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Burden Sharing Under the Paris Climate Agreement

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By GLENN SHERIFF [*]

Two decades after creation of the UN Framework Convention on Climate Change (UNFCCC), parties have reached a general political consensus in support of reducing global greenhouse gas (GHG) emissions, but debate continues over how to share equitably the burden of mitigation across countries. As part of the December 2015 Paris Agreement, countries submitted Nationally Determined Contributions (NDCs) for GHG mitigation. I analyze these mitigation targets to evaluate the degree to which they resemble any specific burden-sharing proposals. Results could have several applications as the UNFCCC process continues, including simulating how mitigation commitments may evolve as countries become wealthier and considering how increased ambition might be allocated while maintaining the current implicit burden-sharing allocation.

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Coordinating action among potential beneficiaries is a key obstacle to achieving a global target of global greenhouse gas (GHG) emissions. From its inception in 1992, the UN Framework Convention on Climate Change (UNFCCC) has recognized "common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" for GHG reduction. In the ensuing years, a large literature has emerged discussing alternative ethical frameworks for making this concept operational.

The 1997 Kyoto Protocol used a two-track allocation scheme in which developing countries had no mitigation requirements and the UNFCCC allocated GHG reductions to developed (Annex 1) countries. By the time the Kyoto Protocol's first commitment period ended in 2012, this bifurcation of responsibilities between developed and developing countries was no longer politically tenable. Prominent Annex 1 countries including the United States and Canada either did not ratify the treaty or pulled out, due in part to the perception that the effectiveness of costly mitigation action was undermined by the possibility of large scale emissions increases in developing countries. Meanwhile, projections of strong emissions growth in developing countries such as China and India made it clear that even elimination of emissions from Annex 1 countries would be insufficient for reducing the risk of catastrophic climate damage to an acceptable range.

In contrast, the 2015 Paris Agreement sidestepped the issue by avoiding a centrally-determined allocation. Although the UNFCCC maintained the goal of an emissions trajectory consistent with a 50 percent chance of keeping average temperature change below 2°C in 2100 (the two-degree target), there was no centralized arrangement to allocate emissions reductions to attain that goal, or even to establish an aggregate emissions level for 2030. Instead, parties were requested to propose "Nationally Determined Contributions" (NDCs) to GHG mitigation based on national circumstances.

Apart from reaffirming the principle of common but differentiated responsibilities, the Paris Agreement did not make explicit reference to a specific ethical foundation for allocating emissions reductions. Nonetheless, the distribution of national contributions to GHG reduction might be viewed as reflecting an implicit ethical framework. That is, from an economic welfare perspective it makes little difference ex post whether countries achieve targets set for themselves versus attaining targets of equivalent stringency allocated centrally by the UNFCCC according to an explicit distributional formula.

A large literature evaluates implications of alternative burden sharing arrangements.[1] The standard approach begins with a pre-determined carbon budget, typically derived from the 2°C target. It then posits one or more allocation mechanisms and models implications for various countries or regions.

The analysis developed here takes the opposite approach. I use the actual distribution of NDC mitigation targets to identify a target and set of burden-sharing arrangements with which it is consistent. That is, I start by assuming that countries chose their targets *as if* they were following a shared unobserved ethical allocation mechanism, then empirically derive what that mechanism might be. The goal is to identify how "common but differentiated responsibility" might be operationalized as a function of observable country characteristics such as population, GDP, emissions, fossil fuel dependence, etc.[2]

Global GHG mitigation implied by the sum of Paris NDCs is not expected to achieve the 2°C target (UNFCCC, 2016). Rather, it is hoped that parties will undergo periodic stock-taking exercises to add further ambition to their mitigation targets. It is an open question whether the Paris bottom-up model of voluntary NDCs will prove sufficient to reach the target in future stock-takes.

If not, there may be an interest in a burden-sharing arrangement at the global level. Equity can serve as an important focal point in discussions and reduce negotiation costs (Lange, Vogt, and Ziegler, 2007; Bretschger, 2013). Ringius, Torvanger, and Underdal (2002) argue that a necessary condition for incorporating fairness into a global burden-sharing arrangement is that a "critical mass of actors must ... subscribe to the same norms." A key question in this regard is which principles belong in the core of widely accepted norms, and how they might be used derive "explicitly specified functions that generate a specific scheme of obligations when fed with appropriate input data." The analysis conducted here may provide a first step in identifying potentially relevant data

[1] For a recent review, see Höhne, Den Elzen, and Escalante (2014).

[2] This approach of inferring an equity framework from the outcome of the negotiating process is similar in spirit to the endogenous "sovereign bargaining" equity principle discussed in Cazorla and Toman (2001).

and functional specifications.[3]

This type of analysis could also have several potential applications as the UNFCCC process continues. Holding the estimated ditributional formula fixed, one could simulate how mitigation commitments may evolve over time as country circumstances (e.g., per capita income) change. One could also calculate how parameters could be calibrated to achieve a more ambitious global mitigation target, while preserving the distributional preference structure embodied in the functional form.

Finally, Aldy and Pizer (2016) have identified a need for metrics to evaluate mitigation efforts across countries. They discuss how a metric based solely on emission reductions relative to a historic baseline has the advantages of being easily measured, replicated, and applied to a wide range of countries, but fails to deliver a comprehensive measure of mitigation cost due to its failure to account for differing country circumstances. The framework developed here could potentially serve as an alternative measure that has the advantages of a metric based on simple emissions reductions yet incorporates other observable country characteristics that may better reflect effort. It could thus facilitate cross-country comparisons of mitigation targets going forward.

The analysis proceeds in several steps. Section 1 provides a brief overview of prominent ethical frameworks for allocating GHG reductions. The next sections describe how to use the information presented in NDCs to identify an implicit burden allocation mechanism: Section 2 describes the methodology used to convert NDC targets into a common metric to enable cross-country comparisons and Section 3 discusses a series of econometric tests to see which theoretical allocation mechanisms are consistent with the observed distribution of mitigation targets. The main result of Section 3 is an empirically-derived function mapping country characteristics into GHG mitigation targets. Section 4 proposes a theoretical underpinning for this function, showing how it is consistent with an allocation mechanism used by a central planner wishing to impose an equal marginal *utility* cost of mitigation action across countries. As such it has two key

[3] For other considerations in assessing a global climate policy framework see, for example, Aldy, Barrett, and Stavins (2003).

components: a parameter that determines how a country's target changes as it becomes better off (wealthier), and a parameter that determines the global level of mitigation ambition. Section 5 conducts simulations illustrating how these results may be used to inform future international action on climate change. Section 6 concludes.

