Global unanimity agreement on the carbon budget*

Acuerdo global por unanimidad sobre el presupuesto de carbono

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Abstract

This paper analyzes a stylized model of the global economy in which countries must agree on the carbon budget while the decision on the level of carbon emissions is decentralized, with firms treating their emissions as a production input for which a uniform price is charged. The revenue accumulates in a global fund and is returned to global citizens according to national shares that are announced ex ante. The vector of country shares for the distribution of the carbon revenue assures that countries agree by unanimity on the carbon budget. The equilibrium exhibits the following desired features: (1) the global emissions level is set by unanimous agreement; (2) the demand to emit carbon is decentralized and, hence, there is no need to determine the distribution of permits; and (3) the equilibrium is Pareto efficient. We explore the implication of the model in an application based on RICE-2010.

Keywords: *international environmental agreement, climate economics, climate policy, carbon price.*

JEL classification: *Q54, Q56, Q58, F53, F64.*

Resumen

Este artículo analiza un modelo estilizado de la economía mundial en el que los países deben acordar el presupuesto de carbono mientras que la decisión sobre las emisiones de carbono está descentralizada, y las empresas tratan sus emisiones como un input en su producción por el que han de pagar un precio uniforme. La recaudación se acumula en un fondo mundial y se devuelve a los ciudadanos de todo el mundo según las cuotas nacionales que se anuncian ex ante. El vector de cuotas nacionales para la distribución de los ingresos del carbono garantiza que los países se pongan de acuerdo por unanimidad sobre el presupuesto del carbono. El equilibrio presenta las siguientes características: (1) el nivel global de emisiones se fija por unanimidad; (2) la demanda de emisiones de carbono está descentralizada y, por tanto, no es necesario determinar la distribución de permisos; y (3) el equilibrio es eficiente en términos de Pareto. Exploramos las implicaciones del modelo en una aplicación basada en RICE-2010.

Palabras clave: *acuerdo internacional, economía del cambio climático, política del cambio climático, precio del carbono.*

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* Humberto Llavador acknowledges financial support from the Spanish Agencia Estatal de Investigación (AEI), through the Severo Ochoa Programme for Centres of Excellence in R&D (Barcelona School of Economics CEX2019-000915-S) and grants AEI/FEDER, UE-PGC2018-096370-B-I00 and PID2020-115044GB-I00//AEI/10.13039/501100011033. Stoerk's contribution to this research does not necessarily reflect the opinion of the National Bank of Belgium or the Eurosystem.

DOI: https://doi.org/10.32796/cice.2022.104.7491
Recibido: Abril 2022 · Aceptado: Septiembre 2022

The global emissions problem exhibits the tragedy of the commons (Barrett, 2018), which is simply a dramatic way of saying that, in the emissions "game", the Nash equilibrium is (massively) Pareto inefficient, and that countries must cooperate if they want to avoid this bad equilibrium. Although a climate agreement to reduce emissions has been proved difficult to achieve, the Climate Change Conference (COP) meetings are venues that should be understood as attempts to build trust and solidarity among nations, so a cooperative solution that is Pareto efficient can be achieved (Keohane & Victor, 2016).

In this paper we present a stylized model of the global economy with countries agreeing on the carbon budget, while the decision on the level of carbon emissions is decentralized to the regional level, where firms treat their emissions as a production input for which a price is charged (Weitzman, 2014). The revenues from these charges accumulate in a global fund, and are returned to global citizens according to national shares that are announced *ex ante*. The vector of country shares for the distribution of the carbon revenue assures country unanimity of agreement on the carbon budget. Hence, our model can be viewed as one in which each country's firms demand permits to emit carbon, for which they pay a common price, and the vector of country shares for the distribution of the carbon fund assures countries' unanimity agreement on what the number of carbon permits globally should be. Because firms decide upon their emissions as part of a profit-maximizing plan, no firm has an incentive to emit more than it demands. Because, in choosing its desired global level of carbon emissions, each country maximizes the utility of its representative citizen considering the benefits from consumption, the damages from the global emissions level and the impact of the carbon permits, no country has an incentive to propose a different carbon budget. It is worth emphasizing that, once the mechanism is accepted, there is no need to negotiate the allocation of permits among countries, keeping the instrument of negotiation one dimensional centered on the global carbon budget, which, we argue, is a useful way of framing the climate mitigation challenge and a much easier issue to agree upon than the allocation of emission permits.[1]

In our stylized global economy there is a single good, produced in all countries according to nationally specific production functions, which use labor and capital as inputs, and emit according to country specific carbon intensities with respect to output. The markets for capital and output are standard. The market for carbon emissions is not. As mentioned, the demands for carbon emissions of countries are set by the profit-maximizing firms in each country, which must pay for standard inputs and proposed emissions. The supply of global emissions is unanimously agreed upon by countries. In equilibrium, all markets clear: in particular, all countries agree upon the desired global carbon budget, which equals (in equilibrium) the sum total of the demands for carbon emissions of the world's firms.

