Journal of Public Economics 158 (2018) 103–112

Contents lists available at ScienceDirect

Journal of Public Economics

journal homepage: www.elsevier.com/locate/jpube

Collective action in an asymmetric world☆

Cuicui Chen, Richard Zeckhauser*

Harvard University,United States

ARTICLE INFO

Keywords:
International public good
Alliance
Nash equilibrium
Lindahl equilibrium
Asymmetric game
Climate change
Greenhouse gas emissions
Climate Club

JEL classification:
H4
C7
D7

ABSTRACT

A central authority possessing tax and expenditure responsibilities can readily provide an efficient level of a public good. Absent a central authority, voluntary arrangements must replace coercive ones, and significant under-provision must be expected. International public goods are particularly challenging due to the substantial asymmetries among nations. Small-interest nations have strong incentives to ride cheaply. Our empirical results reveal cheap riding intentions in providing for climate change mitigation, a critical international public good. The evidence is provided by individual nations' Intended Nationally Determined Contributions voluntarily pledged for the Paris Climate Change Conference. We find that larger nations made much larger pledges in proportion to both their Gross National Incomes and their historical emissions. Implications for the Nordhaus Climate Club and carbon-tax proposals are discussed. To achieve Pareto optimality despite disparate cheap-riding incentives, we propose the Cheap-Riding Efficient equilibrium. That solution takes the Nash equilibrium as a base point, and then applies the principles of either the Nash Bargaining solution or the Lindahl equilibrium to proceed to the Pareto frontier.

1. Introduction

Prior to the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change in Paris in December 2015, the European Union and almost all individual nations had submitted their Intended Nationally Determined Contributions (INDCs). Each INDC lays out the climate action the submitter intends to take under the new international climate agreement, the Paris Agreement. An important component of the INDCs are the nations' intended reductions in greenhouse gases (GHGs). Despite enthusiasm for the Paris Agreement, including from economists involved, those pledged reductions (assuming optimistically that they are met) are unlikely to come close to controlling GHGs to the overall level that the scientific community generally agrees is needed to prevent the climate change problem from becoming significantly worse over time.[1]

Traditional and widely proposed mechanisms for pursuing efficient global public good provision in international agreements will fail to control GHGs. Solutions that impose a common requirement, such as a uniform global carbon tax or a uniform GHG reduction obligation, will not get widespread agreement among asymmetrically-situated nations. The alternative approach, which is to get nations together to agree on differentiated burden-sharing, may secure agreement, as we have seen for example with the Kyoto Protocol and the Paris Agreement. However, there remains too strong an element of voluntary decisions in such agreements, as no overarching government unit is available to enforce actions in providing for the global public good. Behaviors of individual nations in this situation will then be best characterized by a Nash equilibrium, which, as is well known in the literature, leads to under-provision of the global public good.

The first goal of this paper is get to the crux of the under-provision problem by looking more closely than does the literature at the behavior of asymmetrically-situated nations in global public good provision. Doing so allows us to gain a deeper understanding of the problem and to better assess the prior solution proposals. We formalize the notion in Olson (1965) of “exploitation of the great by the small.” We empirically test this notion in the context of global climate change mitigation using the INDCs submitted prior to the Paris conference. As hypothesized, “small-interest” nations made disproportionately smaller pledges than did “large-interest” nations. The measure of “interest” turns out to be predominantly based on the Gross National Incomes (GNIs) and past emissions, and neither vulnerability to climate change nor per capita income seem to be relevant. To our best knowledge, this is the first time

---

☆ We thank Joe Aldy, Scott Barrett, Wolfgang Buchholz, Keith Dougherty, Chris Knittel, Jim Roumasset, Rob Stavins, the participants at the Harvard Environmental Economics lunch, the 53rd Annual Meetings of the Public Choice Society, the Harvard Seminar in Environmental Economics and Policy, and the 3rd China Meeting of the Econometric Society, a co-editor, and two anonymous referees for their helpful suggestions and feedback.

* Corresponding author at: 79 JFK Street, Cambridge, MA, 02138 USA.
E-mail addresses: cuicuichen@fas.harvard.edu (C. Chen), richard_zeckhauser@hks.harvard.edu (R. Zeckhauser).

[1] Indeed, Hohne et al. (2015) finds that the unconditional reduction pledges in INDCs would lead to a median warming of around 2.7 °C by 2100 with the full range of 2.2 to 3.4 °C. European Commission (2017) also states that “[the INDCs] are not yet enough to keep global warming below 2 °C.”

https://doi.org/10.1016/j.jpubeco.2017.12.009
Received 24 August 2016; Received in revised form 2 November 2017; Accepted 22 December 2017

that the important role of asymmetric incentive of small-interest and large-interest nations has been recognized in the context of global climate agreements.

The paper then proposes a new solution, the Cheap-Riding Efficient equilibrium (CREE).[2] It fully recognizes such asymmetries. It defines the relative contributions of players of differing size in a manner that both caters to the strong incentive of small-interest players to ride cheaply, yet still achieves Pareto optimality. In this equilibrium, we establish the Nash equilibrium as the starting point. From there, we consider two Pareto-improving paths to the Pareto frontier. One adapts the Nash Bargaining solution; the other relies on the principle of the Lindahl equilibrium. In our illustrative numerical example, the two outcomes are remarkably similar. We recognize that such mechanisms are not currently in place, and that most international efforts at providing global public goods lead to total outputs that are well below what would be optimal. In other words, there are alternative agreements, CREE included, that require greater contributions from all that would bring about a substantial Pareto improvement.

Numerous papers have examined the under-provision problem of public goods with no central authority, including the effect of group size (for example, Isaac and Walker, 1988), the implications of individual heterogeneity (for example, Boadway and Hayashi, 1999; Callander and Harstad, 2015), the role of uncertainty (see Kolstad (2007) and the literature reviewed therein), and the validity of the Nash assumption (for example, Cornes and Sandler, 1984; Sugden, 1985).

A number of solutions have been proposed in the literature. Arce and Sandler (2001) propose setting up a super-national organization that sends signals to nations in order to induce correlated equilibria that are Pareto superior to Nash equilibria. Gerber and Wichardt (2009) study a two-stage mechanism where players commit to the public good by paying a deposit prior to the contribution stage. They show that properly designed deposits support prior commitment and full ex post contributions as a sub-game perfect Nash equilibrium. Barrett (1994) represents public good provision in a repeated prisoners' dilemma game and shows that cooperation can be both individually and collectively rational. Similarly, Heitzig et al. (2011) cast the public good provision game in a repeated game setting and argue that dynamic concerns can enforce efficiency. Abul Naga and Jones (2012) discuss the role of other-regarding preferences, such as altruism, in bringing about efficient provision. One strand of literature studies matching schemes (for example, Barrett, 1990; Falkinger et al., 1996; Boadway et al., 2011; Buchholz et al., 2011; Buchholz et al., 2014), in which players decide on the unconditional and conditional (matching) contributions to the public good. This process can lead to interior matching equilibria at which all agents make strictly positive unconditional contributions. However, none of these solutions pays sufficient attention to the asymmetry inherent in players' situations.

We proceed as follows. Section 2 connects the climate change mitigation problem, or provision of a global public good in general, to the traditional Alliance problem. Section 3 presents empirical evidence demonstrating cheap riding in the INDCs that nations submitted for the Paris Agreement. Section 4 discusses weaknesses of prior proposals for solving the under-provision problem; they do not adequately recognize the disparate incentives of players to ride cheaply. We propose our solution, the CREE, in Section 5. Section 6 concludes.

2. Climate change mitigation - a traditional alliance problem

The provision of global public goods is challenging for two reasons. First, forces that at times motivate contributions by individuals – such as warm glow, prestige, or self interest – will rarely be sufficient to motivate nearly sufficient contributions by nations to a public good that entails substantial expenditures, as does GHG reduction. Second, and more importantly, the potential providers are very differently situated. Some are rich, some poor; some are large, some small, and some bear much greater responsibility than others for past emissions. At any level of the public good, some will secure much greater benefits from its provision – both overall and at the margin – than will others. Thus, China with a population of 1.3 billion, the world's second largest economy, a significant pollution problem, and the intention and ability to lead in the production of green energy technologies, will benefit greatly from the effective control of GHGs. Landlocked Laos, with fewer than 7 million citizens, would benefit little.