I. Burden sharing arrangements

The literature discusses many potential arrangements for allocating GHG mitigation action across countries.[4] Here, I focus on allocations that do not allow for emissions trading or other forms of compensation.[5] To make the econometric analysis as transparent and replicable as possible, I do not evaluate allocation metrics that rely on data generated by modeling (e.g., marginal abatement cost curves).[6] Instead, I restrict attention to distributional frameworks that are simple functions of publicly available data.

I begin by identifying arrangements prominently discussed in the literature and identifying key variables that each would require to determine a country's contributions. The first burden sharing scheme considered, often referred to as the Brazilian Proposal, is based on a country's *responsibility* for climate change and is consistent with the polluter pays principle. It advocates that a country's GHG mitigation responsibility should be a function of its contribution to the problem.[7] Since the global warming impact of GHGs depends on the cumulative stockpile, this approach argues that cumulative emissions could serve as a proxy for a country's responsibility. There is considerable uncertainty involved in this choice of metric including data sources for historic emissions, modeled impact of emissions from a given year on warming, when warming is modeled to occur, treatment of land use and non CO_2 GHGs, and start date.[8] Here, I use historical emissions data beginning in 1970 and divide it by 2010 population to construct cumulative emissions per capita.

[4]For a recent review, see Mattoo and Subramanian (2012).

[5]In such cases the distribution of the burden is distinct from the distribution of mitigation action.

[6]Allocations using model-based approaches can be highly sensitive to time frames, parameters, variables, and methods (Cazorla and Toman, 2001; Aldy, Barrett, and Stavins, 2003).

[7]See Den Elzen, Schaeffer, and Lucas (2005) for an example of this approach.

[8]For a detailed discussion of uncertainty involved in calculating country contributions to warming see Höhne et al. (2011).

Let $\tilde{e}_i$ denote the 2030 emissions target of country $i \in [1,2,...,I]$. To develop a comparable measure of mitigation contributions across countries I evaluate the ratio of target emissions to baseline emissions e_i.[9] If countries base targets on historic responsibility the ratio of target to baseline emissions $\tilde{e}_i/e_i$ would be a decreasing function of cumulative emissions per capita.

The second, *equality*, approach is based on the notion that each human should have an equal claim to the common resource of the planet's ability to absorb GHG emissions. A burden-sharing arrangement based on equality would specify $\tilde{e}_i/e_i$ as an decreasing function of current per capita GHG emissions.

The third, *capability*, approach is based on a country's ability to incur the cost of mitigation action. Under this ethical framework, $\tilde{e}_i/e_i$ should be decreasing in a country's wealth or stage of development.[10] Here 2010 GDP per capita measured at purchasing power parity serves as a proxy for capability.

In addition to these three main factors commonly used in equity analysis (e.g., Rocha et al., 2015), I consider other country characteristics which may affect emissions targets: projected GDP growth, projected population growth, recent change in emissions intensity (CO_2e emissions per GDP), oil reserves per capita, oil rents as a percent of GDP, forest cover as percent of total land area, fossil fuel percent of energy consumption, life expectancy, and a dummy for small island developing states as a proxy for vulnerability.[11]

The final equity notion considered, *sovereignty*, is based on the argument that all countries should be treated equally regardless of national circumstances. Under this arrangement, the baseline distribution of emissions would be preserved with each country having the same proportional reduction. This approach would favor countries that are currently large emitters since it effectively grandfathers the right to emit (Cazorla and Toman, 2001). In contrast, developing countries that have relatively few current

[9]Baseline can be defined in various ways, e.g., relative to a particular historic base year or a future BAU projection. As described below, for this analysis I convert each country's base year to 2010 emissions.

[10]See, for example Cazorla and Toman (2001) and Baer et al. (2008).

[11]Countries have proposed many of these criteria as a basis for burden sharing (Torvanger and Godal, 1999).

emissions are not allowed future growth. Empirically, one might conclude that the distribution of emissions targets is consistent with a sovereignty approach if deviations from the mean reduction are only attributable to random noise, i.e., no observable country characteristics are significant predictors of $\tilde{e}_i/e_i$.

II. Data

In addition to the NDCs published on the UNFCCC website,[12] data come from the following sources. Historic emissions come from the World Resource Institute's Climate Analysis Indicators Tool (CAIT).[13] Current and projected GDP come from the International Monetary Fund's 2015 World Economic Outlook.[14] Current and projected population come from the United Nations World Population Prospects.[15] Other country characteristics (oil reserves, oil rents, forest cover, fossil fuel consumption) come from the World Bank's 2015 World Development Indicators.[16]

As illustrated in Figure 1, countries took several different approaches to expressing NDCs. Most Annex 1 parties chose to express national-level emissions targets relative to a specific base year, typically 1990 or 2005. Non-Annex 1 parties took a variety of approaches including reductions in total emissions relative to a base year, total emissions relative to a business-as-usual (BAU) projection, emissions per capita, or the ratio of emissions to GDP. Some countries instead chose to submit sector-specific targets (e.g., emissions reductions in transportation), mitigation actions without quantified GHG reductions, or emissions trajectories (e.g., a year in which emissions would peak). Moreover, many non-Annex 1 countries provided targets conditional on international support, either alone or in addition to an unconditional target. The analysis here focuses exclusively on parties that submitted quantifiable unconditional NDCs.[17] Here, quantifiable means that the NDC target can be converted to an absolute quantity of GHG

[12] `www4.unfccc.int/submissions/indc/Submission\%20Pages/submissions.aspx`
[13] `cait.wri.org`
[14] `www.imf.org/external/pubs/ft/weo/2015/02/weodata/index.aspx`
[15] `esa.un.org/unpd/wpp/Download/Standard/Population`
[16] `data.worldbank.org/data-catalog/world-development-indicators`
[17] I treat the 28 member countries of the European Union as a single party.

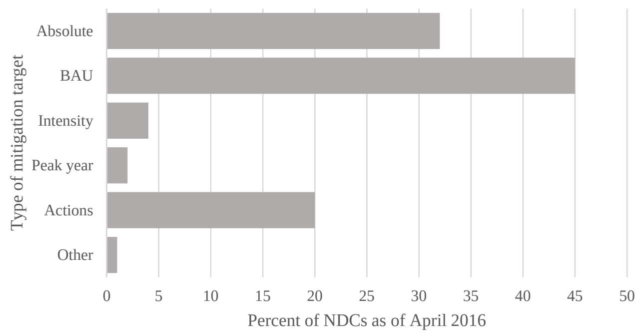

Figure 1. Type of mitigation target in Nationally Determined Contribution as percent of total submitted

Source: UNFCCC (2016)

emissions as described below.

