carried out in the treatment for the first occurring triplet of €0, €2, €2 contributions (T4, blue). Bars indicate standard errors. Stippled line indicates fair share per player. **e** Regression of sanctioned players with the lowest contribution rank in a subgroup received during the first 5 rounds on their additional contributions during the last 5 rounds of the experiment. **f** Regression of sanctioned players with the highest contribution rank in a subgroup received during the first 5 rounds on their additional contributions during the last 5 rounds of the experiment. See text for statist.

they contribute below €6 per round ($P = 0.0004$, $N = 31$, $z = -3.538$, Wilcoxon one-sample test) and then increase contributions to the next round but not significantly so ($P = 0.0863$, $N = 31$, $z = -1.715$, Wilcoxon-matched-pairs test), remaining on average still below €6 (Fig. 4c). When two subgroups jointly sanction a subgroup, the disciplining effect increases significantly ($P = 0.0021$, $N = 16$, $z = -3.081$, Wilcoxon-matched pairs test) with contributions in the next round slightly above €6 on average (Fig. 4c). The disciplining effect vanishes quickly, sanctions in the first half, rounds 1 to 5, do not affect the change in contribution from the first to the second half (rounds 6 to 10) neither in contributors ranking lowest per subgroup (Fig. 4e, $P = 0.9615$, $N = 12$ subgroups, R -squared = $2.452E-4$, F -test = 0.002) nor in contributors ranking highest per subgroup (Fig. 4f, $P = 0.7752$, $N = 12$ subgroups, R -squared = 0.009, F -test = 0.086). Thus, sanctioning has only a short-term disciplining effect.

Sanctioning without disciplining explained. When a subgroup is sanctioned because one player has contributed only €0, the other two players have usually contributed the fair share (€2). Those fair players contribute less during rounds after the sanctioning (T3, Fig. 4d), with only the first instance of sanctioning per subgroup analysed to avoid pseudo-replication. They contribute less ($\text{€}1.972 \pm 0.075$) than comparable players in T4 ($\text{€}2.366 \pm 0.113$), for the first occurring triplet of €0, €2, €2 contributions ($P = 0.01$, $z = -2.558$, $N_1 = 45$, $N_2 = 54$, Mann-Whitney U -test). Thus, the fair contributors react to their subgroup being sanctioned, which is unfair to them. Increased contributions by sanctioned free riders are compensated by the reduced generosity of co-sanctioned fair players, nullifying any sanctioning effect at the entire-group level (Fig. 3d). Sanctioning had a cost of $\text{€}1.486 \pm 0.067$ and being sanctioned of $\text{€}5.944 \pm 0.377$ per player overall, a sum of $\text{€}7.40$ on average, with a range of €0.50 to €16, which reduces the extra account of

€15 to €7.60 ± 0.38, similar to the extra payoff of €6.40 ± 0.24, with a range of €0 to €8, gained per player in T2.

Discussion and conclusions

‘The problem of averting massive climate change—or a global ‘public bad’—would be a global ‘public good’ (Sandler, 2004). Billions of actors affect the global atmosphere. All would benefit from reducing greenhouse gas emissions, but the problem is that an actor benefits whether or not he or she pays any of the mitigation costs. ‘Trying to solve the problem of providing a public good is a classic collective-action dilemma—and potentially the largest dilemma the world has ever knowingly faced’ (Ostrom, 2014). ‘No central authority exists at the global level making authoritative decisions about payments for energy use and investments in new technologies—and enforcing these decisions’ (Ostrom, 2014). ‘It is much easier to craft solutions for collective-action problems related to smaller-scale common pool resources than for the global commons’ (Ostrom, 2014). Ostrom hypothesised that the successful polycentric solutions would also scale up to the global commons (Ostrom, 2014; Ostrom, 2010; Dietz et al., 2003).

We find support for Ostrom’s hypothesis in an economic game by comparing climate mitigation at the ‘global’ level with that in a world subdivided into smaller communities. In our game, the groups of volunteers are subdivided into subgroups and, according to Ostrom’s suggestion, are provided with an incentive of repaid saved energy the closer their subgroup approaches a sub-target. Polycentric groups with incentives for subgroups reach the global target significantly more often than groups without subdivision and without incentives for subgroups. With polycentricity and incentives, subjects choose less often zero-contributions and more often the fair-share contribution. This polycentric approach is about 30 percent more successful in reaching the global target at the entire-group level.