The theory of alliances (Olson and Zeckhauser, 1966) was developed to address just such a situation. Its principal lesson is that larger nations, as measured by national incomes, will contribute disproportionately more to the alliance good (e.g., the defense budget of NATO) than smaller nations. This lesson has been generalized to any global public good: nations with larger interests in a global public good will contribute disproportionately more to its provision. Here, we use "interest" to refer to the marginal benefit that the nation would get from the global public good if it contributed more to it by itself. Because this marginal benefit generically varies with the allocation of contributions, we need to specify the latter to complete the definition of "interest." A useful specification is the proportional contribution plan, with the proportion based on some salient measures of the contributing nations. Thus, a nation has a larger interest than another if it would be willing to contribute more than its proportional share justified by the salient measure.

In combating common security threats, such as in the context of NATO, the salient measure is the national incomes that are at stake if the threat eventuates. Thus, a nation that has twice as great a national income as another would contribute more than twice as much at a self-interested, Nash equilibrium. That nations with greater national incomes tend to contribute disproportionately more is also observed in the combat against ISIS, in which the U.S. provides vastly disproportionately; Pentagon officials complained that some of the 64 partner nations and regional groups, mostly the Arab allies which though threatened more are smaller nations, are not doing nearly enough (Hennigan and Bennett, 2016). This pattern also emerges in non-defense contexts, for example, where Saudi Arabia cut its oil production far more below its optimum than did other OPEC nations when OPEC was still hanging together to cut production. Indeed, Griffin and Xiong (1997) find that small producers (such as Gabon, Qatar, Algeria, Libya, Indonesia, and Nigeria) were subsidized at the expense of large producers (especially Saudi Arabia) in the OPEC arrangement, a phenomenon they call the "small producer bias."

In the context of climate change mitigation, the salient measure can be much more than just national incomes. It may include other measures of tangible benefits from climate change mitigation, such as green orientation, per capita income, and the degree to which a nation would be affected – whether due to damages or costs of avoiding those damages – by climate change. Greater interest could also arise from intangible benefits. Thus, a nation that has emitted a lot in the past might commit to greater reductions due to a feeling of responsibility, a concern for reputation, or an orientation toward fairness. In the next section we will empirically investigate which factors prove important.

Given the under-provision of a global public good due to the strong cheap-riding incentive that small-interest nations have in a Nash equilibrium, the question arises as to why the nations do not get together and bargain their way to an efficient equilibrium (thus bypassing the Nash equilibrium). Such an approach might have potential if the members were all similarly situated, and the number of members were not too large. In a negotiation, a natural focal point in the sense of Schelling (1960) would be that each member contributes the same;

---

[2] While the term "free riding" is typically used to describe such situations, in many cases we see less extreme behavior, which we term "cheap riding." If the potential contributor gets a substantial portion of the benefits from a public good, or if s/he enjoys separate benefits from the action of contributing that are quite apart from the public good, then s/he will likely contribute a positive amount, although that amount would still be below what efficiency would require.

none could expect to pay less than the others. In such a symmetric situation, with only a few players, they could merely identify and agree to the optimal per-capita contribution of individuals, or per-nation contribution in the international context. Positing that contributions could be monitored, efficiency would be achieved.

In the real-life situation, however, matters are far from symmetric. Even if the individuals across the nations were identical, for example in income and preferences, in a negotiation, the small-interest nations could expect the large-interest nations to contribute more. They would argue, correctly, that given proportional contributions large-interest nations benefit much more at the margin. However, determining the appropriate ratio of contributions via negotiation would present a challenge. Large- and small-interest nations would respectively advance arguments as to why the ratio should be smaller or larger. As a result, agreement is unlikely. With each nation following its own principles, under provision is to be expected.

3. Cheap riding in the Paris Agreement

In this section, we empirically document the existence of cheap riding in the INDCs submitted for the Paris Conference. First, we convert the reduction goals in INDCs to absolute amounts of carbon emissions reduction, or the contributions, by estimating each nation's business-as-usual (BAU) emissions in the target year and comparing them to the target emissions. Second, we examine the rank correlations between the individual nations' contributions, properly normalized, and their national income, climate vulnerability, pollution level, historical carbon emissions, and measures of their environmental concerns. We describe the technical details in Appendix A.

Table 1 shows the Pearson rank correlation test results. The rank correlation coefficient between the reduction per dollar of GNI and GNI is positive and highly significant. This means that nations with larger GNIs make disproportionately greater pledges of reductions relative to their GNIs. That GNI appears to be an important determinant of the cheap-riding incentive is consistent with the findings in the NATO defense context (Olson and Zeckhauser, 1966) and the OPEC production-reduction context (Griffin and Xiong, 1997). Per capita GNI produces a positive rank order correlation as well, in accord with the observation that environment is a superior good (Kahn and Matsusaka, 1997).

From Table 1, some observers might be surprised that the vulnerability measures do not produce big contributions. Indeed, they point in the other direction. Some might argue that while GNP seems an obvious measure of size that matters in the defense context, it should matter much less in the context of climate change mitigation. The Maldives, a minuscule nation relative to the United States is often cited in this context. Its very existence would be at risk given sea level rise. Thus, the argument goes, it should contribute a lot in proportion to its GNP to the mitigation cause. We believe, however, that there are clear parallels between the defense and the climate-change-mitigation contexts. The national income at stake is still a more important measure of size than vulnerability for either problem. If the counterargument is based on vulnerability (as with the Maldives argument) in the climate-change-mitigation context, then in the 1960s NATO context Germany and France should have contributed much more relative to the United States. After all, they were much more vulnerable to aggression by the Soviet Union. The large nation in NATO contributed significantly more disproportionately despite having an ocean of protection.[3] If an alternative counterargument is based on per capita income, then Luxembourg, having a very high per capita income, contributed vastly less than the United States. Moreover, with NATO in the 1960s, there was an established organization that had some ability to get small-interest cheap riders to contribute more. Maybe Germany, France, and Luxembourg would have contributed relatively even less had this overarching organization not existed. To return to climate change, one phrasing of the Maldives' implicit argument might be: "We are a tiny blameless nation. Nothing we could do could alter our dire fate. The blameworthy nations of the world have a responsibility to take vigorous action to save us."

Table 1
Pearson rank correlation test results.

Correlation with per-unit reduction	Coefficient	p-Value	# of obs
GNI	0.3433	0.000	106
Per capita GNI	0.2547	0.008	106
% vulnerable rural population	−0.1854	0.038	126
% vulnerable urban population	−0.0641	0.478	125
% population exposed to disaster	−0.0563	0.527	129
Annual temperature	−0.1143	0.189	134
Historical carbon emissions 1970–2012	0.7311	0.000	128

Nations with higher cumulative 1970–2012 carbon emissions[4] also tend to pledge disproportionately more. This suggests that nations might have incorporated historical responsibility in their preferences when they formulated emission reduction pledges. However, since historical emissions and GNI are highly correlated, a controlled analysis is needed to single out the marginal effect of each.

We now look more closely at the roles of GNI and historical emissions, as well as per capita GNI, in determining the cheap-riding incentive in a controlled analysis. We conduct the Kendall partial rank correlation test for each one with the properly normalized contribution while controlling for the other two. The analysis also controls for the vulnerability, pollution, and environmental concern measures.

Table 2 shows that both GNI, as a measure of tangible benefit, and historical emissions, as a measure of intangible benefit, survive as robust determinants of the cheap-riding incentive after adding the controls. Per capita GNI has no relationship. Thus, for two hypothetical nations with the same historical emissions (and per capita GNI, climate vulnerability, pollution level, and environmental concerns), nations with larger GNIs would pledge disproportionately more and thus suffer cheap riding from nations with small GNIs. Similarly, for two hypothetical nations with the same GNI (and other controls), nations that have cumulatively emitted more would pledge disproportionately more.[5]

4. Cheap riding and prior proposals

We evaluate two important prior proposals to try to achieve efficient levels of global climate change control. Despite the fact that cheap-riding incentives loom large in this context, as we have shown in Section 3, neither proposal recognizes this problem.