Due to the complex array of mitigation targets, the first step in the empirical analysis is to convert unconditional NDC targets into a common format: 2030 target emissions in $MtCO_2e$ relative to emissions recorded in CAIT for 2010.[18] For the small number of countries that express a target for a year earlier than 2030, I assume annual emissions to be constant through 2030. For countries that communicate a range of emissions reductions, I use the lower bound (i.e., smallest reduction).

Country emission inventories can use different conventions regarding conversion of non-CO_2 GHGs to CO_2e, accounting for land use, land use change and forestry, etc. With the implicit assumption that total emissions reported by different accounting standards should be roughly proportional in different years, I scale reported emissions to CAIT values reported for the reference year to reduce the potential for the historical comparison

[18] Although the choice of baseline is inherently arbitrary, 2010 is a recent year for which countries would have had access to data when developing their NDCs. For an analysis of the impact of base year on the apparent stringency of emissions targets in the context of the Copenhagen Agreement, see McKibbin, Morris, and Wilcoxen (2011).

to reflect changes in accounting methods between official emissions estimates and CAIT, rather than changes in actual emissions.

I used the following approach to convert NDC mitigation targets to a common metric. For NDC targets expressed relative to:

- historical base year (21 parties)

    1. Using CAIT CO_2e historical emissions data, calculate implied target CO2e emissions for 2030. For example, if the target is a 20% reduction relative to 2005, 2030 emissions would be .8*2005 emissions.
    2. Calculate the ratio of the result of step 1 to 2010 CAIT emissions.

- projected 2030 BAU (36 parties)

    1. If NDC includes a value for 2030 BAU, target emissions were calculated on basis of this projection.
    2. If NDC does not contain a BAU projection, Climate Action Tracker current policy projections, if available, were used to determine 2030 BAU.[19]
    3. If NDC contains emissions data for reference year, 2030 target emissions were adjusted by the ratio of the NDC reference year to the CAIT entry for the same year.
    4. Calculate the ratio of the result of steps 2 or 3 to 2010 CAIT emissions.

- GHG/GDP intensity ratio, emissions per capita, or peak years (8 parties)

    1. If NDC contained relevant information, convert target to either base year or BAU projection as above.
    2. Otherwise use data, e.g., 2030 GDP projections, from other official sources to convert target to base year or BAU projection.

[19] `climateactiontracker.org`

Table 1— Summary Statistics

	Mean	Std. Dev.	Min.	Max.	N
2030/2010 emissions	1.6	0.9	0.5	4.6	65
2010 GDP/capita (thousand PPP)	15	15.9	0.8	70.6	65
2010 GHG emissions/capita (tCO2e)	6.7	6.5	0.3	34.6	65
1970-2010 GHG emissions/capita (tCO2e)	120.8	119	5.7	512.8	65
2030/2010 GDP	1.7	0.3	1.2	2.4	65
2010 GDP (billion PPP)	1172.7	3174.9	0.2	16844.3	65
2030/2010 population	1.3	0.3	0.9	2.3	65
2010 population density (thousand/km2)	0.2	0.9	0	7.2	65
2012/2010 tCO2e/GDP	1.7	9.4	0	75.8	65
2014 oil reserves/capita (thousand bbl)	0.2	0.7	0	5.1	65
Oil rent/GDP (percent)	4.7	10.2	0	45.5	65
Fossil fuel per total energy (percent)	70.5	24.8	17.5	100	54
Missing fossil fuel (dummy)	0.2	0.4	0	1	65
Forest cover (percent)	25.9	20.2	0	69.2	65
Life expectancy (years)	69.6	9.9	46.4	82.8	65

Another 12 parties expressed unconditional economy-wide targets that were not quantifiable using these methods (primarily due to lack of BAU projections or historic emissions data).

Table 1 presents summary statistics for the 65 countries with quantifiable targets.[20] Aggregate 2030 emissions targets for the quantifiable unconditional NDC targets calculated here are about 16 percent above their aggregate 2010 emissions. It is reassuring that this change in emissions is similar to that calculated by (UNFCCC, 2016). Although the UNFCCC does not report estimated emissions for individual countries, it estimates global emissions with unconditional mitigation contributions for all parties to be between 13 and 23 percent higher than 2010.[21]

III. Empirical approach

The method for determining the importance of a particular country characteristic to a country's mitigation target is cross-sectional regression. Ideally, one would like to control for all possible characteristics simultaneously to identify their impact. However, due to

[20]Only 54 of the countries with quantifiable targets have data for "Fossil fuel per total energy." To include all 65 in the regressions, I replace missing values with zeros and introduce a dummy variable, "Missing fossil fuel," taking a value of one for those countries with missing values (Battese, 1997).

[21]The UNFCCC estimates 2030 global emissions to be between 54.4 and 59.3 Gt CO_2e, after accounting for unconditional mitigation contributions, compared with global emissions of 48.1 Gt in 2010 (p. 43).

the small sample size, including irrelevant variables adds noise to the regression, making it difficult to precisely identify the impact of those characteristics that are important.

I employ Bayesian Model Averaging (BMA) to narrow the set of potentially influential variables to a manageable subset of those likely to be influential. The approach is conceptually similar to methods developed by Sala-i-Martin (1997), Sala-i-Martin, Doppelhofer, and Miller (2004), Fernandez, Ley, and Steel (2001), and Magnus, Powell, and Prüfer (2010) in the context of identifying predictors of macroeconomic growth. As a preliminary screening exercise, I run regressions with every permutation of combinations of country characteristics as independent variables. Based on the distribution of estimated parameter values for each independent variable across regressions, the approach calculates a posterior inclusion probability that the independent variable significantly affects the dependent variable.[22]

I then use the BMA results to select more parsimonious models for subsequent analysis. In particular, I use the median probability models (i.e., containing regressors with posterior inclusion probability greater than 0.5). As a rule of thumb, regressors are interpreted as being robustly correlated with the dependent variable if the posterior inclusion probability is greater than 0.5 (see Raftery, 1995; De Luca and Magnus, 2011). Barbieri and Berger (2004) shows that this class of model has several desirable theoretical properties and is often the optimal predictive model.