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[1] Total emissions are, in our opinion, a natural focal point in international negotiations of climate change. Notice that agreeing on a carbon budget is similar to agreeing on a temperature change target (headline statement D.1 in IPCC, 2022).

The virtues of the equilibrium are the following: (1) the global emissions level is not set by negotiations but by unanimous agreement of the national citizenries of the world; (2) the demand to emit carbon is decentralized to the firm level; (3) the equilibrium is globally Pareto efficient – there is no feasible allocation of capital, the good, and emissions that could make all countries better off. Of course, accepting the mechanism implies that the shares according to which the global carbon revenues are returned to nations must appear to be fair, for if they are not accepted, then unanimity on the global emissions level will dissolve. The shares are not negotiated but determined internally by the mechanism.

The mechanism satisfies all three properties that, according to Weitzman (2014), any instrument for negotiating climate change should satisfy, namely, “cost effectiveness, a natural one-dimensional focal point, and a built-in self-enforcement mechanism that internalizes the externality”. While the countervailing force that internalizes the externality in the mechanism works in a similar fashion as in Weitzman (2014),[2] a notable difference is that unanimity agreement is more powerful than the Condorcet winner proposed there. Moreover, our proposal differs substantially in that our focal point is the remaining cumulative carbon budget rather than the carbon price, which has the advantage of drawing on climate science rather than the more uncertain economic climate impacts literature needed to estimate the social cost of carbon. We do, however, share Weitzman’s spirit of seeing this proposal as an exploration into the solution rather than a concrete policy proposal.

1.1. Related literature

Our proposal is not the first to analyze the question of how to induce international collaboration in climate policy. Starting with Chander and Tulkens (1997), this literature has used game theoretic approaches to study the stability of climate policy coalitions under different assumptions. Our work follows in this tradition: abatement is coordinated, and financial transfers are part of our proposal, though they are not explicitly negotiated. In the standard literature, depending on the specific policy setup and assumptions about the behaviour of non-coalition countries, coalitions can be larger or smaller in equilibrium (Ray & Vohra, 2001), leading to a positive amount of climate action. However, calibrations typically find the resulting mitigation to fall short of greenhouse gas emissions cuts required to reach the 1.5 °C objective of the Paris Agreement.[3] Eyckmans and Tulkens (2006), for instance, find resulting warming of close to 4 °C in the most optimistic scenario using a calibration based on the RICE model. Our proposal differs from this literature in substantive terms: if the unanimity equilibrium is implemented, it leads to Paris-compatible levels of

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[2] The desire to set total emissions at low levels thereby reducing climate change damages, countervails the wish of each country to increase their production, and hence their individual emissions.

[3] Models based on bargaining (e.g., Caparrós (2016)) and mechanism design approaches (e.g., Martimort & Sand-Zantman (2016)) generally find qualitatively similar results.

warming. This idea is closest in spirit to the study of self-enforcing agreements, in particular Heitzig et al. (2011) which builds on earlier, more pessimistic literature, e.g. Dutta and Radner (2004).

Our proposal, furthermore, returns to an earlier focus on the importance of transfers to sustain international climate action. Carraro et al. (2006) and Lessmann et al. (2015), for instance, both highlight the importance of using transfers to ensure the stability of a climate coalition. At the same time, real world climate action as negotiated in COP26 agrees to the need for raising US$100 billion per year to provide climate financing to low- and middle-income countries. Our proposal takes this seriously and addresses it.

The remainder of this article is organised as follows: in Section 2, we describe the stylized model, define the unanimity equilibrium and prove its properties. Section 3 illustrates the implications of the mechanisms by simulating a 12-region world that, in the spirit of the Paris Agreement, must agree on the carbon budget until 2050 with the compromise of zero-emissions afterwards. Finally, Section 4 concludes.

2. A global unanimity equilibrium

In this section, we describe the model and study its properties. There are n countries, each endowed with labor, capital, and a technology for producing a single good. Country j is represented by an agent with a quasi-linear utility function

$$u_j(x, E) = x - h_j(E) \qquad [1]$$

where x represents the GDP per capita of the country, h_j is a convex damage function, and E is the global cumulative greenhouse gas emissions. Each country j has an increasing and concave aggregate production function

$$y = G_j(K) \qquad [2]$$

where y is output of the single good and K is capital. It is assumed that $G_j'(0) \rightarrow +\infty$ for all j, and that labor is immobile across countries, but capital is mobile. Therefore, the production function G_j assumes full employment of the country's labor supply, which is implicit in equation [2]. Besides its labor supply, country j is endowed with capital in the amount $\overline{K}_j$.

Emissions are assumed to be proportional to production (Nordhaus, 2018).

$$E_j = \eta_j y_j \qquad [3]$$

We start by deriving the conditions of Pareto efficiency.