First, carbon taxes, along with tradable permits, are the economist's preferred regulatory tool for environmental externalities. To achieve efficiency, a necessary condition is that the tax or the permit price be the same for all nations. But small-interest nations are getting much less benefit relative to what they are spending on the margin. Thus, a uniform tax or permit price ignores the cheap-riding incentive; small-interest nations are likely to find it individually irrational to participate in the uniform-price regime. Transferring vast resources from large-interest to small-interest countries would be highly unattractive politically.[6]

---

[3] That said, vulnerable nations might have incentive to appear to contribute a lot so as to serve as role models. They might say: "Look, if we do not contribute much, others will ask if we are really crying wolf, and do not feel threatened, or do not care."

[4] We thank a referee for suggesting the role of historical emissions in driving the pledges.

[5] Historical emissions are fairly strongly related to GNI. Normalizing both quantities so that the median country is at 100, eight countries have normalized emissions more than 2.5 times GNI. They are the Russian Federation and three former Soviet countries, China, Iran, South Africa, and Trinidad and Tobago.

[6] That being said, the Paris Agreement's Article 6 has provisions for "internationally transferred mitigation outcomes," or ITMOs, which provide parties with the mechanism to trade emission reduction credits for funds.

Table 2
Kendall partial rank correlation test results.

Partial correlation with per-unit reduction	GNI	GNI	Per capita GNI	Per capita GNI	Historical emission	Historical emission
Coefficient	0.1084	0.1703	0.0943	0.0219	0.6168	0.5920
p-Value	0.045	0.020	0.197	0.857	0.000	0.003
Environmental concern	N	Y	N	Y	N	Y
Other controls	Y	Y	Y	Y	Y	Y
# of obs	59	29	59	29	59	29

Notes. "Other controls" for a particular outcome variable include the other two outcome variables, as well as vulnerability and pollution measures.

In his seminal work on Climate Clubs, Nordhaus (2015) illustrates how the Climate Club would work, where all members of the Club would agree to impose a minimum domestic carbon tax of $25/ton.[7] This is subject to the same critique of the carbon taxes/permits above. Thus, the likely result would either be that many nations would simply not join the Club, or that to get them to join, the price would have to be set far below what is desirable. Nordhaus (2015) deals with the non-joiners' strategy by having members impose tariffs on the cheap-riding non-joiners. Whether such an arrangement could work in practice, given concerns about retaliation from the non-joiners, violation of existing trade agreements, and other challenges, has been carefully considered by Nordhaus and hotly debated by others. Addressing that debate would take us well beyond the concerns of this paper. But it is appropriate for us to point out that such an arrangement does not adequately recognize the bargaining power that small-interest beneficiaries have when it comes to the provision of a global public good.

The implication is that major beneficiary nations, like the United States and China, which have by far the largest GNIs of any nations, would find a uniform carbon tax, or joining the Climate Club, strongly in their interest. However, nations with much smaller GNIs, per our findings in Section 3, would likely benefit much less at the margin. Small-interest nations would correctly point out that the strategic situation tilts in their favor. They could feel entitled to impose a much lower carbon tax than the United States and China, the type of result to be expected in a Nash equilibrium.

Given these challenges, we developed an alternative solution that recognizes the bargaining forces that arise because nations differ significantly in the benefits they receive at the margin from a global public good.

5. Cheap-riding efficient equilibrium

We propose a new solution, the Cheap-Riding Efficient equilibrium (CREE), that both achieves efficiency and respects cheap-riding incentives. This solution takes the Nash equilibrium as the starting point and then follows Pareto-improving paths from there to efficiency. First, we set up a simple global public good provision game. Second, we demonstrate that the Nash equilibrium respects cheap-riding incentive but is inefficient. Third, we demonstrate that Lindahl equilibrium does not respect cheap-riding incentives, despite being efficient. We then construct CREE by combining the best of the two: the Nash way of recognizing the cheap-riding incentive and the Lindahl way of achieving efficiency. We also note that replacing the latter with the Nash Bargaining way of obtaining efficiency also achieves our purpose. Thus, we see CREE as a *class* of solutions, which share the Nash equilibrium as the starting point but differ in the path they take to reach the Pareto frontier.

5.1. Model setup

Index the players in the model by $i \in \mathcal{N} = \{1, ..., n\}$, and let the contribution of each player to the public good be $m_i \geq 0$. For simplicity, side payments are ruled out. The public good is simply the sum of all individual contributions, $M = \sum_i m_i$. Denote the sum of contributions by players other than i by $M_{-i} = \sum_{j \neq i} m_j$. Player i gets benefit $V_i(M)$, tangible and intangible, from the public good.

We allow not only for cash contributions, but also for in-kind contributions (the norm with international public goods). Hence we allow players to receive private benefits from their own contributions, quite apart from the public good. Thus, for example, a nation's armed forces contribute to the deterrent level of a military alliance. However, they are also available to assist in the case of a natural disaster. A nation's efforts to curb GHGs by developing clean energy technologies would simultaneously advance its high tech capabilities. In addition, a nation may value the respect that other nations pay to it when it contributes to the public good, or may receive a warm glow. Represent this private benefit as $B_i(m_i)$.[8]

The cost to player i of providing m_i is $K_i(m_i)$. Note, because we are dealing with a situation where contributions are in kind, we might expect the marginal cost of contribution to increase sharply as one contributes more; that is, $K''(\cdot)$ can be not only positive, but significantly so. Player i's net payoff is thus $U_i(M,m_i) = V_i(M) - K_i(m_i) + B_i(m_i)$.

For notational simplicity, in what follows we will just use $C_i(m_i)$ to represent the net private cost, $K_i(m_i) - B_i(m_i)$, so that the utility functions can be written as $U_i(M,m_i) = V_i(M) - C_i(m_i)$. Throughout, we assume that utility functions are common knowledge.

5.2. Nash equilibrium

A Nash equilibrium is an allocation $(m_i^N)_{i \in \mathcal{N}}$ (where the superscript N stands for Nash) such that each player's choice is a best response to what the others do. That is, for each $i \in \mathcal{N}$:

$$m_i^N \in \arg\max_{m_i \geq 0} U_i(m_i + M_{-i}^N, m_i), \qquad (Nash)$$

where $M_{-i}^N = \sum_{j \neq i} m_j^N$. There exists a unique Nash equilibrium if for each i, $V_i' > 0$, $C_i' > 0$, $V_i'' < 0$, $C_i'' > 0$, as shown by applying Proposition 3.1 in Cornes and Hartley (2007).

We now examine cheap riding in the Nash equilibrium. Posit for now that nations differ only in size (for example, population, or national income), the "exploitation of the great by the small" in Olson (1965) refers to the result that large nations will contribute more in proportion to their size at the Nash equilibrium. Taking GNP as the measure of nation size, Olson and Zeckhauser (1966) provide an intuitive proof as follows: suppose by way of contradiction that the large nation, which has twice the GNP of the small nation, contributed twice as much at the Nash equilibrium. The Nash equilibrium requires that the marginal rate of substitution of the private good for the public good (MRS) in each nation equal the marginal cost, which, in our setup, means that $V_1'(M)/C_1'(m_1) = V_2'(M)/C_2'(m_2) = 1$. Let 1 be the large nation and 2 the small. This requirement is not met with the proportional contribution plan, where the large nation contributes twice as much. Indeed, with this contribution plan, it is reasonable that $V_1'(M) = 2V_2'(M)$ because there is twice as much national income to be protected in 1 as in 2, and that $C_1'(m_1) = C_2'(m_2)$ at $m_1 = 2m_2$ because there is twice as much national income that can be taxed in 1 as in 2.

---

[7] Nordhaus (2015) allows individual nations to impose a higher tax. But different taxes in different nations would sacrifice efficiency.

