

NATURE CLIMATE CHANGE | LETTER

A bargaining game analysis of international climate negotiations

Rory Smead, Ronald L. Sandler, Patrick Forber & John Basl*Nature Climate Change* 4, 442–445 (2014) doi:10.1038/nclimate2229

Received 15 October 2013 Accepted 03 April 2014 Published online 11 May 2014

Corrected online 08 August 2014

Addendum (September, 2014)

Climate negotiations under the United Nations Framework Convention on Climate Change have so far failed to achieve a robust international agreement to reduce greenhouse gas emissions. Game theory has been used to investigate possible climate negotiation solutions and strategies for accomplishing them¹. Negotiations have been primarily modelled as public goods games such as the Prisoner's Dilemma², though coordination games or games of conflict have also been used^{3, 4}. Many of these models have solutions, in the form of equilibria, corresponding to possible positive outcomes—that is, agreements with the requisite emissions reduction commitments^{5, 6}. Other work on large-scale social dilemmas suggests that it should be possible to resolve the climate problem^{7, 8, 9}. It therefore seems that equilibrium selection¹⁰ may be a barrier to successful negotiations. Here we use an *N*-player bargaining game in an agent-based model with learning dynamics to examine the past failures of and future prospects for a robust international climate agreement. The model suggests reasons why the desirable solutions identified in previous game-theoretic models have not yet been accomplished in practice and what mechanisms might be used to achieve these solutions.

Main

Many models of climate negotiations attempt to capture a wide range of realistic features of the climate problem so as to achieve descriptive accuracy; studies based on the Stability of Coalitions model exemplify such an approach^{11, 12, 13, 14, 15, 16}. Focusing instead on the dynamical behaviour of a simple bargaining game, we are able to identify possible barriers (and solutions) that may be hidden by more complex models. Most game-theoretic studies on the

climate problem ask whether stable solutions exist, but relatively few use evolutionary or learning dynamics to explore whether they are achievable. Such approaches consider the way that imperfect agents may adapt to each other's behaviour and how this affects the chance of reaching solutions^{17, 18}. We model the learning dynamics in the context of bargaining over an allotment of a fixed emission total.

We use a modified version of the Nash bargaining game¹⁹ with N players representing the negotiating countries or coalitions. Each player's strategy set is the interval $[0, 1]$ representing the range of possible reductions: 1 representing the business as usual (BAU) 100% emissions and 0 representing no emissions. Let d_i correspond to a player's demand for some proportion of their BAU emissions (equivalently, this represents their proposed reduction). Players may also differ in size and similar demands from larger players will mean more emissions. Let s_i represent the size of a player and $t = \sum_i d_i s_i$ represent the total of all demands made adjusting for the size of the players.

Suppose there is also a target value T that must be met if a set of demands is to constitute a successful solution. T is a global reduction goal ranging from 0 to 1 representing the global reduction necessary for an agreement as a proportion of BAU. For a given set of demands from all players the payoff to each of them is defined as:

$$\pi_i(d_i, t) = \begin{cases} d_i & \text{if } t \leq T \sum_i s_i \\ \delta d_i & \text{if } t > T \sum_i s_i \end{cases}$$

If the target value is reached, the demand set is viewed as successful and a possible agreement. The perceived payoff in this case is equal to the amount of the shared resource demanded. If the target is not met, the payoff is devalued by a factor of $0 < \delta < 1$, which represents the importance of reaching an agreement. Lower δ means the more payoffs are devalued in the event of disagreement. The payoff function represents the perceived utility of making a particular demand given the demands of others. The payoff function implies that players will always favour demands closer to their BAU strategy unless increasing their demands threatens to collapse a potential agreement.

The original Nash bargaining game had only two players, each making a single demand, and had fixed disagreement payoffs. Analysis of this game has traditionally taken the form of identifying specific preferred solutions that satisfy different sets of requirements^{20, 21}. Other bargaining studies have considered the effects of introducing additional strategic complexities^{22, 23}. Our approach retains much of the simplicity of the original game and focuses on the challenge that learners face during bargaining²⁴.

To represent adaptive agents within the context of negotiations, we will consider a sequence of simultaneous demands made by each agent, where each demand is visible to all agents.