Definition 1. An allocation of output and emissions $((x_1, E_1), ..., (x_n, E_n))$ is *globally feasible* if there is an allocation of capital $K_1, ..., K_n$ and output $y_1, ..., y_n$ such that:

$$y_j = G_j(K_j), \quad E_j = \eta_j y_j, \quad \sum x_j = \sum y_j, \quad \text{and} \quad \sum K_j = \sum \bar{K}_j, \qquad [4]$$

Definition 2. A globally feasible allocation is *Pareto efficient* if there is no other feasible allocation that gives at least one country higher utility and no country lower utility.

Proposition 1. *The necessary first-order conditions for an allocation to be Pareto efficient are*:

$$\begin{array}{lll} (i) & \forall j & \eta_j \sum_l (h_l)'(E) < 1 \\ (ii) & \forall i,j & \dfrac{(G_i)'(K_l)}{(G_j)'(K_j)} = \dfrac{1 - \eta_j \sum_l (h_l)'(E)}{1 - \eta_i \sum_l (h_l)'(E)} \end{array} \qquad [5]$$

where $E = \sum_j E_j$.

Proof. The conditions for Pareto efficiency are given by solving the following program:

$$\left.\begin{array}{ll} \max x_j - h_j(E) & \\ s.t. & \\ \forall i \neq j, x_i - h_i(E) \geq k_i & (\lambda_i) \\ \sum G_i(K_i) \geq \sum x_i & (\alpha) \\ \sum (\bar{K}_l) \geq \sum K_i & (\beta) \\ E \geq \sum \eta_i G_i(K_i) & (\gamma) \end{array}\right\} \text{Program (PE)}$$

The program is not convex, because of the last constraint (the $\{G_j\}$ are concave functions). Therefore, the Kuhn-Tucker conditions are necessary but not sufficient for the solution of (PE). Define $\lambda_1 = 1$. Then the Kuhn-Tucker conditions are:

$$\begin{array}{ll} (\partial x_i) & \lambda_i = \alpha \quad \text{for all } i \\ (\partial K_i) & \alpha(G_i)' - \beta - \gamma\, \eta_i (G_i)' = 0 \\ (\partial E) & -\sum_i \lambda_i (h_i)'(E) = 0 \end{array}$$

We deduce that $\lambda_i = 1 = \alpha$ for all i; $\gamma = \sum_l (h_l)'(E)$ and

$$\beta = (G_i)'\left(1 - \eta_i \sum_l (h_l)'\right)$$

From this last equation, and using $(G_i)'(0) \to +\infty$, we have the conditions:

$$
\begin{array}{ll}
(\forall i) & 1 > \eta_i \sum\limits_l (h_l)'(E) \\
(\forall i, j) & \dfrac{(G_i)'}{(G_j)'} = \dfrac{1 - \eta_j \sum_l (h_l)'(E)}{1 - \eta_i \sum_l (h_l)'(E)}
\end{array}
$$

These are the stated conditions in the proposition. ■

We now describe how the economy works. There are three markets: for the produced good, whose price will be denoted p; for capital, whose interest rate is r; and for carbon emissions, whose price is c. The firm in each country will demand capital to maximize profits:

$$\Pi_j = pG_j(K_j) - c\,\eta_i G_j(K_j) - rK_j \qquad [6]$$

where it must pay the carbon price for the emissions it creates. All profits, which here include wages because labor is implicit in the production function, are returned to the population of the country. Carbon pricing revenues are deposited in an international fund, and will be distributed to countries as demogrants, where country j will receive back a fraction a_j of total revenues. Thus, along with the price vector (p, c, r), countries observe a vector of shares $(a_1, ..., a_n) \in \Delta^{n-1}$, where Δ^{n-1} is the unit simplex in $\mathfrak{R}^{n-1}$.

The income of country j will be:

$$I_j = \Pi_j + r\overline{K}_j + a_j cE \qquad [7]$$

where E is global emissions, and so cE is the value of the carbon revenues. Each country supplies its entire capital endowment to the market.

It is clear there is a supply and demand for capital, and there is also a supply and demand for the good, because each country will demand the good in amount I_j/p.

The demand for emissions is determined by the firms' profit-maximizing choices, but we have yet to determine the supply of emissions (the carbon budget), which will be set by a unanimous agreement among countries. Note that the preferences of country j over carbon budgets is given by the indirect utility function:

$$V_j(E) = \frac{\Pi_j + r\overline{K}_j + a_j cE}{p} - h_j(E) \qquad [8]$$

For country j, the optimal level of global emissions, E, is therefore given by the first-order condition:

$$(V_j)'(E) = 0 \quad \text{or} \quad a_j \frac{c}{p} = (h_j)'(E) \qquad [9]$$

We close the model by requiring that the n countries *unanimously agree* on the value of E, the cumulative carbon budget. Thus, country representatives "supply" the emission permits *in toto* to firms.

We summarize the equilibrium of the economy as follows.