[8] A more complex model would include an additional argument in the benefit function, which would include a nation's historical emissions, green orientation, etc. Our finding that historical emissions help to explain the nations' pledges indicates that such factors, which produce intangible benefits, can play an important role.

Then, the MRS of the large nation is twice that of the small. This implies that the large nation would want to contribute even more and/or the small nation even less, until they reach the equilibrium requirement.

These insights can be generalized as follows. Take a proportional contribution plan as given. The proportion can be based on a single salient measure, such as the GNP in the defense context, or can be based on a combination of multiple salient measures, such as GNP, population, vulnerability, and green orientation combined in the climate change control context. With the given proportional contribution plan, calculate the MRS of each nation. Unless all the MRSs are equal, nations have incentive to deviate from this proportional contribution plan; nations with larger MRS, call them "larger-interest" nations, would like to contribute more, and nations with smaller MRS, call them "smaller-interest" nations, would like to contribute less. Therefore, the smaller-interest nations effectively ride cheaply on the larger-interest nations by contributing disproportionately less. Formally, if the contribution plan assigns a proportion s_1 to Nation 1 and s_2 to Nation 2, and the MRSs are such that $V_1'(M)/C_1'(m_1) > V_2'(M)/C_2'(m_2)$ for $m_1/m_2 = s_1/s_2$, then Nation 1 would deviate from the contribution plan by increasing m_1 or Nation 2 would deviate by decreasing m_2, leading to a disproportionate plan where $m_1/m_2 > s_1/s_2$.[9]

As a numerical example, we posit that $V_i(M) = a_i\lambda\log M$, $C_i(m_i) = m_i^2/a_i$, where λ and a_i are parameters. We can think of a_i as population, so that the benefit of the global public good M is proportional to the population and the private cost is inversely proportional. Note that the per capita incomes are the same in the two nations; indeed, the marginal cost of private contributions, $C_i'(m_i)$, are the same at the same per capita contributions. The parameter λ is simply a common scalar on the benefit. Then:

$$MRS_i(m_i, M) = \frac{V_i'(M)}{C_i'(m_i)} = \frac{a_i\lambda/M}{2m_i/a_i} = \frac{a_i^2}{m_i}\frac{\lambda M}{2}.$$

Let $a_1 = 1, a_2 = 1/4$. Take the proportional contribution plan as one in which Nation 1 contributes four times as much as Nation 2 (the former has four times as many people). The ratio of the MRSs is:

$$MRS_1(m_1, M)/MRS_2(m_2, M) = \frac{a_1^2}{m_1}/\frac{a_2^2}{m_2} = \frac{1}{4}/\frac{1/16}{1} = 4.$$

The large nation's MRS is four times as big as the small's at a four-to-one contribution; it has four times as large a marginal benefit and the same marginal cost as the small. Our calculation of the Nash equilibrium shows that the large nation contributes 1.372 at the Nash equilibrium, which is sixteen times the small nation's contribution of 0.086, although the former is only four times the size of the latter.

This Nash equilibrium outcome is also far from Pareto optimal. The large nation gets a net payoff of -0.375 and the small nation a net payoff of 0.347. But if the large nation contributed 20% more and the small nation gave twice its original contribution, those net payoffs would rise to -0.319 and 0.480, a major Pareto improvement, though this outcome also is far from Pareto optimal.

5.3. Lindahl equilibrium

Lindahl (1958) conceived of a provision scheme where each player reported how much of the public good s/he wants depending on the share s/he would be required to pay. The cost shares would be determined such that each player desired the same amount of the public good. Formally, a Lindahl equilibrium established individualized public good prices (or cost shares) $(p_i^L)_{i\in\mathcal{N}}$ (where the superscript L stands for Lindahl), a private good price which we normalize to 1, and an allocation $(M^L, (m_i^L)_{i\in\mathcal{N}})$ such that for each $i \in \mathcal{N}$:

$$(m_i^L, M^L) \in \arg\max_{m_i, M \geq 0} U_i(M, m_i),$$

$$\text{subject to:} \qquad p_i^L M \leq m_i, \qquad\qquad (Lindahl)$$

and the market clears: $M^L = \sum_i m_i^L$. There exists a unique Lindahl equilibrium if for each i, $V_i' > 0$, $C_i' > 0$, $V_i'' < 0$, $C_i'' > 0$, by applying Proposition 1 in Buchholz et al. (2008).

Despite achieving efficiency, the Lindahl equilibrium suffers a grave defect: it fails to recognize the incentive to ride cheaply. Thus, in our numerical example, the Lindahl equilibrium has the nations contributing 1.414 and 0.354 respectively, which gives them net payoffs of 0.279 and 0.070 respectively. Here, however, the small nation has a simple threat to make to the large nation: "I will not participate in the Lindahl equilibrium. You can do so, or if you choose we can revert to the Nash equilibrium." The threat is credible, since the small nation is better off at the Nash equilibrium than at the Lindahl equilibrium.

In many asymmetric situations, of course, no nation will be worse off at the Lindahl equilibrium than at the Nash equilibrium.[10] Nevertheless, the fact that the Lindahl equilibrium simply ignores the fact that small-interest nations do relatively much better at the Nash than at the Lindahl equilibrium is critical. To get agreement, any solution must recognize this bargaining advantage possessed by small-interest nations, for the Nash equilibrium is the fallback solution if an agreement is not reached. This implies that small-interest nations are likely to balk at the Lindahl equilibrium. For some parameter values, as we just showed, there will be a smaller-interest player who is strictly worse off at the Lindahl equilibrium, who would simply hold out for the Nash equilibrium. This player would be in a favored bargaining position just because of its small interest. It could be otherwise identical to the other players in terms of per capita income, exposure to threats due to insufficient provision of the public good, and costs of provision.

Appendix B offers an alternative, intuitive way of thinking about the Lindahl equilibrium, the Supply-Demand Arrangement (SDA). We start by asking each player how much s/he is willing to supply if it will be matched by a total of contributions from others that is n times as large. By varying n in $(1, \infty)$, we obtain that player's supply curve, with the horizontal axis representing n and the vertical representing the supply. We can also derive that player's demand curve by multiplying the supply curve by n. The Supply-Demand Arrangement just solves for a vector of matching ratios, where supply equals demand for each player.

5.4. CREE

There are, of course, an infinite number of Pareto optimal outcomes. Our approach employs a method that takes account of differential incentives to ride cheaply, and at the same time provides an intuitively appealing mechanism to get to alternative Pareto optimal outcomes. Our proposed mechanism, Cheap-Riding Efficient equilibrium (CREE), starts by establishing the Nash equilibrium as a base point. The question then is how to proceed from there in an intuitively appealing manner that leaves no player worse off (so that no player will have the incentive to fall back to the Nash equilibrium), while achieving efficiency. Here too, there are an infinite number of possibilities. The basic question is how the players should share the surplus above the Nash equilibrium on the path to the Pareto frontier.

We propose two alternative approaches to sharing the surplus over the Nash equilibrium. A CREE with our first approach uses the thinking of the Lindahl equilibrium to define the further path from the Nash equilibrium to the Pareto frontier. We believe that the prominence of

---

[9] We thank a referee for pointing out that Warr (1983) looks at the effect of varying incomes on private contributions in a Nash equilibrium: a player will contribute less as his or her income is transferred away. Our formulation of the model is different from Warr's in that we do not treat income explicitly, and that we summarize the difference among nations by the marginal rate of substitution, which can depend on many things in addition to income.

[10] This would typically be the case if nations were perfectly symmetric. Shitovitz and Spiegel (1998) and Buchholz et al. (2006) study the conditions on the income distribution that makes all players prefer the Lindahl equilibrium to the Nash equilibrium.

the Lindahl equilibrium in the public goods context, plus its coincidence with the natural Supply-Demand Arrangement interpretation (see Appendix B for details), gives this CREE a particularly strong claim as a focal point.[11] A CREE with the second approach maximizes the product of each player's surplus over the Nash equilibrium, the outcome with the Nash Bargaining solution. This arrangement offers two advantages: it is the most widely applied bargaining solution, and it derives from an appealing set of axioms. We emphasize the need to take the Nash equilibrium as the disagreement point for the Nash Bargaining formulation to apply to our global public goods provision problem.