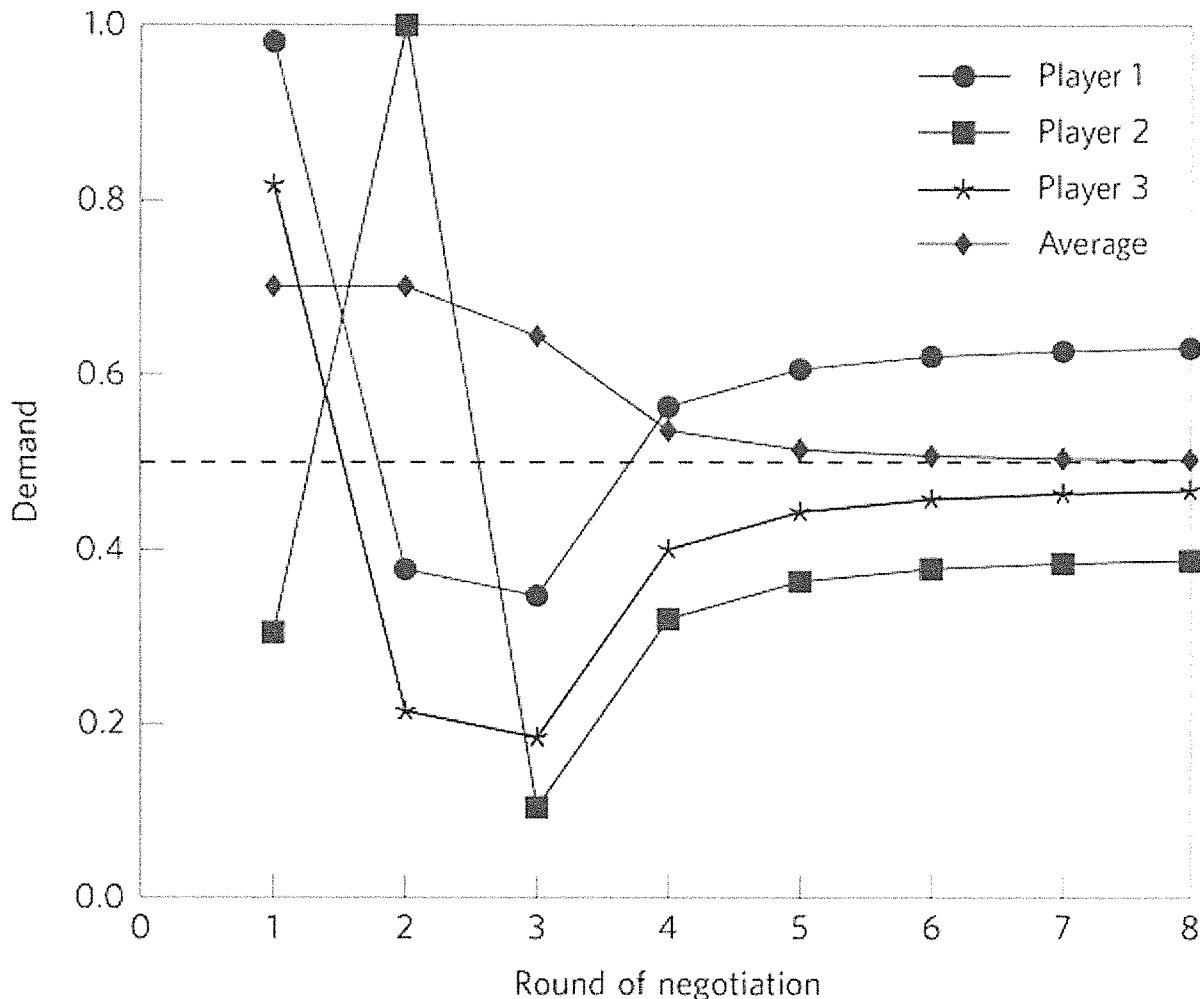
Agents may learn during the negotiations and change their demand between each round of negotiations. We will model the learning process using a variation of simultaneous fictitious play; agents form expectations about the other players' demands based on past behaviour and respond by making a demand that maximizes payoff given these expectations^{25, 26, 27}. Traditional fictitious play forms expectations of others' choices by assuming they are randomizing among observed strategies in a fixed way. In our model, however, agents form expectations by determining the mean of others' previous demands (see the Supplementary Information, for a comparison of this and the traditional approach). In each round, each agent makes a demand to maximize her return given the anticipated demands of others. The resulting state is a function of the interdependent individual choices. Initial demands are randomly chosen among those that agents are willing to consider; any $d_i < \delta$ is excluded. Note that agents are not aware that feasible solutions are possible until they observe a combination of demands such that an individual adjustment could reach the target value. Feasible solutions are sets of demands that are at or under the target value and constitute an equilibrium situation where no player can do better by demanding more or less. Such solutions exist whenever the target value is at least as large as the sum of the minimum demands. If this condition is met, any set of strategies where $t = T \sum_i s_i$ is a strict Nash equilibrium of the game, and no player can deviate from these states without making themselves worse off (Proposition 1 in the Supplementary Information). Consequently, a feasible solution will be stable if it is reached in negotiations. What is not clear, however, is whether agents can reliably reach such solutions.

