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Climate Negotiations in the Lab: A Threshold Public Goods Game with Heterogeneous Contributions Costs and Non-binding Voting

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Abstract We model the climate negotiations and the countries' individual commitments to carbon dioxide reductions as a threshold public goods game with uncertain threshold value. We find that a non-binding unanimous voting procedure on contribution vectors leads to frequent agreement on an optimal total contribution and high rates of compliance, even in the case of heterogeneous marginal contribution costs. However, groups that do not reach agreement perform worse than the baseline treatments without a voting procedure. The contribution vectors chosen by the groups point to a predominant burden-sharing rule that equalizes individual contribution costs, even at the cost of the group's total payoff.

Keywords Burden sharing · Climate change · Heterogeneity · Threshold public good · Threshold uncertainty · Unanimous voting

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1 Introduction

In the 2015 Paris Agreement[1] on the prevention of dangerous climate change, the members of the United Nations Framework Convention on Climate Change (UNFCCC) have prescribed themselves an ambitious goal, namely to reduce carbon emissions in order to limit global warming to "well below" the previously established[2] 2 °C threshold for an acceptable temperature increase above pre-industrial levels, preferably even to 1.5 °C. However, the agreement still leaves open how exactly the burden of emissions reductions is to be shared among the UNFCCC members. The national reduction targets are still open for negotiation.

In this paper, we investigate the UNFCCC climate negotiation procedure and ensuing global and individual abatement efforts from an economic perspective. In a laboratory voting experiment we observe that agreement is reached frequently (roughly two-thirds of the time) and always results in an equal split of the abatement costs, with unequal abatement quantities when there is heterogeneity with respect to marginal abatement costs. As a consequence, the abatement burden is allocated inefficiently.

In particular, we consider a game in which we assume that there exists a unique positive global abatement quantity of carbon dioxide (CO_2) emissions Q^* which is both socially and individually optimal. A tipping point with sudden and irreversible damages (e.g., IPCC 2014, p. 73ff) can create this scenario, but so can a continuously increasing damage function with decreasing marginal damages.[3] If such a quantity exists, then it is also individually optimal for all countries to comply with an agreement that specifies an allocation of Q^* among the countries ratifying the agreement, making it "self-enforcing" (Barrett 1994). However, if one country alone cannot reach this target, a stable situation can also exist if no country decides to honor the agreement ($Q = 0$).

As Barrett (2013) points out, this type of game is not primarily a problem of cooperation, because all countries realize that it is in their personal interest to reduce CO_2 emissions. Nevertheless, the countries face a coordination problem, because the target can be reached by any number of allocations of Q^* among the individual countries. Each country is obviously better off, if it only has to carry a small share of the abatement burden. But at least some countries must reduce emissions, or everyone suffers damages. If the location of the tipping point is uncertain,[4] there is nevertheless a quantity Q^* that is ex-ante optimal. Theoretically, this situation is a threshold public goods game with an uncertain threshold value (Barrett 2013), in which the national abatement efforts are modeled as "contributions" to the "public good" which is the prevention of damages from climate change.

A new component of our game is that we also consider the case where countries face heterogeneous marginal contribution costs, representing the differences between industrialized countries (like the U.S. and the members of the E.U.) with high marginal abatement costs and developing countries (like China and India) with comparatively low marginal abatement costs. This type of heterogeneity has so far not been considered in the context of a threshold public goods game with uncertain threshold.

[1] https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf, last accessed March 27, 2016.

[2] E.g., in the 2009 Copenhagen Accord, http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf, last accessed March 27, 2016.

[3] This corresponds, e.g., to the assumptions by Chander and Tulkens (1995) in their theoretical analysis of emissions abatement. For a different theoretical approach to climatic tipping points see Engström and Gars (2016).

[4] E.g., Hansen et al. (2008) give a range of 350–550 ppm for an atmospheric concentration of CO_2 which could result in sudden damages.

Another new aspect of our model is to combine the standard assumption of voluntary individual contributions with a non-binding unanimous vote on contribution vectors. This is similar to the consensus decision-making procedure used by the UNFCCC to determine national abatement efforts. In this study, we therefore consider a non-binding voting scheme, where, before each player individually chooses only her own contribution, a single attempt at a unanimous collective agreement can be made in order to provide a recommendation for these individual contributions. Just like in the real world, however, the players must still decide for themselves whether or not to follow this recommendation. Under very general conditions, the socially optimal contribution vectors in a threshold public goods game (i.e., the threshold allocations) are also Nash equilibria. Following Benoit and Krishna (1993) or Finus (2001), we can argue that these equilibria are renegotiation-proof, in addition to a non-binding agreement on such a contribution vector being self-enforcing, as mentioned above.[5] As the previously described game exhibits many possible equilibria, we investigate observed differences in the allocation of the abatement burden by means of an economic laboratory experiment.

The remainder of the paper is structured as follows. Section 2 provides additional background information on climate change. Section 3 relates our investigation to previous experimental studies on burden sharing, as well as on voting in public goods games. The experimental design and procedure are described in Sect. 4, followed by the derivation of the hypotheses in connection with burden sharing in Sect. 5. Section 6 presents the results of our experimental investigation. Section 7 concludes with possible political implications of this work.

2 Background: Climate Change

Over the past century, a global temperature increase of about 1 °C has been documented (e.g., IPCC 2014, p. 2) and attributed to accumulating greenhouse gas (GHG) emissions, most notably CO_2. The median estimate of damage costs from these emissions amounts to 135 $US\$/tCO_2$ (Tol 2013, Table 2), which suggests a linear increase of damages with emissions. In addition, sudden and irreversible damages are expected if GHG concentrations in the atmosphere reach a critical tipping point of about 350–550 ppm for CO_2, the exact value of which is uncertain.[6] This uncertain threshold corresponds to an estimated global abatement quantity of GHG emissions that can only be achieved in a collaborative effort among a large number of countries.

Since the early 1990s, political efforts have been undertaken to negotiate a global cap of CO_2 emissions, which is to be implemented by corresponding abatement measures of the individual countries. Initially, the Kyoto protocol[7] (adopted in 1997) limited reduction efforts to industrialized countries (Annex I), as these countries were deemed historically responsible due to their past industrial growth. Developing countries on the other hand, most importantly China and India, claimed their own right to industrial growth and continued to increase their emissions. As a consequence, the world's four main producers of CO_2 emissions in the year 2014 were China with 10.5 metric gigatons of CO_2 ($GtCO_2$), followed by the United States with 5.3 $GtCO_2$, the European Union with 3.4 $GtCO_2$, and India with 2.3 $GtCO_2$

[5] Compare also a recent survey of theoretical models of climate change cooperation by Hovi et al. (2015) which however assumes a "non-lumpy" linear public goods game.