It is worth noting that while a CREE is not a Nash equilibrium in individual contributions,[12] it is in individual participation. Consider the following game. Countries are deciding whether to join the CREE agreement, which specifies the individual contributions. If at least one of them does not join, there will be no CREE agreement and countries will revert to the Nash equilibrium. Otherwise, the CREE agreement is effective. Then, for each country it is a dominant strategy to join the CREE agreement, and thus CREE is a Nash equilibrium in individual participation. To the best of our knowledge, CREE is probably the simplest Pareto efficient mechanism in global public good provision games that achieves full participation, without any need to distinguish between signatories and non-signatories as is required by many other mechanisms in the literature.

5.4.1. The Lindahl path

In a CREE-Lindahl, the cost sharing scheme is such that each player will want the same **additional** amount of the public good on top of the Nash amount. Formally, a *CREE-Lindahl* consists of individualized public good prices (or cost shares) $(p_i^{CRE})_{i\in\mathscr{N}}$ (where the superscript *CRE* stands for Cheap-Riding Efficient), a private good price which we normalize to 1, and an allocation $(M^{CRE} + M^N, (m_i^{CRE} + m_i^N)_{i\in\mathscr{N}})$ such that for each $i \in \mathscr{N}$:

$$(m_i^{CRE}, M^{CRE}) \in \arg\max_{m_i, M \geq 0} U_i(M + M^N, m_i + m_i^N),$$

$$\text{subject to:} \qquad p_i^{CRE} M \leq m_i, \qquad\qquad (CRE)$$

and the market clears:

$$M^{CRE} = \sum_i m_i^{CRE},$$

where $(m_i^N)_{i\in\mathscr{N}}$ is a Nash equilibrium allocation and $M^N = \sum_{i\in\mathscr{N}} m_i^N$.

The following proposition establishes the existence and uniqueness of the Cheap-Riding Efficient equilibrium.

Proposition 5.1. *There exists a unique CREE-Lindahl if for each i,* $V_i' > 0, C_i' > 0, V_i'' < 0, C_i'' > 0$.

Proof. Take the total contribution from the unique Nash equilibrium as M^N, with individual contributions m_i^N. Then, we can re-write the utility functions as $\bar{U}_i(\cdot,\cdot) = U_i(\cdot + M^N, \cdot + m_i^N)$, so that Problem (CRE) is in effect the same as Problem (Lindahl) with utility functions $\bar{U}_i(\cdot,\cdot)$, in which there exists a unique Lindahl equilibrium by applying (Buchholz et al., 2008). Therefore, there exists a unique CREE-Lindahl.

In our numerical example, the (unique) CREE-Lindahl has the nations contribute (0.252,0.123) in addition to Nash contributions. This results in the total contributions (1.624,0.209), and net payoffs (−0.215,0.432), respectively. This outcome is Pareto optimal. The next proposition shows that CREE-Lindahl generally achieves Pareto optimality.

Proposition 5.2. *Under the conditions in Proposition 5.1, the CREE-Lindahl allocation is Pareto optimal.*

Proof. Bergstrom (1973) establishes Pareto optimality of the Lindahl equilibrium.[13] We adapt that proof here. Suppose by way of contradiction that there is a CREE-Lindahl allocation $(M^{CRE} + M^N, (m_i^{CRE} + m_i^N)_{i\in\mathscr{N}})$ that is not Pareto optimal. Then there is an alternative allocation $(\widetilde{M}^{CRE} + M^N, (\widetilde{m}_i^{CRE} + m_i^N)_{i\in\mathscr{N}})$ such that Player i does strictly better and the other players do weakly better. Because the utility functions are strictly monotone, they represent locally non-satiated preferences. Hence, Player i's constraint must be violated and the other players' constraints weakly violated at the alternative allocation, that is $p_i^{CRE}\widetilde{M} > \widetilde{m}_i$, and $p_j^{CRE}\widetilde{M} \geq \widetilde{m}_j$ for $j \neq i$. Adding up these inequalities gives $(\sum_{i\in\mathscr{N}} p_i^{CRE})\widetilde{M} > \sum_{i\in\mathscr{N}} \widetilde{m}_i$. To ensure market clearance, $\sum_{i\in\mathscr{N}} p_i^{CRE} = 1$. Therefore, $\widetilde{M} > \sum_{i\in\mathscr{N}} \widetilde{m}_i$, a contradiction.

The next proposition shows that the CREE-Lindahl takes care of the cheap riding incentives, in the sense that each player prefers the CREE-Lindahl allocation to the Nash equilibrium allocation, and usually strictly so. Intuitively, when asked how much of the public good above the Nash outcome is desired at a given cost-sharing rule, any individual player can always choose to desire nothing (and thus to contribute nothing) on top of the Nash outcome. Hence, they cannot be worse off at CREE-Lindahl than at the Nash equilibrium. Furthermore, for a player who would contribute a positive amount at the Nash equilibrium and partially contribute in CREE-Lindahl, s/he would strictly prefer to participate in CREE-Lindahl. Indeed, since such a player would already have equated marginal benefit with marginal cost at the Nash equilibrium, contributing a little bit more as specified in CREE-Lindahl would only be marginally more expensive, but would bring non-marginal benefit due to the non-marginal increase in the 'bang' in terms of the level of the public good. Moreover, the path from the Nash equilibrium to the Pareto frontier is not ad hoc; it has the appealing justification that led to the initial identification of the Lindahl equilibrium.

Proposition 5.3. *Under the conditions in Proposition 5.1, each player prefers the CREE-Lindahl allocation to the Nash equilibrium allocation. The preference is strict for any player i with* $m_i^N > 0$ *and* $m_i^{CRE} < M^{CRE}$.

Proof. That each player (weakly) prefers the CREE-Lindahl allocation is obvious by noting that for each player i, the Nash bundle (M^N, m_i^N) corresponds to setting $M = 0, m_i = 0$ in the individual maximization problem in Problem (CRE), which trivially satisfies the constraints therein. In other words, $M = 0, m_i = 0$ is a candidate solution to the individual maximization problem, and therefore the value of the objective function at that candidate solution, or the utility at the Nash equilibrium, is no greater than the optimized value at $M = M^{CRE}$, $m_i = m_i^{CRE}$.

Now we show that player i strictly prefers the CREE-Lindahl allocation whenever $m_i^N > 0$ and $m_i^{CRE} < M^{CRE}$, by establishing the impossibility of (0,0) as the solution to the individual maximization problem in Problem (CRE). First, note that $m_i^N > 0$ implies that the individual maximization problem in Problem (Nash) has an interior solution, which implies in turn that the first order condition holds. That is, $V_i'(M^N) = C_i'(m_i^N)$. Now, in the individual maximization problem in Problem (CRE), since the individual constraint obviously binds, we substitute m_i/p_i^{CRE} for M in the objective function and effectively make the problem an unconstrained maximization problem. That problem will have a corner solution if and only if the first order derivative of the objective function with respect to m_i is no greater than zero at $M = 0, m_i = 0$. The first order derivative is $1/p_i^{CR} V_i'(m_i/p_i^{CR} + M^N) - C_i'(m_i + m_i^N)$. Evaluating that at $M = 0, m_i = 0$ gives $1/p_i^{CRE} V_i'(M^N) - C_i'(m_i^N) = (1/p_i^{CRE} - 1)V_i'(M^N) > 0$, because of the Nash first order condition and the fact that $p_i^{CRE} = m_i^{CRE}/M^{CRE} < 1$.

---

[11] The CREE-Lindahl degenerates to a Lindahl equilibrium if we take the Nash equilibrium allocation to be the starting point for the Lindahl process. They will also be equivalent if the players have identical preferences (e.g., have the same GNIs if it is nations, and that is the sole driving factor), hence are symmetrically situated, and we focus on the focal point solution at which all players contribute the same amount.

[12] In practice, as with many international agreements, reputational concerns or fear of sanctions make it more likely that nations will adhere to the CREE agreement after they sign to become part of it.

[13] He requires local-non-satiation for the public good, as is guaranteed in our context.