Even if there are feasible solutions there may be other possible outcomes that are less desirable. In particular, it is possible for negotiations to break down and for everyone to opt for their BAU strategy. If the distance between the target and the sum of the maximum demands is greater than what any one player can reduce, disagreement equilibria exist. Moreover, these disagreement equilibria also constitute strict Nash equilibria of the game and thus can be possible outcomes for adaptive agents in the game (Proposition 2 in the Supplementary Information). Therefore, the game includes a potential obstacle to successful negotiations that is not related to the stability of feasible solutions: whether learners can find these solutions and avoid disagreement equilibria.

We used computer simulations to determine whether agents that learn during negotiations can find feasible solutions and how likely they are to reach these solutions. These simulations also allow us to assess the effects of changes in the bargaining situation. In what follows, we will assume a target value of $T = 0.5$ representing a goal of reducing emissions to 50% of BAU. Higher target values make agreement easier and lower target values make agreement more difficult. Suppose that any negotiations that get within 1% of the target value within 100 rounds count as a success. Simulations reveal that both feasible solutions and disagreement equilibria are observed and that players typically converge on equilibria quickly. In a typical negotiation,

agents will begin with widely dispersed demands and react strongly to early rounds before converging on either a feasible solution or the disagreement equilibrium (Fig. 1).

Figure 1: The demands of three players during the initial rounds of negotiation from a characteristic example simulation where players converge on a feasible solution.