[6] See IPCC (2014) (p. 73ff.), Hansen et al. (2008), and Tol (2013).

[7] http://unfccc.int/resource/docs/convkp/kpeng.pdf, last accessed March 27, 2016.

(Source: Olivier et al. 2015).[8] This accounts for 60.2% of the total CO_2 emissions of that year. Nevertheless, both the U.S. and the E.U. have pledged a reduction of their national emissions as part of their nationally appropriate mitigation actions (NAMAs), whereas both China and India continue their growth, albeit at a somewhat reduced rate.

A global estimate for marginal abatement costs ranges between 25 and 150 $US\$/tCO_2$ (Tol 2013). This demonstrates that the prevention of global warming is economically feasible, with a benefit-cost ratio between 0.9 and 5.4.[9] Although precise estimates of marginal abatement cost curves for individual countries are difficult (see Ackerman et al. 2013), it is obvious from an economical point of view that these curves are increasing, because the cheapest abatement measure will always be adopted first. As a consequence, it is plausible that China or India, which have not pursued significant abatement measures so far, face lower marginal abatement costs than the U.S. or the E.U. Consequently, the current situation, where only Annex I countries have announced to reduce their emissions significantly, cannot be efficient.

3 Related Literature

Previous studies on burden sharing in the climate negotiations have discovered that the framing of the task can affect the prevalent burden-sharing rule (Brekke et al. 2012), that given a low risk of damages richer countries might mitigate proportionally less than poor countries (Burton-Chellew et al. 2013), that the motivation of rich countries to mitigate more than poor countries may be unrelated to the perception of wealth differences (Milinski et al. 2011), and that heterogeneity in wealth or the expected damages may improve the success chance of international climate agreements (Waichman 2014). Furthermore, Gallier et al. (2016) find that voting on the burden-sharing rule improves contributions to a voluntary contribution mechanism over a scenario without voting, but only if agreement is reached. The authors also observe a preference for an “equal-payoff scheme”.

Our own investigation extends this research in several ways. First and foremost, our assumption of heterogeneity with respect to marginal abatement costs has so far not been associated with burden-sharing in the climate negotiations. Accordingly, in previous studies any allocation of the same total abatement burden resulted in the same total welfare or efficiency level. Second, in previous studies in which the burden-sharing rule is determined by voting, the theoretical solution is usually different from the baseline scenario without voting.[10] By assuming a non-binding vote on contributions that is “cheap talk” and does not affect the theoretical solutions, we can test if the burden-sharing rule is affected by the decision-making process.

The studies most closely related to ours are Barrett and Dannenberg (2012, 2014), who consider an experiment with one-shot interaction and find that increasing the range of possible threshold values decreases the probability of successful provision, with almost no chance of success for high threshold uncertainty. We instead investigate a setting with repeated interaction in which the groups can learn to coordinate their behavior, similar to the experiments by Suleiman et al. (2001) or McBride (2010). In contrast to the frequently studied collective-risk dilemma (e.g. Milinski et al. 2008), the groups need to reach a threshold in each of these

[8] See UNEP (2015) for a similar ranking of future emissions.

[9] Using the median damage estimate of 135 $US\$/tCO_2$ by Tol (2013).

[10] For example, in Gallier et al. (2016) the theoretical solution of several treatments results in all players investing their entire endowment, yielding a specific proportion of contributions for rich and poor players.

(independent) iterations in our setting, instead of making cumulative contributions to only a single threshold event at the end of the game.[11]

It is a common assumption in all of these experiments, including ours, that any contributions to the public good are lost whether or not the threshold is reached, i.e., there is no refund. By contrast, in a game with a known threshold and full refund of contributions, but otherwise similar parameterization as ours, Feige (2016, Chapter 4) reports that groups with heterogeneous contribution costs do not allocate the threshold value efficiently (so that players with low costs contribute as much as possible), but instead aim to achieve an equal cost burden for all group members. Furthermore, previous experiments involving other types of heterogeneity in threshold public goods games also frequently show that heterogeneous groups—either with unequal endowments (e.g., Rapoport and Suleiman 1993) or unequal valuations of the public good (e.g., Croson and Marks 2001)—contribute less and thus are less successful in providing the public good than homogeneous groups. Alberti and Cartwright (2016) conduct a within-group variation of players' endowments from "symmetric" to "very asymmetric" and observe that most groups continue to allocate contributions equally in the later stages of the experiment.

Previous studies investigating pre-play communication or non-binding agreements in public good provision report mixed results with respect to compliance: In the study by Kroll et al. (2007) a non-binding majority vote performs only slightly better than the baseline treatment without a vote, apparently because many players "cheat" on the agreement and contribute less. Barrett and Dannenberg (2012), using a form of pre-play communication, observe that most of their subjects (80%) honor their pledges for individual contributions when provision is individually optimal, but otherwise contribute significantly less than pledged. In Croson and Marks (2001) a recommendation to share the contribution burden is provided by the experimenter, not the players, and subsequently followed only by a low percentage of players. Iris et al. (2016) furthermore observe that delegation, in the sense that each contributing player is elected by several non-contributing team members, reduces total contributions to a public good with threshold uncertainty and voluntary contributions. In Alberti and Cartwright (2016) the players can suggest contribution vectors, which in their experiment predominantly leads to allocations with unequal contribution costs. Finally, Cherry and McEvoy (2013) observe almost perfect rates of compliance with a deposit-refund mechanism for a linear public goods game.

4 Experimental Design and Procedures

The experiment consists of four treatments, following a 2×2 factorial design. In all cases, a threshold public goods game with uncertain threshold value serves as the stage game for the repeated interaction of the same group of players (partners setting), who choose their own individual contributions to the public good in each of ten independent rounds. The four treatments differ with respect to the presence of a non-binding unanimous vote on contribution vectors before each contribution choice (i.e., with and without such a vote), as well as to the marginal contribution costs of the players (homogeneous or heterogeneous).[12] The treatments and our investigated hypotheses are described below in more detail (see also

[11] The studies by Tavoni et al. (2011) and Dannenberg et al. (2015) also employ sequential contributions.

[12] The treatment names are a combination of the decision rules (i.e., NBV for the non-binding vote, RG for the baseline repeated game) and the existence of heterogeneity (HOM or HET). The instructions to all treatments are available as an electronic supplement.