Contrary to the predictions of a dynamic evolutionary model (Vasconcelos et al., 2013; Pacheco et al., 2014) we do not find that sanctioning, even when frequent, helps avoiding simulated dangerous climate change. There is a difference between model and experimental assumptions. In the model, each subgroup can avert climate change by exceeding only its subgroup threshold. Therefore, it makes sense in the model if group members sanction free-riders within their own subgroup. In the present study, subgroups can avert climate change only when subgroups jointly invest to exceed the ‘global’ threshold, as in reality. It does not help if the Netherlands reach their group target whereas Germany fails—the climate will be the same for both countries (Milinski, 2014). When subgroups sanction other subgroups for a round of contributing below fair share, having a free-rider among them, the free-rider is disciplined. However, subgroup sanctioning also hits the fair contributors and provokes them to reduce their further share neutralizing the positive effect of sanctioning. Sanctions that are perceived as unfair can deter altruistic behaviour (Fehr and Rockenbach, 2003). An experiment on sanctions applied to an entire group on account of a single free-rider found that such collective sanctions are ineffective (Chapkovski, 2021), corroborating our findings.

Ultimately, climate change is caused by human behaviour. Indeed, ‘one lesson from decades of research in psychology is that human behaviour is strongly embedded in communities, be it neighbourhoods, information groups, or networks of friends or professionals. These social networks may often help to convey clues for change, remove barriers to change, and provide the norms and sometimes support needed for

sustainable behavioural change’ (Huckelba and Van Lange, 2020). Humans use their toolbox for decision-making when identifying the most useful option on their own behalf (Andrews et al., 2018). The toolbox can be increased by integrating psychological concepts into feasible interventions to reduce greenhouse gas emissions (Van Lange et al., 2018; Nielsen et al., 2021) at the level of small communities.

The overall landscape of climate governance has started to exhibit some of the characteristics of polycentricity foreseen by Ostrom (2010), ‘that is, more diverse, multi-levelled, and with a much greater emphasis on bottom-up initiatives’ (Jordan et al., 2015). Research has shown that the advent of new forms of climate governance has made the overall landscape more polycentric: ‘Spanning many spatial levels and working through many modes and domains of actions. This pattern bears out many, but not all, of Ostrom’s predictions’ (Jordan et al., 2015). A polycentric approach to climate governance has been argued to ‘provide the best chance we have of accelerating progress toward global climate stabilisation’ (Cole, 2015). We have provided experimental evidence for this reasoning using methods of experimental economics. We find, though at a small experimental scale, that polycentric settings with benefits for subgroups can in principle, as we conclude with caution, help protect a global common good such as a stable global climate. By contrast, sanctioning free-riding subgroups has proved ineffective.

How can we experimentally study interactions at larger scales, such as states collaborating in mitigating climate change, even though there is always the risk of free-riding of some states on the investments of others as Ostrom mentions in several places? It is possible that some states can enforce higher investments from other states, as a simulation of climate conferences has shown in an economic experiment (Milinski et al., 2016). Selfish players were preferentially elected as representatives, who turned out to be extortioners (c.f. Press and Dyson, 2012). Their steadfast strategies enforce cooperation from other representatives who compensate completely the deficit caused by extortionate players so that mitigation was successful—not a nice but successful interaction among simulated ‘states’.

Data availability

Data are available from <https://hdl.handle.net/21.11116/0000-000B-5C25-5>.

Received: 26 January 2022; Accepted: 8 November 2022;

Published online: 10 December 2022

References

- Andrews TM, Delton AW, Kline R (2021) Is a rational politics of disaster possible? Making useful decisions for others in an experimental disaster game. *Pol Behav.* <https://doi.org/10.1007/s11109-021-09700-2>
- Andrews TM, Delton AW, Kline R (2018) High-risk high-reward investments to mitigate climate change. *Nat Clim Change* 8:890–894
- Barret S, Dannenberg U (2012) Climate negotiations under scientific uncertainty. *Proc Natl Acad Sci USA* 109:17372–17376
- Berkes F, Feeney D, McCay BJ, Acheson JM (1989) The benefits of the commons. *Nature* 340:91–93
- Boehm C (2019) Gossip and reputation in small-scale societies. In: Giardini F, Wittek R eds *Oxford handbook of gossip and reputation*. Oxford Univ. Press, Oxford, UK, pp. 253–274
- Chapkovski P (2021) Strike one hundred to educate one: measuring the efficacy of collective sanctions experimentally. *PLoS ONE* 16:e0248599. <https://doi.org/10.1371/journal.pone.0248599>
- Cole DH (2015) Advantages of a polycentric approach to climate change policy. *Nat Clim Change* 5:114–118