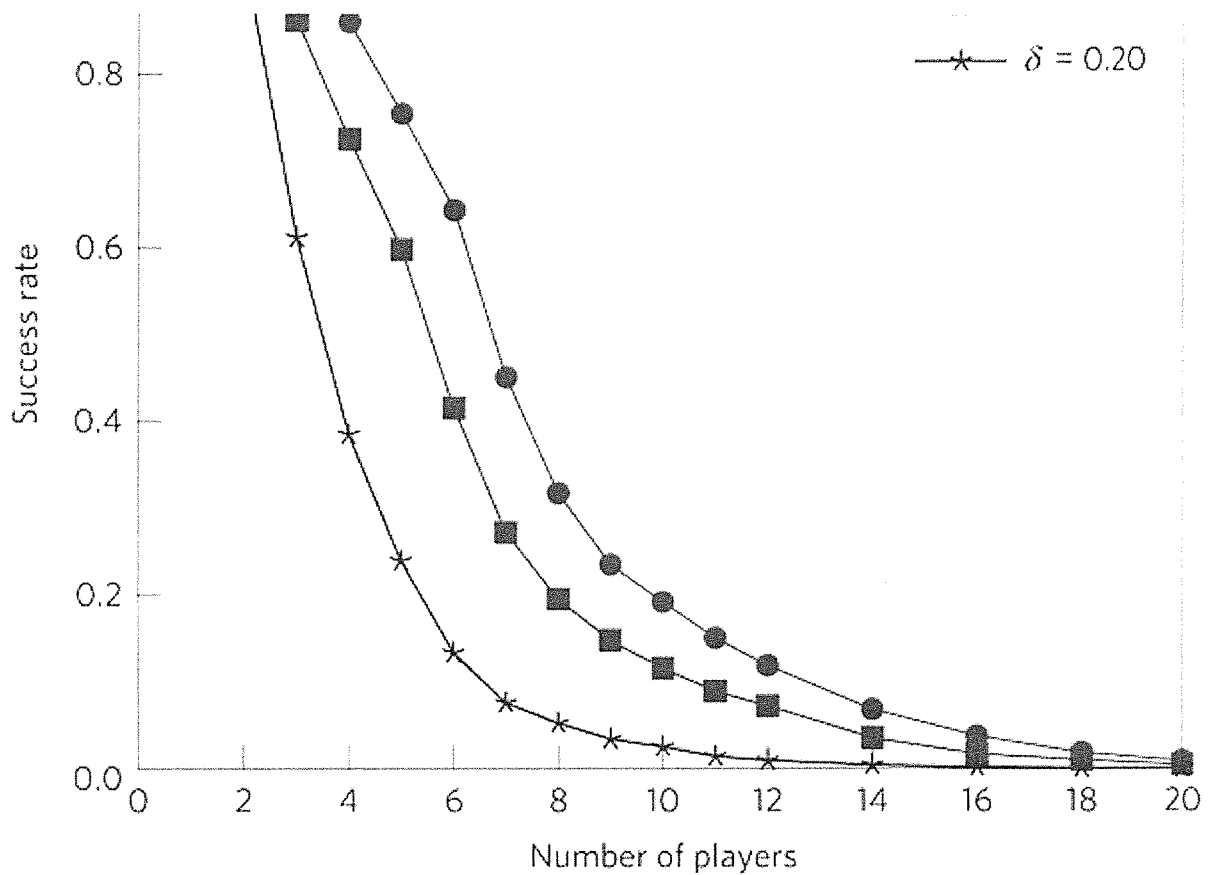


Players are of equal size. $\delta = 0.1$.

There are a variety of factors that affect the chance of success. One such factor is the number of players. Although negotiations can produce both agreement and disagreement equilibria with any number of players, the chance of successful negotiation dramatically decreases as the number of players increases (Fig. 2).

Figure 2: The frequency of reaching a feasible solution as a function of the number of players involved.





10^5 simulations per data point. All players are of equal size.

The discount factor for disagreement outcomes can also substantially impact the chance of reaching a successful agreement. The higher δ , the higher the minimum acceptable demand is for each player. Higher minimum demands means higher average initial demands as well as more constraints on the sets of demands that can constitute successful agreements.

Heterogeneity of the size of players has a positive impact on reaching an agreement. As a subset of players is made larger, the success rate for negotiations increases (Table 1). The reason that heterogeneity helps to reach a positive solution is that it introduces some constraints on the dynamics; games with less flexible players resemble games with fewer players. Examining cases with players of varying sizes also reveals that successful negotiations tend to be those where the larger players make proportionally larger concessions (Table 2). As larger players have a larger impact on total emissions, adjustments on their part tend to make up a more substantial part of reaching the reduction target. Players responsible for larger shares of global BAU should expect to make larger proportional reduction commitments in successful negotiations.