Table 1 Treatments and parameterization

	HOM	HET
Treatments (number of groups)	NBVHOM (7)	NBVHET (8)
	RGHOM (9)	RGHET (9)
Total number of groups	16	17
Players in group n	4	
Total number of subjects	64	68
Endowment e	55 ExCU	
Maximum individual contribution $\bar{q}$	10 CU	
Marginal contribution costs (high) c_H	1.5 ExCU per CU	3 ExCU per CU
Marginal contribution costs (low) c_L	–	1 ExCU per CU
Possible threshold values T	$T_{min} = 12$ CU, $T_{max} = 16$ CU	
Damage payment d	25 ExCU	
Ex-ante socially optimal total contribution Q^*	16 CU	
$Q^*/n\bar{q}$	40%	
Ex-ante socially optimal total payoff $E_T[\Pi(\mathbf{q}^*)]$	196 ExCU	204 ExCU
Step return for $\mathbf{q}^*$	4.17	2.08 to 6.25
Number of rounds	10	

Table 1). In all treatments a neutral framing is used so that the subjects do not associate the experiment with the climate negotiations.

4.1 Stage Game

Our underlying game is based on the model by Suleiman et al. (2001), which is adapted by Barrett (2013) to the context of climate change. The game also has similarities to the one examined by Feige (2016, Chapter 4).

A group of $n = 4$ risk-neutral players decides on the contributions to a public goods game with a threshold T. This threshold takes on one of two values—$T_{min} = 12$ CU (Contribution Units) or $T_{max} = 16$ CU—each with a probability of 1/2. Each player i starts with the same endowment $e = 55$ ExCU (Experimental Currency Units) which can be used to pay for her contribution q_i to the public good, choosing any amount between 0 CU and 10 CU in steps of 0.5 CU.

In the heterogeneous case (HET), the players differ with respect to their marginal costs of contribution, meaning the conversion rate from endowment to contribution. The group contains two player types—one with high marginal contribution costs, $c_H = 3$ ExCU per CU, and the other with low marginal costs, $c_L = 1$ ExCU per CU—which are assigned at random before the game, but then remain fixed. The group contains two players of each type. If the players are homogeneous (HOM), we have $c_H = c_L = 1.5$ ExCU per CU.

The group's total contribution given by $Q = \sum_i q_i$ must reach the threshold T, i.e., $Q \geq T$. Otherwise each player suffers a damage payment $d = 25$ ExCU which is deducted from her endowment in addition to any contribution costs.[13]

[13] Feige (2016) instead assumes that the contribution costs are refunded in this case.

Player i's payoff $\pi_i(q_i)$ is accordingly given by:

$$\pi_i(q_i) = \begin{cases} e - c_i q_i & \text{if } Q \geq T \\ e - c_i q_i - d & \text{if } Q < T \end{cases} \tag{1}$$

The group's total payoff is denoted by $\Pi(\mathbf{q}) = \sum_i \pi_i(q_i)$ where $\mathbf{q} = (q_1, \ldots, q_4)$ is the group's contribution vector.

Note that both possible threshold values—$T_{min} = 12$ CU and $T_{max} = 16$ CU—can only be reached if at least two players make contributions. However, because $c_H T_{max} < 2d$, any two (or more) players can profit from a collective effort to reach the threshold, because the total costs are lower than the avoided damages.

Following Suleiman et al. (2001) we can argue that a total contribution of $Q^* = T_{max}$, the highest possible threshold value, is (ex-ante) socially optimal, and further, that any (ex-ante) socially optimal contribution vector $\mathbf{q}^* = (q_1^*, \ldots, q_4^*)$ with $\sum_i q_i^* = Q^*$ is also a Nash equilibrium (in expected payoffs), provided that no individual player has higher contribution costs than the avoided damage of 25 ExCU, i.e. $\forall i : c_i q_i \leq d$.

The four group members are intended to model the roles of China and India, as low-cost players, and the U.S. and the E.U., as high-cost players. Although assuming only two possible threshold values may appear as a rather strong simplification of the broad interval offered by scientific estimates, the current political situation after the Paris Agreement is well reflected by this scenario: On the one hand, there is the safe option of keeping global warming below 1.5 °C with a total contribution of at least 16 CU and guaranteed success. On the other hand, there is the risky target of 2 °C with a total contribution of 12–15.5 CU and a high probability of damages.

In order to show that our parameterization otherwise provides a realistic benefit-cost ratio, we draw on Croson and Marks (2000) to calculate the step return of this game. In our case, this measure is defined as the sum of damages nd, which the group can avoid by providing the public good, divided by the sum of contribution costs $\sum_i c_i q_i^*$ that this provision requires in the case of a socially optimal contribution vector $\mathbf{q}^*$. For the homogeneous treatments this results in a step return of $100/24 \approx 4.17$, which is within the range of 0.9 to 5.4 mentioned in Sect. 2. The step return for the heterogeneous case ranges between $100/48 \approx 2.08$, if only the two high-cost players contribute, and $100/16 = 6.25$, if only the two low-cost players contribute. These values are also not unrealistic when applied to the climate negotiations and furthermore lie well within the range of previous experimental studies on threshold public goods games (between 1.2 and 9.53; Croson and Marks 2000).

4.2 Voting Procedure in the Repeated Stage Game

In each round, the players first simultaneously choose their individual contributions (C), then the subjects are informed about the randomly determined threshold value (T)[14] as well as the contributions, contribution costs, and earnings of all players in their group (see Table 2). Where applicable, this information is displayed with the ID of the associated player (e.g., "Player C"). Furthermore, after the first round the subjects can call up the results from past rounds whenever they have to make a decision. At the end of the experiment, the earnings of a single randomly selected round are paid to each player.

With respect to the climate negotiations, these baseline treatments represent a scenario without the possibility of a collective decision: Each country decides individually how much

[14] In order to make sure that all groups in all treatments face the same sequence of threshold values, the actual random draw occurs before the experiments by determining the threshold value for each of the ten rounds through a coin toss.

Table 2 Procedures

Decision rule	Sequence of events
Baseline without vote (RG)	[CT]×10
Non-binding vote (NBV)	[VCT]×10

C voluntary contribution, *V* vote on contributions, *T* threshold event

to contribute, i.e., its national abatement efforts. In this scenario the coordination problem can only be overcome by tacit coordination, assuming that the players learn over time to rely on the other group members' willingness to cooperate.