- UNFCCC (2015) COP21 UN climate change conference Paris 2015 <https://unfccc.int/process/conferences/pastconferences/paris-climate-change-conference-november-2015/paris-agreement>
- Dannenberg U, Löschel A, Paolacci G, Reif C, Tavoni A (2015) On the provision of public goods with probabilistic and ambiguous thresholds. *Environ Resour Econ* 61:365–383
- Dietz T, Gardner GT, Gilligan J, Stern PC, Vandenbergh MP (2009) Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proc Natl Acad Sci USA* 106:18452–18456
- Dietz T, Ostrom E, Stern P (2003) The struggle to govern the commons. *Science* 302:1907–1912
- Fehr E, Rockenbach B (2003) Detrimental effects of sanctions on human altruism. *Nature* 422:137–140
- Fischbacher U (2007) z-Tree: Zurich toolbox for ready-made economic experiments. *Exp Econ* 10:171–178
- Friedlingstein P et al. (2021) Global Carbon Budget 2021. *Earth System Science. Data* 14:1917–2005
- Gavrilets S (2021) Coevolution of actions, personal norms and beliefs about others in social dilemmas. *Evol Hum Sci* 3:e44. <https://doi.org/10.1017/ehs.2021.40>
- Green JF, Sterner T, Wagner GA (2014) Balance of bottom-up and top-town in linking climate policies. *Nat Clim Change* 4:1064–1067
- Hardin G (1968) The tragedy of the commons. *Science* 162:1243–1248
- Hausfather Z, Peters GP (2020) Emissions—the ‘business as usual’ story is misleading. *Nature* 577:618–620
- Huckelba L, Van Lange PAM (2020) The silent killer: consequences of climate change and how to survive past the year 2050. *Sustainability* 12:3757. <https://doi.org/10.3390/su12093757>
- IPCC (2021) Summary for policymakers. Climate change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds.) Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32
- Jacquet J, Hagel K, Hauert K, Marotzke J, Röhl T, Milinski M (2013) Intra- and intergenerational discounting in the climate game. *Nat Clim Change* 3:1025–1028
- Jordan A, Huitema D, Van Asselt H, Forster J (2018) Governing climate change. In: Jordan A, Huitema D, Van Asselt H, Forster J (eds.) Governing climate change: polycentricity in action? Cambridge Univ. Press, 359–383
- Jordan AJ, Huitema D, Hildén M, Van Asselt H (2015) Emergence of polycentric climate governance and its future prospects. *Nat Clim Change* 5:977–982
- Kline R, Seltzer N, Lukinova E, Bynum A (2018) Differentiated responsibilities and prosocial behaviour in climate change mitigation. *Nat Human Behav* 2:653–661
- Marotzke J, Semmann D, Milinski M (2020) The economic interaction between climate change mitigation, climate migration and poverty. *Nat Clim Change* 10:518–525
- Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR (2009) Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* 458:1158–1162
- Milinski M, Hilbe C, Semmann D, Sommerfeld R, Marotzke J (2016) Humans choose representatives who enforce cooperation in social dilemmas through extortion. *Nat Commun* 7:10915
- Milinski M (2014) Modeling a polycentric approach to the problem of climate change: comment on “climate change governance, cooperation and self-organization” by Pacheco, Vasconcelos & Santos. *Phys Life Rev* 11:593–594
- Milinski M, Röhl T, Marotzke J (2011) Cooperative interaction of rich and poor can be catalyzed by intermediate climate targets. *Clim Change* 109:807–814
- Milinski M, Sommerfeld RD, Krambeck H-J, Reed FA, Marotzke J (2008) The collective-risk social dilemma and the prevention of simulated dangerous climate change. *Proc Natl Acad Sci USA* 105:2291–2294
- Milinski M, Semmann D, Krambeck H-J, Marotzke J (2006) Stabilizing the Earth’s climate is not a losing game: supporting evidence from public goods experiments. *Proc Natl Acad Sci USA* 103:3994–3998
- Milinski M, Semmann D, Krambeck H-J (2002) Reputation helps solve the ‘tragedy of the commons’. *Nature* 415:424–426
- Nielsen KS, Stern PC, Clayton S, Dietz T, Capstick S, Whitmarsh L (2021) How psychology can help limit climate change. *Am Psychol* 76:130–144
- Ostrom E (2014) A polycentric approach for coping with climate change. *Ann Econ and Finance* 15:97–134
- Ostrom E (2012) Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Econ Theory* 49:353–369
- Ostrom E (2010) Polycentric systems for coping with collective action and global environmental change. *Glob Environ Change* 20:550–557
- Ostrom E (2009a) Polycentric systems for coping with climate change. Policy Research Working Paper 5095; Workshop in Political Theory and Policy Analysis, Indiana University, Report prepared for the WDR2010 Core Team, Development and Economics Research Group, World Bank, Washington, DC