5.4.2. The Nash Bargaining path

The Nash Bargaining solution also provides an intuitively appealing way to proceed from the Nash equilibrium to the Pareto frontier while respecting cheap riding incentives. Proposed by Nash (1950), this formulation enjoys strong axiomatic support. Loosely speaking, a Nash Bargaining solution is a vector of payoffs that maximizes the product across all players of the gains over some disagreement point. In our context, the disagreement point is necessarily the Nash equilibrium.[14]

Formally, a *CREE-Nash Bargaining* is an allocation $(m_i^{CRE} + m_i^N)_{i \in \mathcal{N}}$ such that:

$$(m_i^{CRE})_{i \in \mathcal{N}} \in \arg \max_{(m_i)_{i \in \mathcal{N}}} \Pi_i \left[U_i\left(\sum_i m_i + M^N,\, m_i + m_i^N \right) - U_i(M^N, m_i^N) \right],$$

$$\text{subject to:} \quad U_i\left(\sum_i m_i + M^N,\, m_i + m_i^N \right) \geq U_i(M^N, m_i^N),$$

$$\forall\, i \in \mathcal{N},$$

where $(m_i^N)_{i \in \mathcal{N}}$ is a Nash equilibrium allocation and $M^N = \sum_{i \in \mathcal{N}} m_i^N$.

It is obvious that the CREE-Nash Bargaining is unique, Pareto optimal, and individually rational, under the conditions for existence and uniqueness of the Lindahl equilibrium.

Interestingly, in our numerical example, though the parameter values were not chosen for this purpose, the CREE-Lindahl allocation is remarkably close to the CREE-Nash Bargaining allocation. In fact, they differ by less than 0.4%: the (unique) CREE-Nash Bargaining has the nations contribute (0.251,0.123) in addition to Nash contributions, resulting in the total contributions (1.623,0.209), and net payoffs (− 0.213,0.431), respectively. Future work should determine what degree of closeness applies for other utility functions and other parameter values.

5.5. Summary of the numerical example

Table 3 and Fig. 1 summarize our results. To recap, the Nash equilibrium reflects the incentive to ride cheaply, but it is far from Pareto optimal. The Lindahl equilibrium, which is identical to the Supply-Demand Arrangement, achieves one of the Pareto optimal allocations, but it does not reflect the cheap-riding incentive. Thus, small-interest players are likely to balk at this solution. Indeed, for some parameter values, there will be one player (and possibly more) who is strictly worse off at the Lindahl equilibrium. Such a player would simply hold out for the Nash equilibrium. The CREE-Nash Bargaining and the CREE-Lindahl, however, both achieve Pareto optimality and both respect the cheap-riding incentive, while enjoying intuitive appeal.

It should be noted that our CREE solutions achieve Pareto efficiency, subject to the constraint that each nation produces its own reductions. Thus, at a CREE formulated with in-kind contributions, such as GHG reductions, it is not possible to reallocate the contributions to increase the welfare of one nation without hurting another. However, they do not achieve *production* efficiency unless one of three conditions holds: 1. The marginal costs of reductions are the same across nations in the relevant range. 2. Nations can buy offsets from other nations to help fulfill their reduction goals. 3. The contributions are made in cash, after which the cash is used to purchase the cheapest available reductions wherever available.

6. Conclusion

The sum of voluntarily pledged GHG reduction pledges from individual nations in the Paris Agreement is woefully below what will be required to hold global warming by 2100 below 1.5–2 °C as compared to pre-industrial times. This outcome reflects nations' powerful cheap-riding incentives, particularly nations that have lesser interest because of smaller GNIs or more modest historical emissions of GHGs. Hence, the voluntary pledge approach to the provision of global public goods is unlikely to come close to producing an efficient level of total contributions.

This analysis shows that the solution to global climate change must recognize the differential bargaining power of nations, where those receiving greater benefits, tangible and intangible, must contribute more than in proportion to their benefit levels. For many important public goods, including those provided by nonprofit organizations and collections of nations, there is no central authority to both provide the good and levy the exactions to pay for it. Negotiating to efficiency is conceivable when players are symmetrically situated. However, achieving an efficient level of provision with players whose circumstances differ substantially, as is the case with global public goods, encounters the challenge of nations' substantially different strengths of interest, implying greatly differing incentives to ride cheaply.

Our CREE solution explicitly takes account of strength of preference to define a significant starting point, the Nash equilibrium. It then moves by general agreement to a much greater level of reductions. Two principles for structuring such movements are considered, the Lindahl equilibrium and the Nash Bargaining solution. Each enables the players to reach the Pareto frontier. Hence, the mechanism respects uneven cheap-riding incentives, yet still achieves Pareto optimality. Interestingly, in the numerical example considered, the Lindahl and Nash Bargaining paths produce extremely similar results.

There would be many complications in the implementation of CREE to control climate change. Equity is not served when we rely on strength of preference. Side-payments may be necessary to improve production efficiency. Additional mechanisms might be needed to make sure nations stick to the CREE plan, once they have agreed to it. But the overarching lesson is that it is necessary to have an agreement that incorporates two competing objectives, catering to the unequal bargaining power of those with intense and moderate preferences, and having all players contribute proportional to their preferences. CREE strikes the appropriate balance, and achieves an outcome where all benefit significantly, and none would be better off at the Nash outcome. It also follows comprehensible, logical, and justifiable principles.

As citizens of the two nations that lead the world in level of GNI and historical GHG emissions, we recognize that our work here (inadvertently) reveals the weak bargaining positions of our homelands.[15] It seems inevitable that they will have to bear a disproportionate share of the burden if there is to be an effective agreement to arrest climate change through significant reductions in GHG emissions. The leaders of our homelands, one current and the other former, seem to have grasped this when, as early as in November 2014 and then again months before the Paris Conference, they issued two U.S.-China Joint Announcements on Climate Change outlining their ambitions and commitments. Implicitly, these announcements simultaneously recognized the inevitable inadequacies of any agreement that might result should they, the

---

[14] From the literature, it does not appear that the disagreement point in a Nash Bargaining formulation should automatically be a Nash equilibrium, either in our context specifically or in general. Nash (1950) does not make this point. In teaching Nash Bargaining, the disagreement value is typically taken to be zero or left unspecified. In applied work, the choice of the disagreement point depends on the specific context. (See, for example, Horn and Wolinsky, 1988.) We emphasize that the Nash equilibrium (rather than zero payoffs or any other consequence of disagreement) is necessarily the disagreement point in our global public goods provision context. This is because the Nash equilibrium, importantly, recognizes the cheap-riding incentive of small players, the jumping off point of this paper.

[15] The European Union, which consists of 28 countries, made a unified pledge. Together, the Union's GNI puts it in first place, slightly ahead of the United States. Its historical emissions would come second, moderately ahead of China.

Table 3
Allocations at various solutions in our example.

	Large's contribution	Small's contribution	Total contribution	Large's payoff	Small's payoff
Nash equilibrium	1.372	0.086	1.458	−0.375	0.347
Lindahl equilibrium/SDA	1.414	0.354	1.768	0.279	0.070
CREE-Nash Bargaining	1.623	0.209	1.832	−0.213	0.431
CREE-Lindahl	1.624	0.209	1.833	−0.215	0.432

Notes. The large nation is four times as large as the small nation; the utility functions are $U_1 = 4\log(M) - m_1^2$ and $U_2 = \log(M) - 4m_2^2$, respectively.