The two voting treatments also use the procedure of the repeated game described above: ten independent rounds of voluntary contributions (see Table 2). However, in each round of the voting treatments, the group first makes a collective decision (V) which can provide a recommendation for the subsequent voluntary contribution choice (C). Afterwards, the players are told the randomly determined threshold value (T) for this round.

In the voting treatments, the negotiations are modeled as a unanimous vote on vectors of individual contributions to a public good. More precisely, each player proposes a contribution vector $\mathbf{q} = (q_1, \ldots, q_4)$, after which the group votes on these proposals using the unanimity rule. Every player must vote for exactly one proposal, so that agreement is automatic if all players propose the same vector.[15] We assume that the players are not informed about the proposals or votes of their group members until all players in the group have a made a proposal or cast a vote, respectively, so that all actions occur simultaneously. At any subsequent decision, however, the players can call up any previous proposals and votes made by themselves or their group members. Furthermore, no matter the outcome of the vote, the contributions are subsequently made voluntarily, so that a player can adhere to a recommendation or ignore it.

In this repeated game, the possible use of conditional strategies generates a large set of subgame-perfect equilibria (in expected payoffs).[16] Each of these equilibria constitutes a path of ten contribution vectors, one for each round. All socially optimal contribution vectors can be reached by such equilibrium paths, because these vectors are already Nash equilibria of the stage game.[17] Although, strictly speaking, the addition of the voting stage changes the equilibrium set (because the strategies now also specify proposals and votes), it does not affect the set of contribution vectors that can be reached by these equilibria, because the vote is cheap talk.

The set of socially optimal contribution vectors is of particular interest for several reasons. First, this set constitutes the game's non-transferable utility (NTU) core, consisting of all payoff vectors that cannot be improved upon by a single player or a subgroup (coalition) of players (Moulin 1988, p. 102). Bagnoli and Lipman (1989, 1992) derive a similar result for voluntary contributions in a threshold public goods game with a refund of contributions if the threshold is missed, showing that all (welfare-maximizing) threshold allocations are

[15] In two additional treatments, the vote was split into two stages: first a vote on the total contribution, then a vote on the allocation of this total contribution among the group members. As these treatments did not generate any additional insights, however, the results are not reported here. See also Feige (2016, Chapter 6), which describes another experimental series with a binding vote conducted for an earlier version of this paper.

[16] For more details see Feige (2016, Chapter 1, Section 1.1.4, and Chapter 5, Section 5.2.2).

[17] Any other contribution vector (with the exception of zero contributions) requires an equilibrium path that prescribes different actions in at least two rounds (as the final round must always end in a stage-game equilibrium). We ignore these vectors in the following, as they require complex equilibrium strategies which we do not consider relevant for tacit coordination.

contained in the transferable utility (TU) core. Furthermore, because the worst that a deviating player can do is contribute zero, which is also individually optimal, the TU core of this game is equivalent to the γ-core (Chander and Tulkens 1995).

Second, any subgame-perfect equilibria that implement socially optimal contribution vectors are renegotiation-proof (e.g., Benoit and Krishna 1993; Finus 2001). This means that, no matter what the threshold value turns out to be in a given round, a player cannot improve her expected payoff in the following round by a unilateral change of action. She cannot benefit from increasing or decreasing her contribution, because her current contribution is individually optimal.[18] And neither can she change the outcome by proposing and voting for a different contribution vector, because the vote is non-binding.

Finally, a cheap-talk agreement on a socially optimal contribution vector is self-enforcing. It is easy to see that both stability requirements, mentioned, e.g., by Barrett (1994), are satisfied: The agreement is *externally stable*, because the only way an agreement can be reached is if all players unanimously vote in its favor; there is nobody else to join. The agreement is also *internally stable*, because any individually advantageous decrease in contributions exceeds the increase in expected damages from missing the threshold.

Note, however, that the non-binding voting treatments also have equilibria in which a unanimous agreement is reached, but Q^* is contributed in a different combination of individual contributions. In such a babbling equilibrium (e.g., Farrell 1993) the players might anticipate that the public good will be provided with or without the vote, so that the outcome of this vote becomes meaningless. Other equilibria exist in which the group agrees on a threshold allocation, but nobody makes any contributions. Both situations could also occur in the climate negotiations, especially considering that the political signal of a successful agreement seems to have an intrinsic positive value independently of whether or not the agreement will ever be implemented.

4.3 Other Procedural Details

The subjects for the experiment were recruited via ORSEE (Greiner 2015) from a student pool at the Karlsruhe Institute of Technology (KIT). The computer-based experiment was then conducted with z-Tree (Fischbacher 2007) in the last week of January 2016 at the KD2Lab. A total of 132 participants earned €15.27 (US$16.64 at the time of the experiment) on average in all four treatments. The subjects spent about 1.5 h in the laboratory.

During the experiment the subjects were asked not to talk to each other and to turn off their cell phones. They were seated at computers, each of which was placed in an enclosed and sound-proof cubicle. The instructions to the experiment were handed out to the subjects in written form as well as read aloud at the beginning of the experiment. Every subject had to complete a comprehension test consisting of 12 or 13 questions depending on the treatment. The experiment did not start until everybody had answered every question correctly.

5 Experimental Hypotheses on Burden Sharing

The theoretical analysis of our experimental design points to the existence of multiple equilibria. In fact, our experimental investigation is in part motivated by this multitude of possible solutions. What all of these solutions have in common is that they sum up to the same

[18] The situation is similar to the battle-of-the-sexes game given as Example 2 in Benoit and Krishna (1993) as well as the chicken game used by Carraro and Siniscalco (1993) to motivate the stability of agreements to reduce emissions.

total contribution of 16 CU; they only differ in the way this total contribution is allocated among the group members. Each particular socially optimal contribution vector thus represents one particular burden-sharing rule (of several hundred possible candidates). Standard game-theoretical arguments are insufficient for identifying one particular burden-sharing rule in this game, let alone for predicting treatment differences in contribution behavior, which yields the following null hypothesis:

Hypothesis 1 In the investigated treatments, there is no difference in total contributions or contribution vectors (a) between homogeneous and heterogeneous groups or (b) between voting and non-voting groups.