Definition 3. A *global unanimity equilibrium* is a price vector (p, c, r), a share vector $(a_1, ..., a_n) \in \Delta^{n-1}$, an allocation $(x_1, ..., x_n, K_1, ..., K_n, E_1, ..., E_n)$, and a global supply of emission permits E equalling the global cumulative carbon budget such that:

a) for each country j, (K_j, E_j) maximizes firm profits $\Pi_j = pG_j(K_j) - cE_j - rK_j$, subject to the constraint $E_j = \eta_j G_j(K_j)$;

b) for each country j, E maximizes its utility

$$V_j(E) = \frac{\Pi_j + r\bar{K}_j + a_j cE}{p} - h_j(E)\,;$$

c) country j's demand for the good is

$$x_j = \frac{\Pi_j + r\bar{K}_j + a_j cE}{p}\text{ ; and}$$

d) all markets clear:

$$\sum \bar{K}_j = \sum K_j,\quad \sum E_j = E,\quad \text{and}\quad \sum x_j = \sum G_j(K_j)$$

The following proposition shows that the global unanimity equilibrium is Pareto efficient and that it allocates the carbon pricing revenue proportional to marginal damages.

Proposition 2

A. *Any global unanimity equilibrium satisfies the first-order conditions for Pareto efficiency.*

B. *In equilibrium, the share of global carbon pricing revenue that country j receives is proportional to its marginal damages* $(h_j)'(E)$.

Proof. The first order conditions for profit maximization are, for all countries j:

$$(G_j)'(K_j)(p - c\eta_j) = r \quad \text{or} \quad (G_j)'(K_j)\left(1 - \frac{c}{p}\eta_j\right) = \frac{r}{p} \qquad [10]$$

The first order conditions for the unanimous agreement on the level of the cumulative global carbon budget E are, for all j:

$$(h_j)'(E) = a_j \frac{c}{p} \qquad [11]$$

from which it follows that $\sum(h_j)'(E) = c/p$. Substituting this into equation [5] gives, for all j: $(G_j)'(K_j)(1 - \eta_j \sum(h_j)'(E)) = r/p$. Conditions (i) and (ii) of Proposition 1 follow immediately, proving claim A.

Claim B follows immediately from equation [11]. ■

Observe that the global unanimity equilibrium is a species of Lindahl equilibrium. As mentioned earlier, the virtues of the solution are global Pareto efficiency, unanimity of agreement on global cumulative greenhouse gas emissions and a clear distribution of carbon pricing revenue.

3. An application

We use the data from the Regional Integrated model of Climate and the Economy (RICE) to simulate a 12-region world whose regions negotiate, in the spirit of the Paris Agreement, a carbon budget for their next 40 years (2015-2055), with the assumption of zero emissions afterwards.[4] RICE provides the necessary regional disaggregation for the current analysis. The twelve regions correspond to United States (US), the European Union (EU), Japan, Russia, Eurasia, China, India, Middle East, Africa, Latin America, Other High Income countries (OHI), and Other Asian countries. To approximate the dynamic situation, we endow each region with an annual stock of capital, an annual population, and a carbon intensity parameter that represent annual average values for the period under consideration. Utility is measured by the present value (in international \$) of the average annual consumption net of climate change damages. Finally, climate change damages are computed as the monetized present value (also in international \$) of warming costs to the end of the century associated to cumulative emissions. Details are provided in the next subsection.

3.1. Calibration

We use the data from the baseline run in RICE, representing a business-as-usual scenario.[5] Here we explain in detail the adjustment of the model proposed above to the data in RICE. We describe utility and production functions, carbon intensities, and endowments (stocks of capital and population) for each of the twelve regions.

Utility is measured as the present value of average annual consumption $v(x_j)$, net of climate damages $h_j(E)$ related to annual greenhouse gas emissions E,

$$u_j(x_j, E) = v(x_j) - h_j(E) \tag{12}$$

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[4] Since we will use the quasi-linear relationship between temperature change and cumulative emissions, negotiating a carbon budget is equivalent to setting a temperature change target.

[5] More specifically, we obtain the data from the RICE-2010 Excel spreadsheet version 4.012510.

Both consumption and damages are measured in trillions of international US dollars. For a discount factor ρ and a period of N years, the present value of consumption is simply

$$v(x_j) = \sum_{t=1}^{N} \rho^t x_j = \frac{\rho - \rho^{N+1}}{1 - \rho} x_j \qquad [13]$$

We construct region-specific climate damage functions in three steps. First, we calibrate an exponential function mapping warming to annual climate damages reported in RICE. Secondly, we exploit the nearly-linear relationship between warming an global cumulative emissions to write annual damages as a function of cumulative emissions. Finally, we calculate the present value to obtain total climate damages.