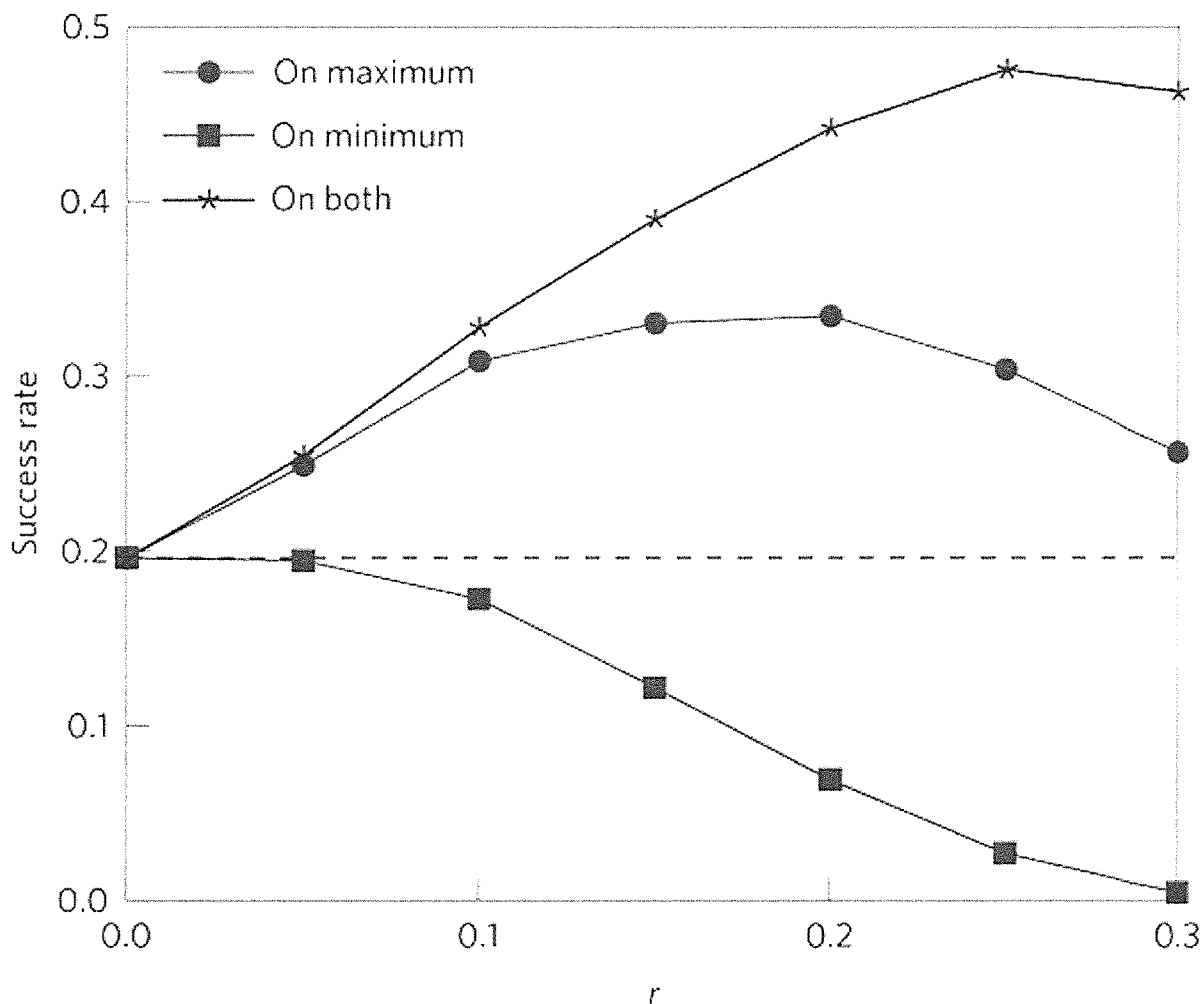
Table 1: Frequency of success in an eight-player negotiation where players 1 and 2 are varied in size (s_1 and s_2) making up an increasing proportion of global business as usual

(BAU).

Table 2: Average demand in successful agreements as a function of an agent's size.

The initial starting point of the negotiation process is crucial to the end result. If too many players start with very high demands, negotiations usually break down. The reason for this is that the further above the target the total demands are, the more collective action it takes to reach the target. Although the result is intuitive it has an important moral: any mechanism that encourages initial demands that are closer to the target value will increase the chance that an agreement is reached. Introducing restrictions on initial demands to limit their size has a positive effect on the success of negotiations. This positive effect can be enhanced by also restricting minimum initial demands (Fig. 3). Restricting both maximum and minimum initial demands improves the success rate by ensuring both reasonable starting demands and flexibility in future rounds of negotiation.

Figure 3: The effect of introducing restrictions on initial demands.



When restrictions (r) are placed on initial demands, such demands are drawn with uniform distribution

from $(\delta + r, 1)$ or $(\delta, 1 - r)$ for restrictions on minimum demands or maximum demands, respectively. When restrictions are placed on both maximum and minimum, initial demands are drawn from $(\delta + r, 1 - r)$. Here $\delta = 0.1$ with eight players of equal size.

We can also represent the possibility of side deals, or reduction agreements made before the bargaining process. To do this, we reduce the maximum possible demand for one or more players thus restricting the strategy space for those players. This will have the effect of reducing, on average, the players' initial demands as well as constraining their maximum demands during the negotiation process. Such prior reductions can have a dramatic impact on the likelihood of successful negotiations. Examining prior reductions in cases with agents of different sizes also reveals some interesting effects. For instance, a prior reduction from a large number of smaller players is better than an equivalent reduction from a small number of larger players (Table 3). This suggests that prior agreements among smaller players can be more important for success than similar prior agreements from larger players. However, if these prior reductions are accompanied by higher minimum demands, perhaps because players that make prior reductions feel entitled to higher demands during negotiations, then the success rate tends to decline. Prior reductions—constraints on maximum demands—will be less effective or counter-productive if they are accompanied by constraints on minimum acceptable demands.

Table 3: Success rates under different prior commitments in 10,000 simulations of eight agents, two of which comprise 25% of total player size each.