However, Schelling (1980), among others, suggests that some of these many solutions are "focal" and therefore particularly attractive. For instance, the subjects might focus on any one of the following three contribution vectors for reasons of symmetry (cf. Feige 2016, Chapter 4, Section 4.3):

- Equal contribution quantity $\mathbf{q^{EQ}}$: All players make the same contribution, so that $\forall i, j : q_i = q_j$.
- Equal contribution costs $\mathbf{q^{EC}}$: All players carry the same cost burden, so that $\forall i, j : c_i q_i = c_j q_j$.
- Equal payoffs $\mathbf{q^{EP}}$: All players earn the same individual payoff, so that $\forall i, j : \pi_i(q_i) = \pi_j(q_j)$.

All of these rules have their counterparts in the climate negotiations (cf. Brekke et al. 2012). Equal contribution quantities could be interpreted as equal per capita emissions or an equal percentage reduction of emissions. Equal contribution costs roughly corresponds to an equal proportion of abatement costs to emissions, equal payoffs to an equal proportion of abatement costs to GDP.

Surprisingly, economic efficiency or welfare maximization seem to have received no attention so far in the context of climate change. In our game, (ex-ante) welfare-maximizing contribution vectors $\mathbf{q^{WM}}$ are easily determined by minimizing the total contribution costs among socially optimal contribution vectors. In homogeneous groups, all socially optimal contribution vectors are also welfare-maximizing, because all players have the same marginal contribution costs. In heterogeneous groups, welfare is maximized if the two low-cost players contribute T_{max} on their own, e.g., by each of them contributing 8 CU. In the climate negotiations this would mean that China and India carry a much larger share of the abatement burden than the E.U. or the U.S., in stark contrast with the currently still existing proposal to constrain emissions *only* of (historically responsible) developed countries.

Table 3 shows the implications of the different burden-sharing rules for our experiment, assuming in all cases the same (ex-ante) socially optimal contribution of $Q^* = 16$ CU (the maximum threshold value). In the homogeneous treatments, all four rules are simultaneously satisfied if every player contributes 4 CU. In the treatments with heterogeneous marginal costs, $q_H = 2$ CU and $q_L = 6$ CU ensures that all players have the same contribution costs and, due to homogeneous endowments, the same individual payoff, so that $\mathbf{q^{EC}} = \mathbf{q^{EP}}$. However, this contribution vector is inefficient, because the two high-cost players make positive contributions. Accordingly, in heterogeneous groups different burden-sharing rules prescribe different contribution vectors: $\mathbf{q^{EQ}} \neq \mathbf{q^{EC}} \neq \mathbf{q^{WM}}$.

Our experimental investigation resides on the premise that the majority of groups follow the same burden-sharing rule in all treatments, either due to similar individual preferences among the group members or as a result of a collective compromise. We plan to identify this predominant rule by systematically excluding the other rules, showing that the observed

Table 3 Contributions and total payoffs associated with (type-symmetric) burden-sharing rules

	HOM	HET
Equal quantity (EQ)		
q_H	4 CU	4 CU
q_L	–	4 CU
$E_T[\Pi(\mathbf{q}^{\mathbf{EQ}})]$	196 ExCU	188 ExCU
Equal costs/payoffs (EC/EP)		
q_H	4 CU	2 CU
q_L	–	6 CU
$E_T[\Pi(\mathbf{q}^{\mathbf{EC}})]$	196 ExCU	196 ExCU
Welfare maximization (WM)		
q_H	4 CU	0 CU
q_L	–	8 CU
$E_T[\Pi(\mathbf{q}^{\mathbf{WM}})]$	196 ExCU	204 ExCU

contribution vectors are significantly different from these rules' predictions. In each case, the testable hypothesis corresponds to the following scheme (substituting EQ, EC, EP, or WM for [XX]):

Hypothesis 2 In all investigated treatments, the individual contributions are consistent with burden sharing rule [XX].

6 Results

We first look at the aggregate results in all four treatments for total contributions and the expected success rate, i.e., the probability of public good provision given a particular total contribution.

Result 1 *There are no significant treatment differences with respect to average total contributions and expected success rates.*

On aggregate, there are only small differences among the treatments with respect to total contributions. For example, the development of total contributions by round and group displayed in Fig. 1 shows that in all baseline and most voting groups the total contribution oscillates around or even converges to the social optimum of 16 CU.[19] A similar pattern is usually only observed for games with a full refund like those in Croson and Marks (2001).

Furthermore, all treatments result in similar average total contributions (ranging from 14.86 to 15.82 CU, see Table 4), which directly translates into similar expected success rates (ranging from 81.11 to 86.25%) for providing the public good. As the minor treatment differences are statistically insignificant, we cannot reject Hypothesis 1 with respect to total contributions. On the other hand, these results provide favorable conditions for the investigation of burden sharing, because a difference in total contributions can now be ruled out as an

[19] In all treatments the sequence of threshold values in CU is 16, 12, 16, 12, 12, 12, 12, 12, 16, 12. The long sequence of low thresholds (Round 4–8) may be the cause of a significant increase of average total contributions from Round 9 (14.74 CU) to Round 10 (15.44 CU). Wilcoxon signed-rank test, all groups combined: $z = 2.7$, $p = 0.007$.

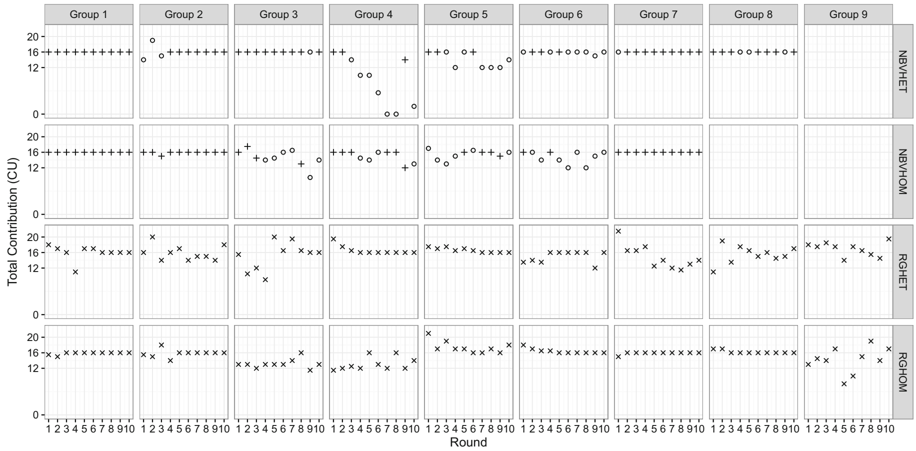

Fig. 1 Development of total contributions over ten rounds in each group by treatment. The individual data points distinguish between groups that agree on a contribution vector (+), groups that vote but disagree (∘), and groups that do not vote (×)

Table 4 Average total contributions over all ten rounds

Total contribution in CU		
All	Agreed	Disagreed
NBVHOM		
15.36 (1.36)	15.80 (0.81)	14.52 (1.77)
RGHOM		
15.33 (2.00)	n.a.	n.a.
NBVHET		
14.86 (3.33)	15.96 (0.28)	12.91 (5.00)
RGHET		
15.82 (2.19)	n.a.	n.a.