As noted by Mattoo and Subramanian (2012), Averchenkova, Stern, and Zenghelis (2014), and illustrated in Figure 2, the three main characteristics discussed as a means for allocating emissions reductions, GDP per capita, emissions per capita, and cumulative emissions per capita are highly correlated. Table 2 reports regression results and variance inflation factors for the full model and three models that include only one of these three variables. As can be seen in model (1), the three variables show signs of collinearity, with variance inflation factors close to or above the value of 10 conventionally used to identify multicollinearity issues.[23] In models (2) – (4), omitting two of these variables

[22] Calculations use the `bma.ado` Stata program (De Luca and Magnus, 2011).
[23] Multicollinearity does not appear to be an issue with the remaining variables.

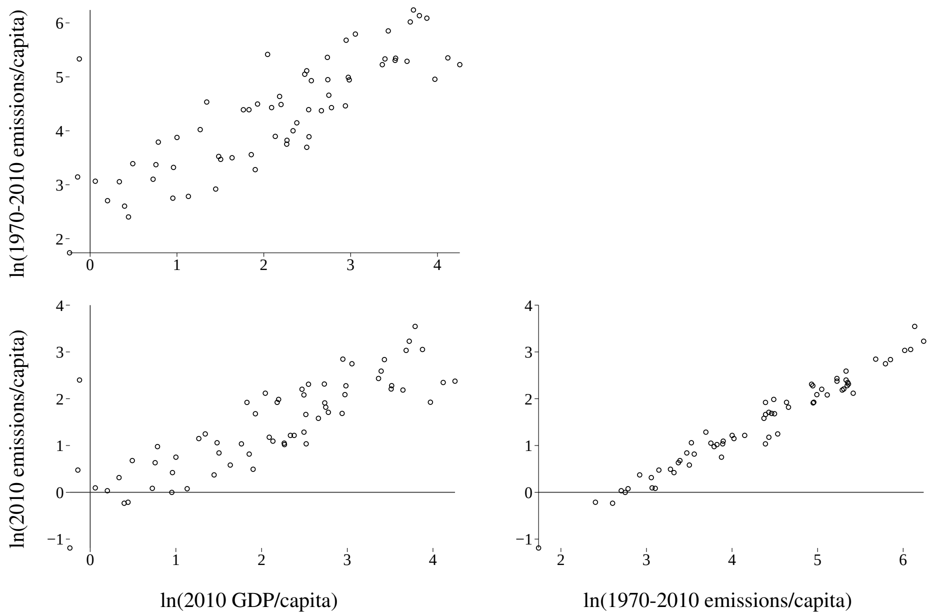

Figure 2. Relationship between log per capita emissions, cumulative emissions, and GDP

substantially reduces multicollinearity, such that none of the remaining variables has a variance inflation factor close to 10.

The presence of multicollinearity combined with the small sample size limits the potential for statistical analysis to attribute emissions targets exclusively to one of these three attributes. I therefore run three sets of regressions with the natural log of the ratio of 2030 target emissions to 2010 emissions as the dependent variable and the natural logs of one of these three characteristics as independent variables. Other explanatory variables are also expressed in natural logs (with the exception of variables that have many zero values, like oil rents as percent of GDP).

IV. Results

Table 3 presents results from the three sets of BMA regressions. Each set of regressions has the natural logarithm of the ratio of 2030 target emissions calculated on the basis of a country's NDC to 2010 emissions reported in CAIT as the dependent variable, the set of eleven common auxiliary variables listed in Table 3, and one of three additional auxiliary

Table 2—Variance Inflation Factors

	Dependent variable: ln (2030/2010 emissions from NDC)							
	(1)		(2)		(3)		(4)	
	Estimate	VIF	Estimate	VIF	Estimate	VIF	Estimate	VIF
ln(2010 GDP/capita)	-0.120	7.091	-0.119	3.423				
	(0.114)		(0.081)					
ln(2010 tCO2e/capita)	0.130	40.636			-0.094	2.918		
	(0.373)				(0.083)			
ln(1970-2010 tCO2e/capita)	-0.133	41.142					-0.100	3.242
	(0.362)						(0.078)	
ln(2020/2010 GDP)	1.051**	2.026	1.117***	1.677	1.117***	1.753	1.064**	1.873
	(0.460)		(0.355)		(0.378)		(0.400)	
ln(population)	0.003	2.025	0.003	2.013	0.004	2.023	0.004	2.020
	(0.033)		(0.031)		(0.033)		(0.033)	
ln(population growth)	0.524	2.870	0.572	2.633	0.545	2.642	0.508	2.683
	(0.377)		(0.396)		(0.412)		(0.414)	
ln(emissions intensity growth)	-0.031	1.239	-0.031	1.216	-0.032	1.232	-0.032	1.227
	(0.022)		(0.022)		(0.023)		(0.023)	
ln(life expectancy)	-0.150	3.470	-0.161	3.261	-0.537	2.286	-0.527	2.282
	(0.609)		(0.532)		(0.446)		(0.460)	
Fossil fuel per total energy (percent)	0.004	4.977	0.004	4.366	0.005	4.803	0.005	4.624
	(0.003)		(0.003)		(0.003)		(0.003)	
Missing fossil fuel (dummy)	0.214	3.092	0.228	2.801	0.286	2.860	0.277	2.827
	(0.266)		(0.232)		(0.237)		(0.236)	
Oil reserves/capita	-0.005	1.457	-0.007	1.444	-0.006	1.454	-0.005	1.457
	(0.039)		(0.038)		(0.038)		(0.038)	
Oil rent/GDP (percent)	-0.000	1.625	0.000	1.605	-0.001	1.562	-0.001	1.543
	(0.005)		(0.005)		(0.005)		(0.005)	
ln(pop. density)	0.055	2.595	0.057	2.176	0.049	2.527	0.047	2.537
	(0.045)		(0.045)		(0.046)		(0.046)	
ln(forest cover)	-0.021	1.676	-0.019	1.665	-0.021	1.662	-0.022	1.659
	(0.039)		(0.039)		(0.041)		(0.040)	
Small island	0.211	2.314	0.230	2.246	0.212	2.236	0.198	2.223
	(0.226)		(0.229)		(0.235)		(0.240)	
Constant	0.711		0.307		1.743		2.042	
	(2.719)		(2.238)		(1.914)		(1.916)	
R^2	0.539		0.537		0.527		0.529	
Observations	65		65		65		65	

Note: Robust standard errors in parentheses. *, **, and *** indicate P-values of 10, 5, and 1 percent.

variables: log 2010 GDP per capita, log 2010 GHG emissions per capita, and cumulative 1970-2010 GHG emissions per capita.