Our model addresses the possibility that the problem in reaching an international climate agreement is not one concerning the existence of successful solutions but of realizing them in negotiations. It captures two important features of international negotiations simultaneously: distribution and coordination. A successful agreement requires coordination in the form of compatible demands, but all players also have an incentive to reduce emissions as little as possible. The idealizations and simplicity of the model mean that lessons for policy recommendations should be treated with caution²⁷. Nevertheless, insofar as the model captures the core of continuing negotiations, we have identified some potential difficulties for international climate agreements as well as possible ways to address these difficulties.

There are sufficient interactions within the United Nations Framework Convention on Climate Change (UNFCCC) process to satisfy the learning conditions in the model, which is itself applicable to both Kyoto-style grand bargain approaches and Copenhagen-style collaborative reduction approaches to reaching an agreement. In both cases, parties observe the declarations of others and respond with their own declarations. Thus, the model is neutral on the process for how reduction commitments are made: merely altering the mechanism is unlikely to change the outcome. It also suggests that when positive outcomes are reachable, they are achieved

relatively quickly. Such considerations imply that unless the conditions of the UNFCCC negotiations change dramatically, future success is doubtful. However, the model indicates ways in which the chances of a successful agreement could be improved.

First, the large number of players (countries) involved in the negotiations seems to present a significant barrier to a positive outcome from the negotiation process. However, introducing the right kind of constraints on players can improve the prospects for agreement. For example, if the United States and China were to reach a bilateral reduction agreement outside the UNFCCC, which they then brought into the negotiation, the chance of success increases. Indeed, any players, large or small, can do a service to the process by making agreements outside of it—and reaching side agreements should be relatively easy precisely because they involve just a few players. Rather than undermining the UNFCCC process, additional negotiation venues could help facilitate a broader international agreement^{28, 29}. In fact, it seems that prior commitments from a larger number of smaller emitters can be more important than similar commitments from fewer larger emitters. An important proviso is that reduction commitments accompanied by increased constraints on the minimum acceptable share of emissions can make negotiations harder. External commitments and side agreements need to be made in a way that constrains the maximum demands but does not lock in higher minimum demands.

The model also suggests that the likely outcome of negotiations is sensitive to initial demands. If too many players are too far away from their proportional share of reductions, negotiations are likely to break down. Any mechanism that encourages initial demands closer to the target values will increase the likelihood of success.

The results suggest that a successful outcome is more likely the greater the expected disvalue of failure. The worse the parties see failure to address global climate change to be, the more likely they are to reach agreement. Similarly, an agreement is more likely the smaller the perceived costs of implementing the reductions necessary to reach commitments. For instance, technological developments leading to inexpensive low-emission energy sources may mean lower maximum demands as well as a greater willingness to consider higher amounts of reduction. Economic or political incentives could also influence the perceived payoff for successful agreement as well as the initial demands in negotiations, both of which could increase the chance of reaching a successful agreement. However, the model suggests that it is unlikely that small changes along these fronts will bring about solution feasibility. Rather, dramatic shifts would be required to significantly change the likelihood of success.

Change history

Corrected online 08 August 2014 In the Supplementary Information file for this Letter, the authors have added a section titled "Description of simulation procedure", which provides a

detailed account of the primary simulation procedure used in the study. This section is intended to allow others to directly replicate the results, and contains some detail and accompanying explanation omitted from the original version. The revised version also includes notational corrections to the proof of Proposition 1.

References

1. Finus, M. *Game Theory and International Environmental Cooperation* (Edward Elgar, 2001).
2. Gardiner, S. M. *A Perfect Moral Storm* (Oxford Univ. Press, 2011).
3. Barrett, S. *Environment and Statecraft: The Strategy of Environmental Treaty-Making* (Oxford Univ. Press, 2003).
4. Decanio, S. J. & Fremstad, A. Game theory and climate diplomacy. *Ecol. Econ.* **85**, 177–187 (2013).
5. Heitzig, J., Lessman, K. & Zou, Y. Self-enforcing strategies to deter free-riding in the climate change mitigation game and other repeated public good games. *Proc. Natl Acad. Sci. USA* **108**, 15739–15744 (2011).
6. Dietz, T. & Zhao, J. Paths to climate cooperation. *Proc. Natl Acad. Sci. USA* **108**, 15671–15672 (2011).
7. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge Univ. Press, 1990).
8. Ostrom, E. Collective action and the evolution of social norms. *J. Econ. Perspect.* **14**, 137–158 (2000).
9. Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B. & Policansky, D. Revisiting the commons: Local lessons, global challenges. *Science* **284**, 278–282 (1998).
10. Samuelson, L. *Evolutionary Games and Equilibrium Selection* (MIT Press, 1998).
11. Altamirano-Cabrera, J. & Finus, M. Permit trading and stability of international climate agreements. *J. Appl. Econ.* **9**, 19–47 (2006).
12. Dellink, R., Finus, M. & Olieman, N. The stability likelihood of an international climate agreement. *Environ. Res. Econ.* **39**, 357–377 (2007).
13. Finus, M., Altamirano-Cabrera, J. & Van Ierland, E.C. The effect of membership rules and voting schemes on the success of international climate agreements. *Public Choice* **125**, 95–127 (2005).
14. Altamirano-Cabrera, J., Finus, M. & Dellink, R. Do abatement quotas lead to more successful climate coalitions? *Manch. Sch.* **76**, 104–129 (2008).