Step 1. Define the region-specific exponential function that maps temperature increases to annual climate damages:

$$d_j(\Delta T) = \alpha_{1j} e^{\alpha_{2j} \Delta T} \qquad [14]$$

where damages are measured in annual trillions of international dollars, and temperature change ΔT is in degrees centigrade above pre-industrial levels. We choose the parameters to calibrate the functions to the damage costs in the baseline run of RICE-2010 for the period 2005-2215.[6] Figure 1 shows the fit for the twelve regions. The value of the parameters are reported in the last two columns of Table 1. It is important to notice that economic climate damage are almost surely underestimated in RICE (see, e.g. on tipping points, to name but one reason).[7] With this caveat in mind, our parametrization of [14] provides a good fit to RICE's damages, as shown in Figure 1.

Step 2. We use the nearly-linear relationship between cumulative global emissions and warming (Matthews et al., 2009, 2018; IPCC, 2022) to write

$$\Delta T_t = \varphi 10^{-3} E_t^{cum} \qquad [15]$$

where φ is the ratio of warming to cumulative CO_2 emissions in °C/TtCO_2, known as the Transient Climate Response to Emissions (TCRE), and E_t^{cum} are cummulative anthropogenic emissions in GtCO.[8] We take $\varphi = 0.45$ (°C per 1000 GtCO_2) as the best estimate reported in the last IPCC report (D.1.1 in IPCC, 2022).

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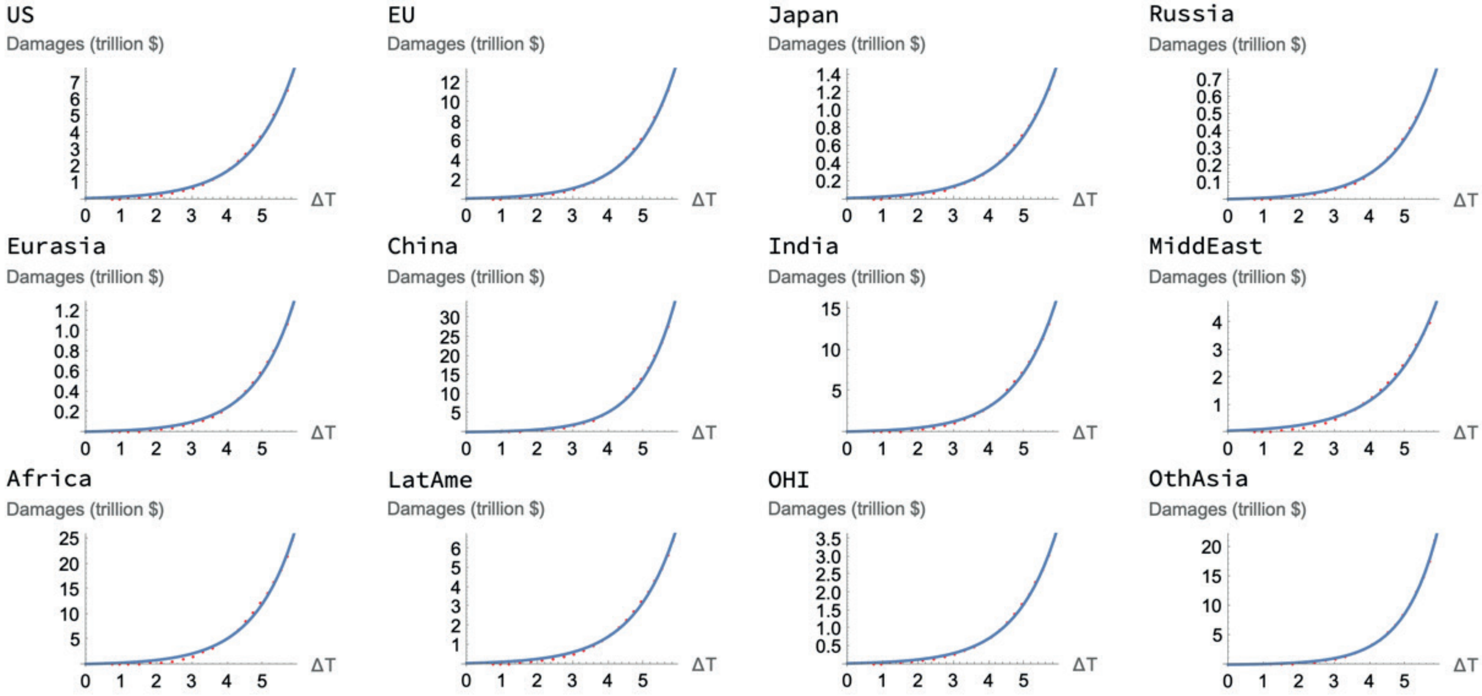
[6] The period 2005-2215 corresponds to temperature increases under 6 °C. See Table A.1 in the Appendix.

[7] A robustness check in the Appendix shows that larger damages result in qualitatively similar, but more extreme, outcomes.

[8] For computational simplicity, we opt to ignore the short delay between cumulative emissions and the onset of associated temperature change shown in Dietz and Venmans (2019).