Each BMA specification represents the weighted average of 8,192 models.[24] Two variables have posterior inclusion probabilities above 0.5: log 2010 GDP per capita (0.59) and the ratio of 2020 to 2010 GDP (0.95-0.98). Only cumulative emissions per capita (0.47) has a posterior inclusion probability close to this threshold.

[24]The constant term is the only variable forced to be included in each permutation (De Luca and Magnus, 2011).

Table 3— Bayesian Model Averaging Posterior Inclusion Probabilities

	Dependent variable: ln(2030/2010 emissions from NDC)					
	(1)		(2)		(3)	
	Estimate	PIP	Estimate	PIP	Estimate	PIP
ln(2010 GDP/capita)	-0.081*	0.590				
	(0.080)					
ln(2010 tCO2e/capita)			-0.042	0.315		
			(0.074)			
ln(1970-2010 tCO2e/capita)					-0.076	0.474
					(0.095)	
ln(2020/2010 GDP)	1.358***	0.982	1.418***	0.982	1.290***	0.946
	(0.417)		(0.431)		(0.504)	
ln(population)	-0.000	0.077	-0.000	0.079	-0.000	0.079
	(0.009)		(0.009)		(0.009)	
ln(population growth)	0.151	0.259	0.200	0.318	0.171	0.284
	(0.310)		(0.350)		(0.328)	
ln(emissions intensity growth)	-0.006	0.211	-0.007	0.232	-0.008	0.241
	(0.015)		(0.016)		(0.017)	
ln(life expectancy)	-0.108	0.173	-0.193	0.259	-0.159	0.225
	(0.326)		(0.397)		(0.364)	
Fossil fuel per total energy (percent)	0.000	0.096	-0.000	0.103	0.000	0.101
	(0.001)		(0.001)		(0.001)	
Missing fossil fuel (dummy)	0.056	0.209	0.088	0.291	0.076	0.260
	(0.137)		(0.165)		(0.156)	
Oil reserves/capita	-0.004	0.089	-0.005	0.096	-0.004	0.091
	(0.028)		(0.031)		(0.029)	
Oil rent/GDP (percent)	0.000	0.081	0.000	0.079	0.000	0.080
	(0.002)		(0.002)		(0.002)	
ln(pop. density)	0.025	0.358	0.025	0.343	0.020	0.286
	(0.040)		(0.041)		(0.038)	
ln(forest cover)	-0.003	0.098	-0.003	0.099	-0.003	0.102
	(0.013)		(0.014)		(0.014)	
Small island	0.041	0.162	0.037	0.151	0.031	0.136
	(0.125)		(0.122)		(0.112)	
Observations	65		65		65	
Models	8192		8192		8192	

Note: PIP - posterior inclusion probability. Standard errors in parentheses. Estimates based on weighted average of all possible permutations of included dependent variables. * , ** , and **indicate posterior inclusion probabilities of 50, 75, and 90 percent.

Based on the BMA results I estimate the two median probability models presented in Table 4. These specifications generate similar results. The distribution of NDC targets is consistent with both the capability and responsibility criteria; the ratio of target to baseline emissions is decreasing in either. The magnitudes of the effects are similar across the two characteristics, a one percent increase in GDP per capita is associated with an approximate 0.15 percent decrease in the ratio of 2030 to 2010 emissions. The corresponding estimate for cumulative emissions is a 0.17 percent decrease. In addition,

Table 4—Median probability models

	Dependent variable: ln (2030/2010 emissions from NDC)	
	(1)	(2)
ln(2010 GDP/capita)	-0.150***	
	(0.049)	
ln(1970-2010 tCO2e/capita)		-0.172***
		(0.063)
ln(2020/2010 GDP)	1.348***	1.221***
	(0.282)	(0.368)
Constant	-0.106	0.387
	(0.222)	(0.435)
R^2	0.428	0.418
Observations	65	65

Note: Robust standard errors in parentheses. *, **, and *** indicate P-values of 10, 5, and 1 percent.

the targets appear to be strongly influenced by a criterion not typically mentioned in the burden-sharing literature: anticipated GDP growth. A one percent increase in the projected 2020/2010 GDP growth ratio is associated with an increase in the 2030 emissions ratio of between 1.22 and 1.35 percent.

The two specifications have similar explanatory power, and neither can be definitively ruled out as a plausible candidate. However, since the cumulative emissions has a lower posterior inclusion probability and its median probability model has less explanatory power, I focus on the GDP per capita specification for the remainder of the discussion.

V. Interpretation

The median probability model estimated in Section IV suggests that country GHG emission targets are a decreasing function of wealth and an increasing function of GDP growth projections. In this section, I provide intuition for the functional form estimated by the regression. I show that, under certain assumptions, the allocation of emission targets in the NDCs reflects what could have been chosen by a central planner following a modified cost minimization rule: rather than equate the marginal mitigation cost across countries, she wishes to equate the marginal utility cost of mitigation.

Letting y denote per capita GDP, exponentiation of regression (1) in Table 4 yields the following functional relationship for the ratio of 2030 to 2010 emissions for country i:

$$\frac{\tilde{e}_i}{e_i} = y_i^{\beta_1} \left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2} \exp(\beta_0 + \varepsilon_i), \tag{1}$$

where β_0, β_1, and β_2 are parameter estimates for the constant and respective independent variables, and ε_i is the regression residual for country i.

To begin, it is helpful to re-arrange and square Eq. (1):

$$\left\{\frac{e_i}{\tilde{e}_i}\left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2} \exp(\varepsilon_i)\right\}^2 y_i^{2\beta_1} = \exp(-2\beta_0), \tag{2}$$

The term $\left[\frac{GDP_{i20}}{GDP_{i10}}\right]^{\beta_2}$ can be thought of as a GDP growth "allowance." All else equal, a country with higher expected GDP growth has higher target emissions. Multiplying this term by 2010 emissions yields a proxy for projected 2030 BAU emissions:

$$e_i^{BAU} = e_i \left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2}. \tag{3}$$