Standard errors in parentheses

explanation of any observed treatment differences in individual contributions. The expected success rates are similar to those reported by Barrett and Dannenberg (2014) for the two treatments in which providing $Q^* = T_{max}$ is individually optimal.

These results show that our treatments are sufficiently calibrated to focus on the groups' threshold allocations.

Result 2 *Individual contributions in all treatments, as well as proposals and voting outcomes in voting treatments, are consistent with burden sharing according to equal costs or payoffs.*

Recalling Table 3, equal costs or payoffs (EC/EP) are achieved by individual contributions of 4 CU in the homogeneous treatments and of 2 CU and 6 CU, respectively, for high-cost and low-cost players in the heterogeneous treatments. Table 5 displays means and modes of individual contributions by treatment and, for HET treatments, by player type. The mode of individual contributions is 4 CU in both homogeneous treatments, which is contributed in 66.9% (RGHOM) and 86.8% (NBVHOM) of cases (all groups and rounds). This is consistent with all discussed burden-sharing rules.

Table 5 Averages and modes over all ten rounds for individual contributions by player type

	Individual contribution in CU		
	All	Agreed	Disagreed
NBVHOM			
Mean	3.84 (0.67)	3.95 (0.41)	3.63 (0.96)
Mode	4	4	4
RGHOM			
Mean	3.83 (1.33)	n.a.	n.a.
Mode	4	n.a.	n.a.
NBVHET			
Mean H	1.89 (0.57)	1.98 (0.20)	1.73 (0.89)
Mode H	2	2	2
Mean L	5.54 (1.63)	6.00 (0.00)	4.72 (2.53)
Mode L	6	6	6
RGHET			
Mean H	2.15 (0.85)	n.a.	n.a.
Mode H	2	n.a.	n.a.
Mean L	5.76 (1.55)	n.a.	n.a.
Mode L	6	n.a.	n.a.

Standard errors in parentheses

In treatment RGHET the modal individual contribution is 2 CU for high-cost players (67.2%) and 6 CU for low-cost players (28.3%), followed by 5 CU (15.6%). 4 CU is contributed in only 4.4% (high cost) and 8.1% (low cost) of all cases in this treatment. Similarly, the modal individual contribution in treatment NBVHET is 2 CU for high-cost players (92.5%) and 6 CU for low-cost players (86.9%). Only 1.3% of low-cost contributions and not a single high-cost contribution amounts to 4 CU in this treatment. Both results are consistent with rules EC and EP.

Note that the difference in contribution behavior between homogeneous and heterogeneous treatments is is statistically significant.[20] We can therefore reject Hypothesis 1 for contribution vectors between homogeneous and heterogeneous treatments. The decision-making rule, on the other hand, does not appear to make a difference, except for a more precise coordination in voting groups.

In the two voting treatments, the preference for equal costs or payoffs is already apparent in the cheap-talk stage. In both treatments the most frequently proposed contribution vector (see Fig. 2) corresponds to rule EC/EP. In the homogeneous treatment NBVHOM the respective contribution vector (4 CU for each player) is proposed in 233 of 280 cases (83.2%). If marginal costs are heterogeneous, as in treatment NBVHET, the EC/EP contribution vector ($q_H = 2$ CU, $q_L = 6$ CU) is proposed in 258 of 320 cases (80.9%). In both treatments every subject proposes this vector at least once during the experiment. Of the remaining proposals, many involve a high contribution for a single player—e.g., (10, 2, 2, 2)—and are usually a reaction to this player's previous behavior. Agreement occurs in roughly two-thirds of the

[20] Two-tailed Mann-Whitney-U-test applied to the absolute frequency of 4 CU contribution in each group: RGHOM versus RGHET—$z = 3.532$, $p = 0.00042$; average absolute frequencies: 26.78 of 40 (RGHOM) and 2.22 of 40 (RGHET). NBVHOM versus NBVHET—$z = 3.18$, $p = 0.0015$; average absolute frequencies: 34.71 of 40 (NBVHOM) and 0.25 of 40 (NBVHET).

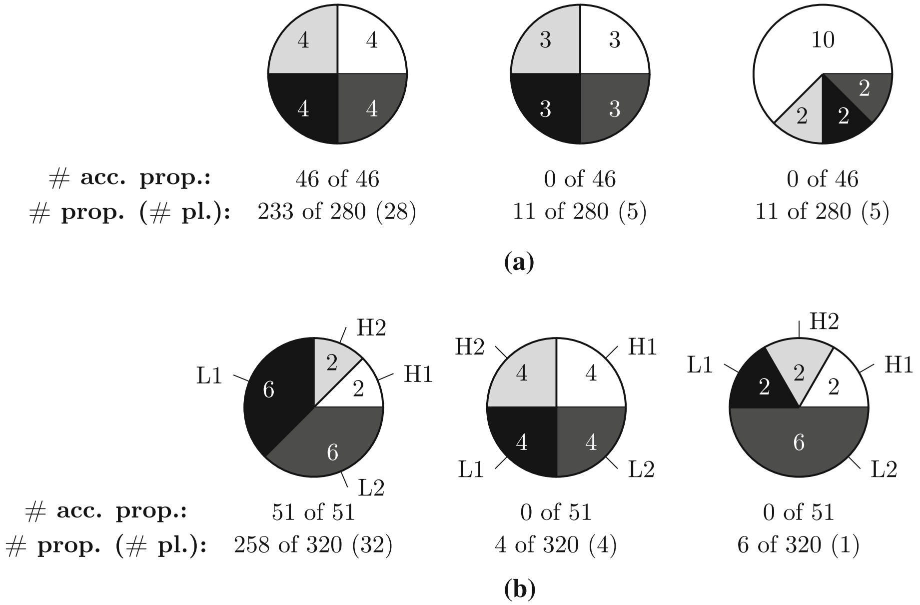

Fig. 2 Unanimously chosen allocations (in relation to accepted proposals) and three most frequent proposals (in relation to total proposals; number of proposing individuals) in treatments NBVHOM and NBVHET. Contributions in CU **a** NBVHOM. **b** NBVHET

cases,[21] and the unanimously adopted proposal always prescribes equal contribution costs for providing the optimum of 16 CU.