FIGURE 1

ESTIMATED ANNUAL DAMAGE FUNCTIONS (BLUE SOLID LINE), AND ACTUAL POINT DATA IN RICE-2010 BASELINE RUN (RED DOTS).



NOTE: Damages measured in trillions of annual international-dollars.
SOURCE: Own elaboration.

Combining [14] and [15], region j climate damages in year t from global cumulative emissions E_t^{cum} are

$$\hat{D}_j(E_t^{cum}) = \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3} E_t^{cum}} \qquad [16]$$

Finally, let E_0^{cum} represent historical cumulative CO_2 emissions for the period 1850 to 2015 –amounting to 2296.5 $GtCO_2$–, and let average annual emission be E for the next N years, and zero afterward. Then, the present value of total climate damages in region j for $\hat{N} > N$ years is[9]:

$$p \times h_j(E) = \sum_{t=1}^{\hat{N}} \rho^t D_j(E, t) = \sum_{t=1}^{N} \rho^t \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0 + tE)} + \sum_{t=N+1}^{\hat{N}} \rho^t \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0 + NE)} \qquad [17]$$

where $D_j(E, t)$ are damages (in monetary terms) at year t in region j from average annual emission E.

Combining equations [13] and [17], we can write the utility of region j as a function of average consumption and average total annual emissions:

$$u_j(x_j, E) = \frac{\rho - \rho^{N+1}}{1-\rho} x_j - \sum_{t=1}^{N} \rho^t \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0 + tE)} - \sum_{t=N+1}^{\hat{N}} \rho^t \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0 + NE)} \qquad [18]$$

Utility represents the present discounted value of consumption net of warming costs from climate change.

Production is represented by a Cobb-Douglas function of labor and capital,

$$G_j(K) = A_j(L_j)^{1-\gamma} K^{\gamma} \qquad [19]$$

where $\gamma = 0.33$ is the elasticity of output with respect to capital. Total factor productivity (TFP) A_j is calibrated to the average values of output, capital and population in the baseline run of RICE for the period 2016-2055.[10] Defining $\kappa_j = A_j(L_j)^{1-\gamma}$, the production function can be expressed as

$$G_j(K) = \kappa_j K^{\gamma} \qquad [20]$$

The values of κ are presented in column 2 of Table 1.

Finally, average annual capital stock $\bar{K}_j$ (in trillions of international \$) and carbon intensity η_j (in $GtCO_2$/trillion \$) are calculated as the average values in the baseline run of RICE-2010 for the period 2016-2055. (Columns 3 and 4 in Table 1).

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[9] Cumulative emissions until year t are $E_t^{cum} = E_0^{cum} + tE$ if $t \leq N$, or $E_t^{cum} = E_0^{cum} + NE$ if $t \leq N$. Therefore, from equation [16], $D_j(E,t) = \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0^{cum} + tE)}$ for $t \leq N$, and $D_j(E,t) = \alpha_{1j} e^{\alpha_{2j}\varphi 10^{-3}(E_0^{cum} + NE)}$ for $t \geq N$.

[10] Figure A1 in the Appendix shows that these estimated TFPs are very close to the average of the reported TFP values in RICE-2010.

TABLE 1
CALIBRATED VALUES BASED ON THE DATA FROM THE BASELINE RUN OF RICE-2010

	Production parameter κ_j	**Stock of capital** $\bar{K}_j$ **(trillion \$)**	**Carbon intensity** η_j $(\mathbf{GtCO_2/trillion\$})$	**Damage function parameters**	
				α_{1j}	α_{2j}
Region					
US	8.0926	63.5154	0.2761	0.0672	0.8080
EU	8.3429	66.1483	0.2024	0.0867	0.8564
Japan	2.7546	13.5586	0.1887	0.0134	0.7970
Russia	1.8737	7.7646	0.5044	0.0052	0.8470
Eurasia	1.8338	7.5898	0.4563	0.0075	0.8750
China	7.4834	55.6930	0.4790	0.1019	0.9876
India	4.8316	30.3280	0.2878	0.1003	0.8595
MiddEast	3.2878	17.3715	0.4318	0.0580	0.7484
Africa	5.0156	32.0531	0.2540	0.1717	0.8525
LatAme	5.5100	36.9398	0.2068	0.0528	0.8247
OHI	3.2531	17.0958	0.3497	0.0235	0.8559
OthAsia	4.7999	30.3416	0.2516	0.0501	1.0333

SOURCE: Own elaboration.

Summarizing, each region is characterized by a utility function with region specific damages from climate change, a production function with region specific TFP, population, stock of capital, and a carbon intensity parameter. All calibrated values are collected in Table 1.