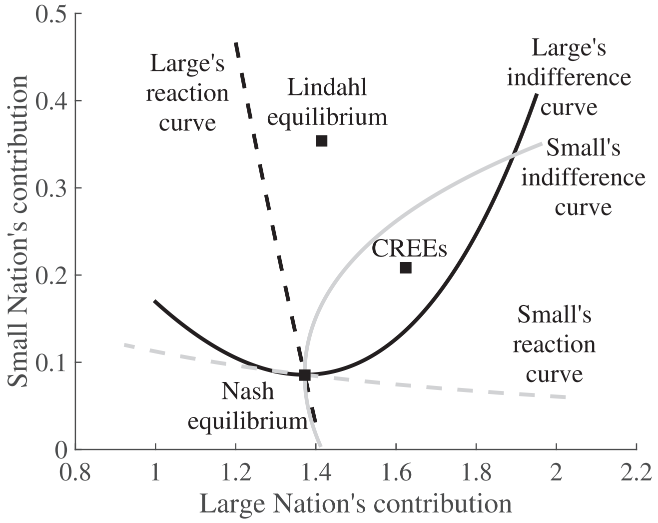

Fig. 1. Allocations at various solutions in our example. Notes. The CREEs include the CREE-Nash Bargaining and the CREE-Lindahl, which differ by less than 0.4% in our example. The large nation is four times as large as the small nation; the utility functions are $U_1 = 4\log(M) - m_1^2$ and $U_2 = \log(M) - 4m_2^2$, respectively.

biggest-interest players, insist on proportional burden sharing. This hinted at the ultimate potential for "agreed riding," a forceful, albeit unbalanced, agreement that respects the bargaining strength of smaller-interest nations.

Appendix A. Technical details of Section 3

We collected all the INDCs that had been submitted to the UNFCCC submission portal[16] by December 5, 2015, a total of 158 INDCs. Despite the cut off date for our data collection effort being earlier than the Paris Conference, we only miss 3 INDCs. Of the 158 INDCs, 23% are percentage reductions from historical emissions levels, 44% are percentage reductions from BAU emission forecasts, a couple involve reductions on a per capita or per dollar of GDP basis, and the rest do not include any specific numbers in their submitted pledge. We focus on unconditional reductions, as opposed to conditional reductions, to be consistent with the voluntary nature of our global public good provision model. Some nations did not submit their INDCs.

We use carbon emissions despite the fact that many pledges are in terms of GHG emissions. The reason is that the historical data on individual nations' GHG emissions are very limited. We hence trade off the match with the pledges for the accuracy of forecasts, and assume that the reduction in carbon emissions will be proportional to that in GHG emissions.

To convert the reduction goals in the INDCs to an absolute amount of reduction, we need to know the BAU emissions. For the three big emitters, China, the U.S., and the EU-28, there are existing analyses that assess the fine details of the emission determinants. We simply take their BAU emission forecasts. Energy Research Institute (2009) predicts that China's BAU emissions will be around 12,500 million tons in 2030.[17] The United States Department of State (2015) synthesizes multiple data sources and predicts the U.S. BAU carbon emissions to be 5,705 million tons in 2025. Barbu (2015) predicts that the EU-28's BAU GHG emissions in 2030 will be 27% lower than the 1990 level.

For the rest, we use nation-wise auto-regression models to forecast their BAU emissions in 2030, drawing upon (Aldy et al., 2017). We choose nation-wise auto-regression models because we find that they achieve a much smaller mean squared forecasting error of the aggregate carbon emissions on the last five years of available data, than other major carbon forecasting models, including Holtz-Eakin and Selden (1995), Schmalensee et al. (1998), and Auffhammer and Steinhauser (2012). Specifically, we regress the current log per capita carbon emission on the previous-year log per capita carbon emission, log population density, log per capita GDP, and a linear time trend, using data up to 2012, the last year for which the carbon emissions data are available from the CAIT Climate Data Explorer (World Resources Institute, 2015). We employ the estimated coefficients to forecast each nation's 2030 carbon emission by relying on the population and GDP forecasts in United States Department of Agriculture (2015), and then iteratively use the prior year's carbon emission forecasts. We then calculate the absolute amount of reduction from the 2030 BAU emissions that

---

[16] Available at http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

[17] For readers concerned about strategic over-reporting by the Chinese government, that forecast is within the range of 8000–18, 000 million tons of energy-related BAU emissions generated by 12 engineering or general-equilibrium modeling platforms reviewed in Grubb et al. (2015). It is also below what our auto-regression model would have predicted.

the pledges represent.[18] The carbon emissions that we use do not include land use, land-use change, and forestry activities emissions, which is consistent with the practice of most pledges. For nations that submitted pledges with reduction goals, the reduction is calculated by taking the difference between our BAU emission estimates and the emission target indicated or implied in each individual INDC.

To nations that submitted pledges without a reduction goal, we assign a more negative normalized reduction (hence one that is less likely to bind) than that of the most non-binding pledge we have estimated; we treat those nations as less generous than those which state explicit reduction goals in their INDCs. For nations that did not submit a pledge at all, we assign an even more negative normalized reduction; we treat them as the least willing to abate.

We also collect data on nations' climate vulnerability, pollution level, and measures of environmental concerns. The vulnerability measures include the percentages of urban and rural population living in coastal areas where elevation is below 10 m (Center for International Earth Science Information Network (CIESIN)/Columbia University, 2013), historical annual average temperature, and the percentage of population subject to drought, flood, and extreme temperature events. The pollution measures include energy use from fossil fuels, NO_x emission, and PM 2.5 concentration. We construct the per capita GNI by dividing GNI by population. These data, except otherwise noted, are all from World Bank (2016). We identify environmental concern measures by the percentage of subjects in World Values Survey Association (2016) who respond positively to environment-related questions on active membership in environmental organizations, importance of looking after the environment, protection of environment over economic growth, participation in environmental demonstration for the past two years, and confidence in environmental organizations. Data are available upon request.

Appendix B. Supply-demand arrangement

We provide an alternative, intuitive way of thinking about the Lindahl equilibrium, the Supply-Demand Arrangement. Each individual has an amount s/he would like to contribute, if his or her supply will be matched by a total of contributions from others n times as large. This matching ratio can also be thought of as the inverse of the price of the total contributions from others s/he demands (the price of his or her contribution is normalized to 1). The higher the matching ratio, the lower the price of total contributions from others. Under a Supply-Demand Arrangement, the vector of the prices that each individual faces is such that for each individual, the demand is exactly fulfilled by the total supply of all others.

Formally, a Supply-Demand Arrangement consists of individualized prices for the public good provided by others, $(p_{-i}^{SD})_{i\in\mathscr{N}}$ (the superscript SD stands for Supply-Demand), a private good price, which we normalize to 1, and an allocation $(m_i^{SD})_{i\in\mathscr{N}}$. That allocation is such that for each $i \in \mathscr{N}$:

$$(m_i^{SD}, M_{-i}^{SD}) \in \arg\max_{m_i, M_{-i}} U_i(m_i + M_{-i}, m_i),$$

$$\text{subject to:} \quad p_{-i}^{SD} M_{-i} \le m_i, \qquad SD$$

and the market clears:

$$M_{-i}^{SD} = \sum_{j\neq i} m_j^{SD}, \text{ for each} i.$$

The next proposition establishes the equivalence between the Lindahl equilibrium and the Supply-Demand Arrangement.

Proposition B.1. *A Supply-Demand Arrangement allocation is identical to a Lindahl equilibrium allocation.*

Proof. Given a Supply-Demand Arrangement $((p_i^{SD})_{i\in\mathscr{N}}, (m_i^{SD})_{i\in\mathscr{N}})$, for each i, let

$$M = m_i^{SD} + M_{-i}^{SD}, \qquad p_i = \frac{p_{-i}^{SD}}{1 + p_{-i}^{SD}}.$$

Then for each i, (m_i^{SD}, M) solves i's Problem (*Lindahl*) with price p_i. The identity from Lindahl to Supply-Demand Arrangement can be similarly established.

References

Abul Naga, R.H., Jones, P., 2012. Better to give than to receive? Altruistic provision of a global public good. Econ. Lett. 115 (3), 480–483. http://linkinghub.elsevier.com/retrieve/pii/S0165176511006318http://dx.doi.org/10.1016/j.econlet.2011.12.108.

Aldy, J.E., Chen, C., Pizer, W.A., 2017. Evaluating the Paris Agreement Mitigation Pledges With Statistical Forecasting Models. Harvard Kennedy School Working Paper.

Arce, M.D.G. , Sandler, T., 2001. Transnational public goods: strategies and institutions. Eur. J. Polit. Econ. 17, 493–516. http://dx.doi.org/10.1016/S0176-2680(01)00042-8.