The rates of agreement are similar to the 60% agreement observed by Walker et al. (2000) in their unanimity treatment, which has a binding vote, however, with the stage game serving as a fallback outcome in case of disagreement. Equal costs/payoffs is also the predominantly chosen contribution vector in Feige (2016).

Despite the predominance of EC/EP contributions, a large percentage of subjects in treatment RGHET do not adhere to this burden-sharing rule and accordingly might prefer other allocations. However, we can also show that the two other rules (EQ and WM) play no role for the groups' contribution choices.

Result 3 *In the heterogeneous treatments, contribution vectors do not involve equal contribution quantities (rule EQ) nor are they (ex-ante) welfare-maximizing (rule WM).*

Figure 3 displays the frequency of groups whose contribution vectors are consistent with equal contribution costs or payoffs (rule EC/EP) on a round-by-round basis for each investigated treatment. The remaining contribution vectors with a total contribution close to the social optimum (15 CU $\leq Q \leq$ 17 CU) are either close to EC/EP, so that either the average contributions of high-cost and low-cost players fits the rule[22] or, otherwise, only a single subject deviates from the rule (∼EC/EP),[23] or do not correspond to any of the previously defined rules (Other). Equal contribution quantities (EQ rule) or welfare maximization (WM

[21] NBVHOM: 46 of 70 or 65.7%, NBVHET: 51 of 80 or 63.8%.

[22] Two RGHET groups coordinate on (2, 2, 5, 7), for example.

[23] Frequent examples include (3, 4, 4, 4) for homogeneous groups.

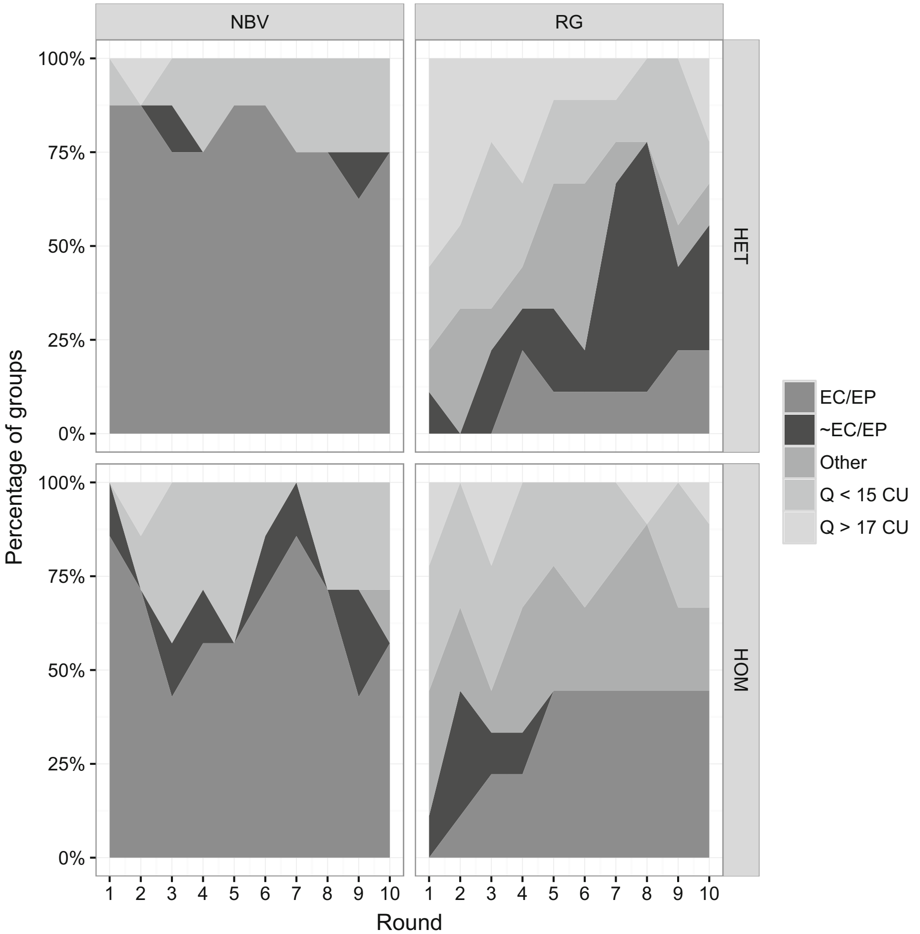

Fig. 3 Development of contribution vectors by treatment. Vectors with a total contribution of $15 \leq Q \leq 17$ CU are categorized as resulting in equal contribution costs or payoffs (EC/EP) or a close outcome (∼EC/EP)

rule) are implied by EC for homogeneous costs. No heterogeneous group chooses a contribution vector that is even close to either rule. Accordingly, these rules are not listed in Fig. 3. Moreover, we can reject Hypothesis 2 for these two burden-sharing rules.

Most studies with homogeneous players also observe a predominance of equal contribution quantities, costs and payoffs, whereas studies with heterogeneous endowments predominantly report higher contributions from richer players (e.g., Rapoport and Suleiman 1993; Brekke et al. 2012), but with unequal contribution costs or payoffs. More precisely, these studies indicate that contribution costs are allocated in proportion to the players endowments. If this pattern applies to our experiment as well, then equal endowments imply equal contribution costs, supporting rule EC.[24]

[24] In fact, Feige (2016, Chapter 4) describes a treatment with a similar parameterization and heterogeneous endowments, but certain threshold value, which corroborates this expectation.

Table 6 Mixed-effects regression for total contributions (in CU)

	Model 1	Model 2
Heterogeneous costs	0.04	0.05
	(0.54)	(0.50)
Voting	−0.49	−1.59**
	(0.54)	(0.56)
Agreement reached	n.a.	1.71***
		(0.38)
Round	−0.09**	−0.08*
	(0.04)	(0.04)
Constant	16.08***	16.01***
	(0.50)	(0.46)
Observations	330	330
Groups	33	33
BIC	1454	1441

Standard errors in parentheses
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

As both Cherry and McEvoy (2013) and Gallier et al. (2016) observe a difference in cooperativeness depending on whether groups agree or not, a similar effect could also extend to the burden-sharing rule. This is what we investigate next.