15. Finus, M. & Nr, D. Game theoretic research on the design of international environmental agreements: Insights, critical remarks, and future challenges. *Int. Rev. Environ. Res. Econ.* **2**, 29–67 (2008).
16. Finus, M., Saiz, M. E. & Hendrix, E. M. T. An empirical test of new developments in coalition theory for the design of international environmental agreements. *Environ. Develop. Econ.* **14**, 117–137 (2008).
17. Weikard, H. & Dellink, R. Sticks and carrots for the design of international climate agreements with renegotiations. *Ann. Oper. Res.* <http://dx.doi.org/doi:10.1007/s10479-010-0795-x> (2010).
18. Santos, F. C., Pacheco, J. M. & Lenaerts, T. Evolutionary dynamics of social dilemmas in structured heterogeneous populations. *Proc. Natl Acad. Sci. USA* **103**, 3490–3494 (2006).
19. Nash, J. The bargaining problem. *Econometrica* **18**, 155–162 (1950).
20. Kalai, E. & Smorodinsky, M. Other solutions to Nash's bargaining problem. *Econometrica* **43**, 513–518 (1975).
21. Binmore, K. G. *Game Theory and the Social Contract II: Just Playing* (MIT Press, 1998).
22. Rubinstein, A. Perfect equilibrium in a bargaining model. *Econometrica* **50**, 97–109 (1982).
23. Muthoo, A. *Bargaining Theory with Applications* (Cambridge Univ. Press, 1999).
24. Young, P. An evolutionary model of bargaining. *J. Econ. Theory* **59**, 145–168 (1993).
25. Brown, G.W. in *Activity Analysis of Production and Allocation* (ed Koopmans, T.C.) Iterative solutions of games by fictitious play. 374–376 (Wiley, 1951).
26. Fudenberg, D. & Levine, D. *The Theory of Learning in Games* (MIT Press, 1998).
27. Madani, K. Modeling international climate change negotiations more responsibly: Can highly simplified game theory models provide reliable policy insights? *Ecol. Econ.* **90**, 68–76 (2013).
28. Weischer, L., Morgan, J. & Patel, M. Climate clubs: Can small groups of countries make a big difference in addressing climate change? *Rev. Eur. Community Int. Environ. Law* **21**, 177–192 (2012).
29. Diring, E. Climate change: A patchwork of emissions cuts. *Nature* **501**, 307–309 (2013).

Download references

Author information

Affiliations

**Department of Philosophy & Religion, Northeastern University, 360 Huntington Ave
Boston, Massachusetts 02115, USA**

Rory Smead, Ronald L. Sandler & John Basl

**Department of Philosophy, Tufts University, 14 Upper Campus Road Medford,
Massachusetts 02155, USA**

Patrick Forber

Contributions

R.L.S. and R.S. oversaw the project. R.S. and P.F. developed the models and ran simulations. R.L.S. and J.B. analysed the status of current climate negotiations and policy. R.L.S., R.S., P.F. and J.B. jointly developed how to apply the model to climate negotiations, derived general recommendations and wrote the paper.

Competing financial interests

The authors declare no competing financial interests.

Corresponding author

Correspondence to: Rory Smead

Supplementary information

PDF files

1. Supplementary Information (268KB)

Nature Climate Change ISSN 1758-678X EISSN 1758-6798

This journal is printed on recycled paper

Header image source: ESA/NASA

© 2014 Macmillan Publishers Limited. All Rights Reserved.

partner of AGORA, HINARI, OARE, INASP, ORCID, CrossRef and COUNTER