Auffhammer, M., Steinhauser, R., 2012. Forecasting the path of U.S. CO_2 emissions using state level information. Rev. Econ. Stat. 94, 172–185.

Barbu, A.-D., 2015. Trends and Projections in Europe 2015 Tracking Progress Towards Europe's Climate and Energy Targets. EEA Report No 4/2015.

Barrett, S., 1990. The problem of global environmental protection. Oxf. Rev. Econ. Policy 6, 68–79.

Barrett, S., 1994. Self-enforcing international environmental agreements. Oxf. Econ. Pap. 46, 878–894. http://www.jstor.org/stable/2663505http://dx.doi.org/10.1017/CBO9781107415324.004.

Bergstrom, T., 1973. On Efficient Provision of Social Overhead Goods. Yearbook of East European Economics. 4.

Boadway, R., Hayashi, M., 1999. Country size and the voluntary provision of international public goods. Eur. J. Polit. Econ. 15, 619–638. http://dx.doi.org/10.1016/S0176-2680(99)00029-4.

Boadway, R., Song, Z., Tremblay, J.F., 2011. The efficiency of voluntary pollution abatement when countries can commit. Eur. J. Polit. Econ. 27, 352–368. http://dx.doi.org/10.1016/j.ejpoleco.2010.10.003.

Buchholz, W., Cornes, R., Peters, W., 2006. Lindahl vs. Cournot Nash: the role of the income distribution. Public Finance Analysis 62, 28–49.

Buchholz, W., Cornes, R., Peters, W., 2008. Existence, uniqueness and some comparative statics for ratio and Lindahl equilibria. J. Econ. 95, 167–177. http://dx.doi.org/10.1007/s00712-008-0024-0.

Buchholz, W., Cornes, R., Rübbelke, D., 2011. Interior matching equilibria in a public good economy: an aggregative game approach. J. Public Econ. 95, 639–645. http://dx.doi.org/10.1016/j.jpubeco.2010.12.010.

Buchholz, W., Cornes, R., Rübbelke, D., 2014. Potentially harmful international cooperation on global public good provision. Economica 81, 205–223.

Callander, S., Harstad, B., 2015. Experimentation in federal systems. Q. J. Econ. 130 (2), 951–1002. http://dx.doi.org/10.1093/qje/qjv008.Advance.

Center for International Earth Science Information Network (CIESIN)/Columbia University, 2013. Low Elevation Coastal Zone: Urban-Rural Population and Land Area Estimates, Version 2. http://sedac.ciesin.columbia.edu/data/set/lecz-urban-rural-population-land-area-estimates-v2.

Cornes, R., Hartley, R., 2007. Aggregative public good games. J. Public Econ. Theory 9, 201–219. http://dx.doi.org/10.1111/j.1467-9779.2007.00304.x.

---

[18] Calculations are available from the authors.

Cornes, R., Sandler, T., 1984. The theory of public goods: non-Nash behaviour. J. Public Econ. 23, 367–379. http://dx.doi.org/10.1016/0047-2727(84)90036-7.

Institute, Energy Research, 2009. 2050 China Energy and CO2 Emissions Report (CEACER). Beijing: Science Press, 2009.

European Commission, 2017. Paris Agreement. http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm.

Falkinger, J., Hackl, F., Pruckner, G.J., 1996. A fair mechanism for efficient reduction of global CO-emissions. Public Finance Analaysis 53, 308–331.

Gerber, A., Wichardt, P.C., 2009. Providing public goods in the absence of strong institutions. J. Public Econ. 93, 429–439. http://dx.doi.org/10.1016/j.jpubeco.2008.10.006.

Griffin, J.M., Xiong, W., 1997. The incentive to cheat: an empirical analysis of OPEC. J. Law Econ. 40, 289–316. http://www.jstor.org/stable/10.1086/467374%5Cnhttp://www.jstor.org/stable/10.1086/467374http://dx.doi.org/10.1086/467374.

Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z., Agnolucci, P., 2015. A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy. Clim. Pol. 15, 7–39. http://www.tandfonline.com/doi/full/10.1080/14693062.2015.1101307http://dx.doi.org/10.1080/14693062.2015.1101307.

Heitzig, J., Lessmann, K., Zou, Y., 2011. Self-enforcing strategies to deter free-riding in the climate change mitigation game and other repeated public good games. Proc. Natl. Acad. Sci. 108, 15739–15744. http://www.pnas.org/content/108/38/15739.abstracthttp://dx.doi.org/10.1073/pnas.1106265108.

Hennigan, W., Bennett, B., 2016. U.S. to Urge Partners to Do More to Fight Islamic State amid Complaints from Pentagon. Los Angeles Times.

Hohne, N., Blok, K., Jeffery, L., Rocha, M., 2015. Paris Agreement: Near-Term Actions Do Not Match Long Term Purpose, But State Is Set to Ramp up Climate Action. Climate Action Tracker Statement.

Holtz-Eakin, D., Selden, T.M., 1995. Stoking the fires? CO2 emissions and economic growth. J. Public Econ. 57, 85–101. http://www.sciencedirect.com/science/article/pii/004727279401449Xhttp://dx.doi.org/10.1016/0047-2727(94)01449-X.

Horn, H., Wolinsky, A., 1988. Bilateral monopolies and incentives for merger. RAND J. Econ. 19, 408–419.

Isaac, R.M., Walker, J.M., 1988. Group size effects in public goods provision: the voluntary contributions mechanism. Q. J. Econ. 103, 179–199. http://dx.doi.org/10.1017/CBO9781107415324.004. arXiv:arXiv:1011.1669v3.

Kahn, M.E., Matsusaka, J., 1997. Demand for environmental goods: evidence from voting patterns on California initiatives. J. Law Econ. 40, 137–174.

Kolstad, C.D., 2007. Systematic uncertainty in self-enforcing international environmental agreements. J. Environ. Econ. Manag. 53, 68–79. http://dx.doi.org/10.1016/j.jeem.2006.08.001.

Lindahl, E., 1958. Just Taxation: A Positive Solution. In: Musgrave, R., Peacock, A. (Eds.), Classics in the Theory of Public Finance. Macmillan, London, pp. 98–123.

Nash, J.F., 1950. The bargaining problem. Econometrica 18, 155–162.

Nordhaus, W., 2015. Climate clubs: overcoming free-riding in international climate policy. Am. Econ. Rev. 105, 1339–1370.

Olson, M., 1965. The Logic of Collective Action: Public Goods and the Theory of Groups. Schocken Books, New York.

Olson, M.J., Zeckhauser, R., 1966. An economic theory of alliances. Rev. Econ. Stat. 48, 266–279.

Schelling, T., 1960. The Strategy of Conflict. Harvard University Press, Cambridge.

Schmalensee, R., Stoker, T.M., Judson, R.A., 1998. World carbon dioxide emissions: 1950–2050. Rev. Econ. Stat. 80, 15–27. http://ideas.repec.org/a/tpr/restat/v80y1998i1p15-27.htmlhttp://dx.doi.org/10.1162/003465398557294.

Shitovitz, B., Spiegel, M., 1998. Cournot Nash and Lindahl equilibria in pure public good economies. J. Econ. Theory 83, 1–18.

Sugden, R., 1985. Consistent conjectures and voluntary contributions to public goods: why the conventional theory does not work. J. Pub. Econ. 27, 117–124. http://dx.doi.org/10.1016/0047-2727(85)90032-5.

United States Department of Agriculture, 2015. The International Macroeconomic Data Set. http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx.

United States Department of State, 2015. The United States Climate Action Report 2014.

Warr, P.G., 1983. The private provision of a public good is independent of the distribution of income. Econ. Lett. 13, 207–211. http://dx.doi.org/10.1016/0165-1765(83)90087-3.

World Bank, 2016. World Development Indicators. http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators.

World Resources Institute, 2015. CAIT Climate Data Explorers. http://cait.wri.org.

World Values Survey Association, 2016. World Values Survey Wave 6 (2010–2014), Official Aggregate v.20150418. Aggregate File Producer: Asep/JDS, Madrid Spain.