3.2. Computing the Global Unanimity Equilibrium

We proceed as follows to solve for the Global Unanimity Equilibrium as described in Definition 3. First, write $r = 1 - p - c$, using that the price vector (p, c, r) is restricted to the unit simplex Δ^2, to obtain the demand of capital as a function of prices from the first-order conditions for the profit maximization of the firms:

$$K_j = (G_j)^{-1} \left(\frac{1-p-c}{p-c\eta_j} \right) \left(\frac{\gamma}{1-c-p} (p-c\eta_j)\kappa_j \right)^{\frac{1}{1-\gamma}} \qquad [21]$$

Plug equation [21] into the market clearing conditions of capital and emissions to obtain:

$$\sum_j \bar{K}_j = \sum_j Kj \Rightarrow \left(\frac{\gamma}{1-c-p}\right)^{\frac{1}{1-\gamma}} \sum_{j=1}^{12} (\kappa_j \eta_j (p-c\eta_j))^{\frac{1}{1-\gamma}} = \sum_{j=1}^{12} \bar{K}_j \,; \tag{22}$$

$$\sum_j \eta_j G_j(K_j) = E \Rightarrow \left(\frac{\gamma}{1-c-p}\right)^{\frac{\gamma}{1-\gamma}} \sum_{j=1}^{12} \eta_j \kappa_j ((p-c\eta_j)\kappa_j)^{\frac{\gamma}{1-\gamma}} = E \tag{23}$$

The first order condition of the unanimity equilibrium implies $\sum_j (h_j)'(E)p/c = \frac{\rho - \rho^N}{1-\rho}$, which, using equation [17] and after some manipulation, becomes:

$$\sum_{j=1}^{12} \alpha_{1j} \hat{\alpha}_{2j} \theta_{0j} \left(\frac{N(\rho - \rho^{-N+\hat{N}+1})(\theta_{1j}(E))^N}{1-\rho} + \left(\frac{\theta_{1j}(E)}{1-\theta_{1j}(E)} \right)^2 (1-(\theta_{1j}(E))^N) \right) +$$
$$+ \sum_{j=1}^{12} \alpha_{1j} \hat{\alpha}_{2j} \theta_{0j} \frac{\theta_{1j}(E)(1-(N-1)(\theta_{1j}(E))^N)}{1-\theta_{1j}(E)} = \frac{(\rho-\rho^{-N})c}{1-\rho} \tag{24}$$

where $\hat{\alpha}_{2j} := \frac{\varphi \alpha_{2j}}{10^3}$ and $\theta_{0j}(E) := \rho e^{\hat{\alpha}_{2j}E}$.

Walras's Law assures us that the good's market clears. Equations [22]-[24] represent a system of three equations with three unknowns. We program Mathematica (v.12.3) to solve for the price of output p^*, the price of emissions permits c^*, and the total level of emissions E^*. Other values are obtained as follows:

- K_j^*, the stock of capital for region j, follows from equation [21];
- the price of capital is $r^* = 1 - p^* - c^*$;
- total revenue from emission permits equals $c^* \times E^*$;
- the share of total revenue for region j follows from equation [24]:

$$a_j^* = \frac{1-\rho}{\rho-\rho^N} \frac{p^*}{c^*} (h_j)'(E^*);$$

- emissions of region j equal $E_j^* = \eta_j \kappa_j (K_j^*)^\gamma$;
- income of region j is $I_j = \rho\kappa_j (K_j^*)^\gamma + r^*(\bar{K}_j - K_j^*) - c^*E_j^* + a_j^* c^* E^*$; and
- the net contribution of region j is $c^*E_j^* - a_j^* c^* E^*$.

3.2. Results

We derive two sets of results in equilibrium: the global cumulative carbon budget that countries would agree on as well as the associated temperature implications; and the carbon price and the associated international financial flows. Results are summarized in Figure 2 and in Tables 2 and 3.

3.2.1. The carbon budget and its temperature implications

Global average emissions are 50.3 $GtCO_2$ for the period 2016-2055, and zero afterwards. Therefore, total cumulative emissions since the beginning of the industrial revolution amount to 4,307 $GtCO_2$, which, according to equation [15] would result in a temperature increase by 2100 around 1.9 °C above pre-industrial levels. Observe that the analysis is conservative in assuming the (almost surely underestimated) costs in RICE and in ignoring any abatement policy beyond the energy efficiency trend embedded in the baseline run of RICE model.

3.2.2. Revenue and its distribution

At equilibrium, emission permits are priced at 54.5$/$tCO_2$, yielding an average global revenue of 2.74 trillion dollars per annum.