- Ostrom E (2009b) Beyond markets and states: polycentric governance of complex economic systems. Prize Lecture, December 8, 2009. Workshop in Political Theory and Policy Analysis. Indiana University, Bloomington IN, pp. 408–444
- Ostrom E, Burger J, Field Norgaard RB, Policansky D (1999) Revisiting the commons: local lessons, global challenges. *Science* 284:278–282
- Ostrom E, Walker J, Gardner R (1992) Covenants with and without a sword: self-governance is possible. *Am Polit Sci Rev* 86:404–417
- Ostrom E (1990) Governing the commons. Cambridge Univ Press, Cambridge
- Ostrom V (1999) Polycentricity-part 1. In: McGinnis M (ed.) Polycentricity and local public economics. University of Michigan Press, Ann Arbor, pp. 52–74
- Pacheco JM, Vasconcelos VV, Santos FC (2014) Climate change governance, cooperation and self-organization. *Phys Life Rev* 11:573–586
- Peters GP et al. (2013) The challenge to keep global warming below 2 °C. *Nat Clim Change* 3:4–6
- Press WH, Dyson FJ (2012) Iterated Prisoner’s Dilemma contains strategies that dominate any evolutionary opponent. *Proc Natl Acad Sci USA* 109:10409–10413
- Randalls S (2010) History of the 2 degrees C climate target. *Wiley Interdiscip Rev—Clim Change* 1:598–605
- Sandler T (2004) Global collective action. Cambridge Univ.Press, Cambridge
- Schneider SH (2001) What is ‘dangerous climate change’? *Nature* 411:17–19
- Skatova A, Bedwell B, Kuper-Smith B (2016) When push comes to stove: compensating and opportunistic strategies in a collective-risk household energy dilemma. *Front Energy Res* 4:1–15
- Smith VL (1986) Experimental methods in the political economy of exchange. *Science* 234:167–173
- Smith VL (2002) Method in experiment: rhetoric and reality. *Exp Econ* 5:91–110
- In: Stammer D, Engels A, Marotzke J, Gresse E, Hedemann C, Petzold J (eds.) (2021) Hamburg Climate Futures Outlook 2021. Assessing the plausibility of deep decarbonization by 2050 (Cluster of Excellence Climate, Climatic Change, and Society (CLICCS), Hamburg, Germany, p. 157
- Szekely A, Lipari F, Antonioni A, Paolucci M, Sanchez A, Tummolini L, Andrighetto G (2021) Evidence from a long-term experiment that collective risks change social norms and promote cooperation. *Nat Commun* 12:5452. <https://doi.org/10.1038/s41467-021-25734-w>
- Tavoni A, Dannenberg A, Kallis G, Loschl A (2011) Inequality, communication, and the avoidance of disastrous climate change in a public goods game. *Proc Natl Acad Sci USA* 109:11824–11829
- Van Lange PAM, Joireman J, Milinski M (2018) Climate change: what psychology can offer in terms of insights and solutions. *Curr Direct Psychol Sci* 27:269–274
- Van Lange PAM, Joireman J, Parks CD, Van Dijk E (2013) The psychology of social dilemmas: a review. *Organ Behav Hum Decis Process* 120:125–141
- Vasconcelos VV, Santos FC, Pacheco JMA (2013) Bottom-up institutional approach to cooperative governance of risky commons. *Nat Clim Change* 3:797–801
- Vollan B, Ostrom E (2010) Cooperation and the commons. *Science* 330:923–924

Acknowledgements

We thank the students of the universities of Greifswald, Hamburg, Kiel and Köln for their participation. We thank A. Hundermark for the z-tree programme and for help with the experiment. We also thank H. Arndt, H. Brendelberger, S. Dobler, and G. Uhl for logistic support. This study was supported by the Max Planck Society for the Advancement of Science.

Author contributions

MM designed the study, performed the research and analysed the data. MM and JM interpreted the data, wrote the paper, and revised the manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Ethical approval

All experimental procedures follow German regulations. For behavioural experiments like ours, neither approval from an ethics committee nor written consent to participate is required according to German regulations. We certify that the study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent

We have received the subjects' written informed consent to participate. They agreed with publication of the results in an anonymous form; full anonymity and true information was guaranteed, and subjects had the option to stop participating at any time.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1057/s41599-022-01436-6>.

Correspondence and requests for materials should be addressed to Manfred Milinski.

Reprints and permission information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2022