Next, suppose the central planner views a country's mitigation costs as a function of projected BAU and target emissions. Specifically, let $m \equiv e^{BAU} - \tilde{e}$ denote total tons CO_2e mitigated, and the mitigation cost function take the following form:

$$c_i(m) = m\frac{e^{BAU}}{e^{BAU} - m}\exp(2\varepsilon_i). \tag{4}$$

The mitigation cost function is increasing in the ratio of BAU to target emissions and a factor, $\exp(2\varepsilon_i)$, based on unobserved (to the analyst) country-specific circumstances. This cost function is well-behaved, increasing and convex in m. Marginal monetary cost of mitigation, $c_i'(m)$, approaches infinity as total mitigation approaches BAU emissions, and is equal to the bracketed term in Eq. (2):

$$c_i'(m) = \frac{e^{BAU}}{e^{BAU}-m}\left[1+\frac{m}{e^{BAU}-m}\right]\exp(2\varepsilon_i) \tag{5}$$

$$= \left[\frac{e^{BAU}}{e^{BAU}-m}\right]^2 \exp(2\varepsilon_i) \tag{6}$$

$$= \left\{\frac{e_i}{\tilde{e}_i}\left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2}\exp(\varepsilon_i)\right\}^2. \tag{7}$$

As noted by Chichilnisky and Heal (1994), the appropriate value to consider when conducting welfare analysis regarding the global allocation of GHG mitigation is the utility of mitigation cost, not the monetary cost. It is generally assumed that social welfare is concave in income. The Atkinsonian social welfare function is a common specification in welfare analysis (see, for example, Anthoff, Hepburn, and Tol, 2009). Given per capita income y_i, country i's utility of income is

$$u(y_i) = \frac{y_i^{1+2\beta_1}}{1+2\beta_1}. \tag{8}$$

Here, $2\beta_1 \in \Re_{--}$ is a parameter quantifying the income elasticity of marginal utility and has an interpretation as inequality aversion (Atkinson, 1970).[25] The marginal disutility of mitigation cost is

$$\frac{\mathrm{d}u(y_i)}{\mathrm{d}y_i} = y_i^{2\beta_1}. \tag{9}$$

A country's disutility of the marginal mitigation cost of meeting a given target $\tilde{e}_i$ can be approximated by multiplying the monetary cost by the marginal utility of income, $c_i'(m)y_i^{2\beta_1}$.

With this structure, the allocation of emissions targets calculated on the basis of Eq. (1) may be interpreted as the solution to the problem of a global central planner tasked with

[25]This utility function has the same form as constant relative (proportional) risk aversion discussed by Pratt (1964).

allocating emissions targets across countries so as to minimize the aggregate welfare cost of attaining a global emissions target $\tilde{E}$:

$$\min_{\tilde{e}_1,\dots,\tilde{e}_I} \left\{ \sum_i y_i^{2\beta_1} c_i(m) | \sum_i \tilde{e}_i \leq \tilde{E} \right\}. \tag{10}$$

Letting $\lambda > 0$ denote the Lagrange multiplier, an interior solution equalizes disutility of marginal mitigation costs across countries:

$$\left\{ \frac{e_i}{\tilde{e}_i} \left[\frac{GDP_{i2020}}{GDP_{i2010}} \right]^{\beta_2} \exp(\varepsilon_i) \right\}^2 y_i^{2\beta_1} = \lambda \text{ for all } i. \tag{11}$$

Rearranging this equation yields each country's target, conditional on λ.

$$\tilde{e}_i = e_i \left[\frac{GDP_{i2020}}{GDP_{i2010}} \right]^{\beta_2} \exp(\varepsilon_i) y_i^{\beta_1} \lambda^{-0.5} \text{ for all } i. \tag{12}$$

The Lagrange multiplier can be interpreted as a global ambition parameter. It is calibrated to ensure that the 2030 emissions total equals the global target $\tilde{E}$:

$$\tilde{E} = \lambda^{-0.5} \sum_i e_i \left[\frac{GDP_{i2020}}{GDP_{i2010}} \right]^{\beta_2} \exp(\varepsilon_i) y_i^{\beta_1}. \tag{13}$$

Dividing Eq. (12) by baseline emissions, and substituting $\exp(\beta_0)$ for $\lambda^{-0.5}$ yields Eq. (1).

To summarize, the allocation of emissions targets observed in quantifiable submitted NDCs is consistent with what would have been chosen by a central planner who:

i) wants to minimize the global utility cost of mitigation;

ii) must achieve global emissions target: $e^{\beta_0} \sum_i e_i \left[\frac{GDP_{i2020}}{GDP_{i2010}} \right]^{\beta_2} \exp(\varepsilon_i) y_i^{\beta_1}$;

iii) uses Atkinsonian welfare weights $y^{2\beta_1}$ to calculate the utility value of a monetary expenditure, where y is 2010 per capita GDP measured at PPP;

iv) estimates the cost of mitigation action m to be $m\frac{e^{BAU}}{e^{BAU}-m}\exp(2\varepsilon_i)$, where BAU emissions are predicted on the basis of baseline emissions and projected GDP growth as $e_i\left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2}$; and

v) values β_0, β_1, and β_2 respectively as listed in regression (1) of Table 4 for the constant, GDP per capita, and GDP growth; and values ε_i as each country's residual from this regression.

VI. Policy Simulations

Having provided an economic interpretation for the empirical results in Section IV, we use the model parameters in Table 4 to conduct two thought experiments. The simulations consider different aspects of the repeated mitigation target revisions ("stock takes") envisaged in the Paris agreement. The first simulation considers the hypothetical question of how mitigation targets might be revised as per capita GDP and cumulative emissions evolve over time, holding fixed global ambition (β_0), marginal utility of income (β_1), GDP growth allowance (β_2), and unobserved national circumstances (ε_i). The second considers how much ambition would be necessary to achieve a 2030 target, holding the other parameters constant.

Both simulations suppose parties agree to let parameters β_1 and β_2 specify the rate at which country i's mitigation obligations should adjust to new data. That is, parties agree that a prospective 20 year mitigation target (recall that the regressions in Section IV were a 2030 target conditional on 2010 data) should be calculated according to:

$$\tilde{e}_{i2030} = e_{i2010}y_{i2010}^{\beta_1}\left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2}\exp(\beta_0+\varepsilon_i). \quad (14)$$

This expression can be reformulated as

$$\tilde{e}_{i2030} = e_{i2010}[1+r_{i2010}], \quad (15)$$

where the 20 year growth rate for country i based on data in 2010 is

$$r_{i2010} = y_{i2010}^{\beta_1} \left[\frac{GDP_{i2020}}{GDP_{i2010}}\right]^{\beta_2} \exp(\beta_0 + \varepsilon_i) - 1. \tag{16}$$

Using this formula, the 20 year growth rate based on 2020 data would be

$$r_{i2020} = y_{i2020}^{\beta_1} \left[\frac{GDP_{i2030}}{GDP_{i2020}}\right]^{\beta_2} \exp(\beta_0 + \varepsilon_i) - 1, \tag{17}$$

and the corresponding a 2030 target calculated on the basis of 2020 data (i.e., 10 rather than 20-year growth) would be

$$\tilde{e}_{i2030} = e_{i2020}[1 + r_{i2020}]^{0.5}. \tag{18}$$

I calculate y_{i2020} and e_{i2020} using projections: population comes from the UN World Population Prospects, GDP comes from the IMF, and emissions projections are calculated based on the annual growth rate implied by the NDC target. Lacking 2030 GDP projections, I assume the 2030/2020 GDP ratio equals the 2020/2010 ratio.