Result 4 *Voting groups in agreement (disagreement) have significantly higher (lower) total contributions than the baseline groups without a vote, but this difference does not affect the predominant burden-sharing rule.*

A closer look at Fig. 1 already reveals that voting groups in agreement (+) almost always contribute a socially optimal 16 CU, except for a handful of cases of non-compliance. In contrast, if a group votes on an allocation, but does not reach unanimous agreement (○), the subsequent total contributions are more widely dispersed and usually below the optimal value. Group 4 of treatment NBVHET provides an extreme example in which repeated disagreement drives the group towards zero contributions.

The mixed-effects regression for total contributions in Table 6 shows that this agreement effect is statistically significant, even when accounting for the fact that the ten voting decisions in each of the 33 groups are correlated. Model 1 contains two treatment dummies ("Heterogeneous Costs" and "Voting"), which do not significantly affect the total contribution, and a "Round" variable showing a significant decrease of contributions over time. Model 2 adds another dummy ("Agreement reached") which is equal to 1 if and only if a voting group reaches agreement in a given round. The dummy reveals a significant positive effect of agreement on total contributions compared to non-voting groups. Moreover, the treatment dummy "Voting" now establishes a significantly reduced total contribution if no agreement is reached compared to non-voting groups.

Considering that most groups reach agreement already in the first round of the experiment, such a behavior cannot be rationally explained. Whenever a group fails to reach agreement, it should instead revert to an earlier, optimal agreement. Some groups indeed do just that. Yet in many cases the failure to agree seems to discourage some of the players, so that they reduce their contributions rather than risking to waste them.

Both Cherry and McEvoy (2013) and Gallier et al. (2016) find comparable effects, with groups in disagreement also contributing less than the baseline group. For the linear public goods game investigated in these studies, however, this actually means that the voting groups are closer to making individually optimal contributions of zero. As a consequence, this observation is still compatible with the prediction for a rational decision-maker, who can also be expected to contribute zero. Moreover, the difference between agreeing and disagreeing groups in Cherry and McEvoy (2013) is a direct consequence of their refund mechanism, whereas in our experiments the groups play the same coordination game whether or not they reach agreement.

In Gallier et al. (2016) disagreement preempts the issue of burden sharing, but this is not the case in our experiment, because the votes are cheap talk. In fact, even players in disagreeing groups predominantly target an equal-cost allocation, with a modal contribution of 4 CU in treatment NBVHOM (67.7% of choices) and modes of 2 CU (81.0%) and 6 CU (62.1%), respectively, for high-cost and low-cost players in treatment NBVHET. That we observe no effect of the decision rule on burden sharing also fits with our final result concerning compliance with the voting agreements.

Result 5 *In all voting treatments the rates of compliance are almost 100%.*

The rates of compliance are near or at 100% in both voting treatments.[25] A closer look at the data shows that in the heterogeneous treatment it is only a single high-cost player who deviates: One high-cost player contributes 0 CU after agreement in Round 9 and the group disagrees in the following (final) round.

The fact that the adopted proposals are socially optimal Nash equilibria in expected payoffs of the stage game explains the high rates of compliance observed here. The compliance rates are otherwise comparable to those reported by Cherry and McEvoy (2013) for the deposit-refund game, despite the fact that complying with the agreement is not the only individually optimal choice in our experiment. In the study by Croson and Marks (2001), an *outside* recommendation of equal contribution quantities in the case of heterogeneous players instead receives little attention by the subjects, possibly because they prefer a different allocation of the threshold value.

7 Conclusion

We show that equal contribution costs, which in our experiment is also associated with equal payoffs, is the predominant burden-sharing rule in our experimental simulation of the climate negotiations as a threshold public goods game. This rule not only drives individual voluntary contributions, but also proposed and adopted contribution vectors under a non-binding vote on contributions. As a consequence, the contribution burden is allocated inefficiently in groups with heterogeneous marginal contribution costs. Although the low variance of the voting outcomes suggests that this result is more due to equal bargaining power and less due to individual fairness preferences, additional experimental investigations are necessary to substantiate this hypothesis.

A similar result in the real climate negotiations would mean that the historical agreement to restrict emissions reductions to Annex I countries is replaced by an agreement that more strongly involves developing countries. However, even though increased abatement efforts by China and India would certainly increase the efficiency of a global abatement strategy (see, e.g., Li et al. 2016), these countries also face a trade-off between economic growth and abatement efforts that may pose an obstacle to its compliance with too strict reduction

[25] NBVHOM: 97.3% comply, 0.5% contribute too much, 2.2% too little; NBVHET: 99.5% comply, 0.5% contribute too little.

targets. Just like in our experiments, assigning an equal abatement cost burden to the major GHG producers could constitute an inefficient, but unanimously acceptable compromise. Of course, adjustments may be necessary for differences in GDP, national emissions, or expected damages from climate change, whose influence on the agreement we did not investigate. The experimental investigation by Feige (2016, Chapter 5) furthermore suggests that transfer payments, e.g., in the form of emissions trading or technology transfers, could provide additional incentives for abatement to developing countries, so that a compromise need not come at the cost of efficiency.

A secondary finding of our study is that average outcomes are only slightly below the social optimum, especially among groups that reach a unanimous agreement. This suggests that the difficulties of reaching a climate agreement in the past and ensuring compliance with it must have other reasons than are commonly suspected (i.e., threshold uncertainty, heterogeneity of players, or the necessity of a global consensus). One possibility is that some countries benefit from a failed agreement, either because of (net) benefits from higher regional temperatures or because of an economic dependence on fossil fuels. Russia, which has large areas of frozen tundra and whose national expenditures heavily rely on oil exports, is a good example on both accounts. That we did not account for this possibility is a limitation to our findings, which however applies to the related literature as well. Again, transfer payments could be used to "buy" the votes of these countries, but such a proposal would entail giving money to rich oil-exporting countries instead of poorer developing countries which is unlikely to receive much support.

A second possibility is that the benefit-cost ratio is less favorable than assumed. This is plausible because the longer the United Nations take to agree on binding mitigation targets, the shorter the time to implement these targets and the higher therefore the costs of doing so. In addition, an increasing investment in adaptation reduces the threat of climate damages and thus the incentive for mitigation (cf. Heuson et al. 2015). Empirical evidence on threshold public goods games (e.g., Isaac et al. 1989) furthermore indicates that a lower benefit-cost ratio increases the likelihood that contributions (and therefore abatement efforts) converge to zero. Our investigation is limited to one particular parameterization with a relatively high benefit-cost ratio to facilitate the investigation of burden sharing and might therefore constitute an exceptional case.

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Compliance with Ethical Standards

Conflicts of interest The authors declare that they do not have any conflicts of interest.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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