The first simulation holds $\beta_0, \beta_1, \beta_2$, and ε_i constant and calculates a revised 2030 target, based on Eq. (18). It addresses the following question: If wealthier countries (as measured by GDP per capita) are willing to assume a greater mitigation effort, and countries become wealthier over time, how will individual countries revise their targets and how far will the increased ambition obtained by this wealth effect go towards reducing global 2030 emissions? The second simulation then adjusts the global ambition parameter β_0 such that the combination of individual country targets achieves a given global 2030 emissions target. As an illustration, I set the global target as a 10 percent reduction from global 2010 emissions. By comparison, the UNFCCC estimates that 2030 emissions should be 20 percent lower than 2010 in order to get global emissions on the "least cost" 2°C path (UNFCCC, 2016).

Table 5 lists the three emission targets expressed relative to 2010 emissions. For comparison, it also shows targets calculated on the basis of cumulative historic emissions (up to 2020 for the simulations) using parameters from regression (2) in Table 4.

The analysis suggests that revising targets based solely on changes in country wealth or cumulative emissions data may not achieve large reductions in global emissions. Although almost all countries are projected to experience an increase in per capita GDP, this growth in wealth results in a small reduction in 2030 emissions targets; the change in total emissions by 2030 drops from a 16 percent increase to an 11 percent increase.

Table 5—2030 emissions targets based on per capita wealth and cumulative emissions (percent change from 2010)

		2020 revision			
		Wealth		1970-2020 Emissions	
Country	NDC target	Constant ambition	Increased ambition	Constant ambition	Increased ambition
Angola	26	22	-2	27	-1
Argentina	20	18	-5	20	-7
Australia	-26	-28	-42	-26	-42
Azerbaijan	-24	-26	-40	-24	-41
Bangladesh	117	106	66	118	68
Belarus	-1	-3	-22	-2	-24
Bosnia and Herzegovina	14	10	-11	13	-13
Botswana	-15	-18	-34	-15	-34
Brazil	-44	-45	-56	-44	-57
Burkina Faso	363	347	260	370	264
Burundi	295	288	214	307	215
Canada	-28	-30	-43	-28	-44
Central African Republic	3	4	-16	5	-19
Chad	180	174	121	188	123
Chile	54	49	20	55	20
China	39	31	6	39	8
Colombia	20	16	-7	21	-7
Costa Rica	-26	-29	-42	-26	-42
Djibouti	36	30	5	37	6
EU	-38	-39	-51	-38	-52
Eritrea	-2	-3	-22	0	-22
Georgia	144	132	87	142	87
Ghana	222	208	148	226	152
Guatemala	45	42	14	47	14
Haiti	102	96	58	103	57
Iceland	-35	-37	-49	-35	-49
India	135	122	79	136	82
Indonesia	0	-4	-23	1	-22
Israel	6	3	-17	7	-17
Jamaica	76	72	39	76	36

Note: "Constant ambition" uses estimated 2030 emissions target based on 2020 wealth and cumulative emissions projections (see Eq. (18)). "Increased ambition" adjusts the ambition parameter such that total 2030 emissions are 10 percent lower than total 2010 emissions.

Continued on next page

Table 5 – continued from previous page

Country	NDC target	2020 revision: Wealth, Constant ambition	Wealth, Increased ambition	1970-2020 Emissions, Constant ambition	1970-2020 Emissions, Increased ambition
Japan	-20	-22	-37	-21	-39
Kazakhstan	-10	-13	-30	-9	-30
Kiribati	-18	-20	-35	-18	-37
Kyrgyzstan	-39	-41	-52	-38	-52
Lebanon	82	77	43	82	41
Malaysia	114	106	66	115	67
Maldives	202	193	136	204	135
Mali	80	77	43	84	42
Mauritania	166	158	109	172	111
Mexico	10	7	-13	11	-14
Moldova	-3	-8	-25	-4	-26
Morocco	58	52	23	59	23
New Zealand	-27	-29	-42	-26	-43
Niger	102	96	59	108	61
Nigeria	174	166	115	179	116
Norway	-46	-47	-57	-46	-58
Oman	101	101	62	108	61
Paraguay	312	298	221	314	221
Peru	43	37	11	43	11
ROK	-4	-7	-25	-4	-26
Russia	-7	-9	-26	-7	-28
Saint Vincent and Grenadines	15	12	-10	14	-12
Senegal	134	127	84	138	84
Serbia	7	6	-14	8	-16
Singapore	38	35	9	39	8
South Africa	7	4	-16	7	-17
Switzerland	-51	-52	-61	-50	-62
Tajikistan	39	34	8	41	9
Thailand	25	20	-3	24	-4
Togo	69	63	31	71	33
Tunisia	120	114	73	121	71
USA	-23	-25	-39	-23	-40
Ukraine	28	25	1	27	-2
Vietnam	194	180	126	194	127
Yemen	79	77	43	80	40
Total	16	11	-10	16	-10

Note: "Constant ambition" uses estimated 2030 emissions target based on 2020 wealth and cumulative emissions projections (see Eq. (18)). "Increased ambition" adjusts the ambition parameter such that total 2030 emissions are 10 percent lower than total 2010 emissions.

Allocating mitigation obligations by cumulative emissions does not help. Population is projected to grow more quickly than emissions in most countries, resulting in a modest drop in cumulative emissions per capita. Consequently, the global emissions level remains essentially unchanged from those achieved by the NDC targets (the allocation across countries does change, however).

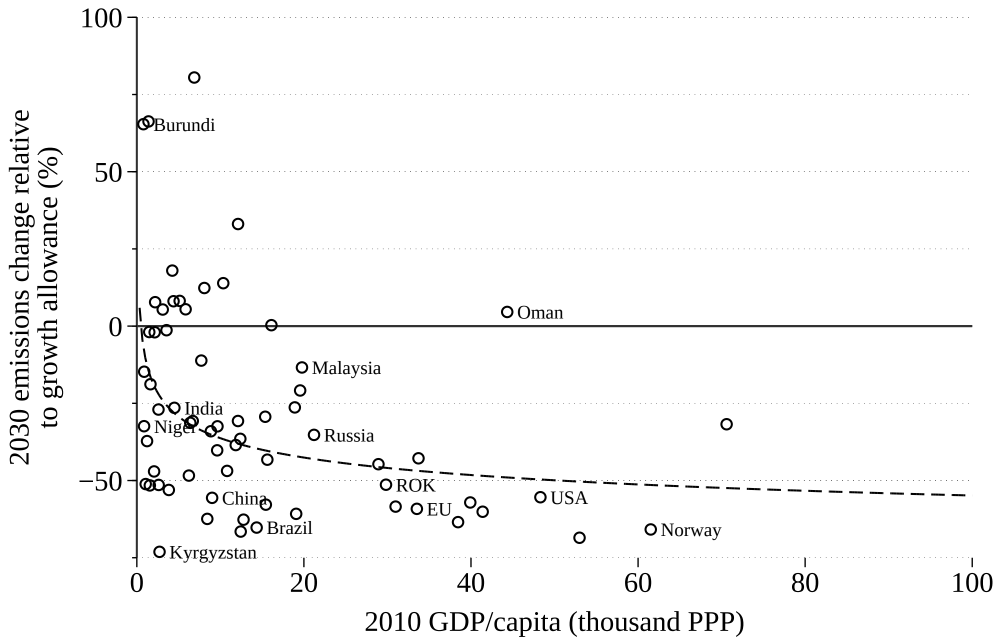

Figure 3. 2020 GHG emissions targets relative to emissions growth allowance

Note: Dots represent NDC 2030 emission targets as percent of BAU emissions implied by growth allowance. Dashed curve represents predicted emissions target as function of GDP per capita using Table 4 regression coefficients.

As suggested by Averchenkova, Stern, and Zenghelis (2014), Table 5 shows little difference at the country level between using wealth versus cumulative emissions as a criterion for burden sharing. The increased ambition scenario illustrates that a substantial increase in mitigation would be required for both developed and developing countries in order to meet the lower global emissions threshold. High income parties like Australia, EU, Japan, and USA see an additional drop in emissions of 10 to 15 percentage points. Poorer countries such as China, Indonesia, and Mexico have a drop of about 20 percentage points, while Bangladesh, India, Malaysia, Nigeria, and Vietnam have reductions of 40 to 55 percentage points, although they still have significant growth in emissions relative to 2010.

Figure 3 presents the percent change from 2030 target emissions relative 2010 emissions with an "allowance for growth" as a function of y_{i2020}. The vertical axis is calculated as

$$\left[\frac{\tilde{E}_{i2030}}{E_{i2010} \left[\frac{GDP_{i2020}}{GDP_{i2010}} \right]^{\beta_2}} - 1 \right] \times 100, \tag{19}$$

and may be considered a proxy for a percent reduction from 2030 BAU emissions growth. The dots depict Paris NDC targets. The dashed line represents the predicted emission reduction as a function of per capita GDP for a country with $\varepsilon = 0$ using parameters estimated in model (1) of Table 4.

Curves depicting estimated regression lines similar to Figure 3 could potentially serve as alternative benchmarking metrics to compare mitigation targets across countries as described by Aldy and Pizer (2016). The first column of Table 4, for example, provides a simple metric based on absolute emissions reductions relative to 2010. By this measure alone, India's contribution (an increase of 135 percent) compares unfavorably to that of Russia (-7 percent), for example. Figure 3, however, suggests that once projected GDP growth is taken into account, the contributions are similar (approximately a 30-35 percent decrease relative to this BAU proxy). The regression line further suggests that taking both GDP growth and per capita wealth into account, India's target compares favorably to Russia (its vertical distance above the line is smaller).

This metric is not comprehensive. There may be good reasons not captured in these data as to why some countries have relatively weak (or strong) targets. Nonetheless, it may be a better measure of relative effort than simple changes in absolute emissions.

In addition to facilitating cross-country comparisons, the estimated regression curves be useful in comparing a country's future mitigation pledges with what would have been predicted based on its own past experience. Such analysis could consider whether a country's mitigation pledge at some future date would be higher or lower than its predicted pledge using an equation similar to Eq. (18) after updating GDP growth and per capita income data, but holding the country's residual (ε_i) fixed.

VII. Conclusion

Since the early 1990s a large literature has emerged discussing equity frameworks for sharing the burden of mitigating GHG emissions across countries. The standard approach is to assume one or more frameworks and model the effects on emissions trajectories.

The submission of emission targets by a wide range of countries as part of the Paris climate agreement has made possible an alternative approach. Rather than assuming a distributional framework and deriving the implied emissions targets, I use data on the emissions targets to infer an implicit distributional framework.

This new approach offers several insights. It allows one to identify which country characteristics have significant effects on mitigation targets. Although not a widely discussed ethical criterion, projected GDP growth has a highly significant effect. Among conventional distributional criteria, two stand out: GDP per capita and cumulative emissions per capita. Thus, the burden-sharing arrangement implied by the distribution of Paris targets is broadly consistent with both the "capability" and "responsibility" ethical frameworks. Interestingly, using these results to reframe emissions reductions relative to a proxy for 2030 BAU emissions (rather than 2010) emissions, leads to a third allocation framework. The estimated functional form can correspond to the solution to an optimization problem in which a global central planner tries to equalize the marginal utility cost of mitigation across countries, i.e., it is economically efficient, conditional on a global target.

Estimating the relationship between these variables and burden sharing also permits a new analytical framework for considering an integral part of the Paris agreement: future "stock takes" or revisions of mitigation targets. I first consider a hypothetical future round of target revisions in which parties modify their targets based on how their circumstances have evolved (per capita GDP and cumulative emissions). As countries get wealthier their mitigation targets become tighter, but the aggregate impact is small: total 2030 GHG emissions drop from a 16 percent increase relative to 2010, to an 11 percent increase. In contrast, using cumulative emissions per capita as a criterion changes the allocation across countries, but does not affect aggregate emissions.

The analytical framework also identifies an "ambition" parameter that can be adjusted to determine an global emissions level without altering the preferences determining the burden-sharing framework. Manipulating this parameter allows one to simulate how alternate global targets affect individual country targets. Results suggest that using capability versus responsibility as an ethical criterion makes little difference in the cross-country allocation of mitigation actions to reach a given global emissions target.

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