The following points are worth emphasizing:

1. Africa, China and India receive the largest shares of total revenue, receiving over half of total revenue (first column in Table 2). This is because they are the regions with the highest marginal costs of warming according to RICE-2010.
2. However, when we account for the contribution to the global fund, China becomes the second largest net contributor, with a net payment of 130.5 billion dollars, only after the 220.3 billion dollars of net contribution by the USA (Figure 2 and first column in Table 3). The net contributions of these two regions alone amount to nearly 60 % of the total amount supplied by those regions who are net contributors.
3. Africa, India and the small less developed countries in Asia are the only net recipients from the global fund. Africa, with 394 billion dollars per annum, is by far the largest net recipient, obtaining close to three-fold the amount received by India (141 billion \$). The net annual payment to India, Africa and Other Asia (\$643 billion per annum) is six and a half times the \$100 billion commitment to the developing world agreed upon in Paris at COP21 and, subsequently, COP26.
4. Although the mechanism does not have any explicit built-in redistributive objective, inequality is reduced compared to 2015 values. For instance, while the US per capita income is 14 times that of Africa in 2015, it reduces to only 8.4 times on average for the period 2016-2055 (columns three and four in Table 3). This equalizing effect originate in the negative relationship between income and climate change costs. Poorer regions are more intensively affected by climate change than richer regions, receiving a larger share of total revenue, hence reducing income differences.

TABLE 2
ALLOCATION OF PERMITS' CLAIMS AND REVENUES

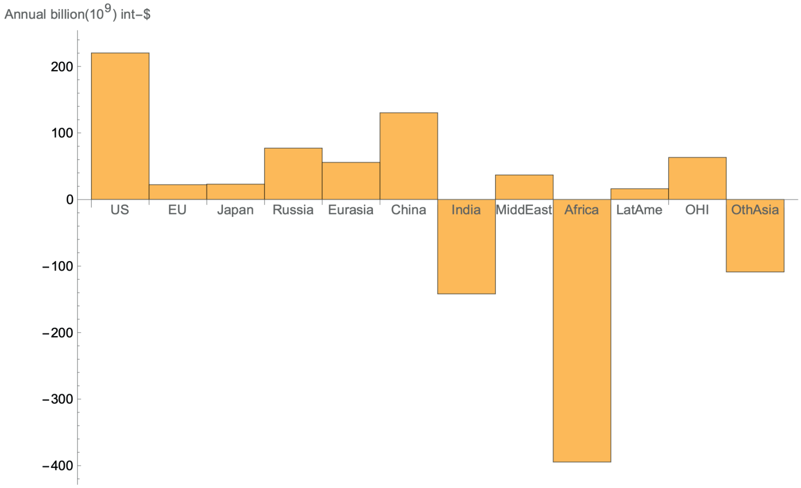
	Share of total revenue			Revenue: $a_j^* \times (c \times E^*)$		
Region	a_j^*	$\frac{a_j^*}{\text{Pop}_j\text{share}}$ %	$\frac{a_j^*}{\text{Pop}_j}$ Per million person	**Total (billion $)**	**$ per capita**	**As % of GDP**
US	0.074	1.653	0.195	201.804	534.01	0.866
EU	0.110	1.626	0.192	301.593	525.03	1.230
Japan	0.014	1.094	0.129	38.958	353.33	0.777
Russia	0.006	0.444	0.052	17.550	143.25	0.622
Eurasia	0.010	0.439	0.052	27.502	141.81	0.996
China	0.190	1.128	0.133	520.733	364.44	2.507
India	0.129	0.732	0.086	352.493	236.47	3.095
MiddEast	0.053	1.465	0.173	144.696	473.08	2.247
Africa	0.216	1.094	0.129	590.794	353.41	4.817
LatAme	0.061	0.732	0.086	166.847	236.45	1.228
OHI	0.030	1.866	0.220	81.804	602.70	1.296
OthAsia	0.106	0.666	0.079	291.329	215.22	2.582

NOTE: The shares of total revenue are endogenously determined in equilibrium according to $a_j^*=\frac{(1-\rho)}{(\rho-\rho^N)}\frac{p^*}{c^*}(h_j)'(E^*)$.

Each country receives revenue equal to $a_j^*(c^*\times E^*)$, where $(c^*\times E^*)$ is total revenue from emission permits. GDP is the average value for the region in 2016-2055, the period under consideration.

SOURCE: Own elaboration.

FIGURE 2
NET CONTRIBUTIONS TO THE GLOBAL FUND



NOTE: Bars represent the difference between the amount contributed and the amount received by each region from the global fund. Only India, Africa and Other Asian (representing Asian small developing countries) are net recipients –they receive from the global fund more than what they contribute from buying pollution permits. USA, China and Russia are the main net contributors. Quantities are in billions of international dollars.

SOURCE: Own elaboration.

TABLE 3

ANNUAL NET PAYMENT FROM EMISSION PERMITS AND ANNUAL INCOME

	Annual net payment		**Annual per capita income**	
	Per capita (thousand of $)	**Share of GDP (% of GDP)**	**Initial per capita (thousand of $)**	**Annual per capita (thousand of $)**
Region				
US	220.313	0.95	48.969	61.644
EU	22.271	0.09	31.041	42.685
Japan	23.076	0.46	35.054	45.473
Russia	77.212	2.74	16.267	23.024
Eurasia	55.754	2.02	8.459	14.237
China	130.461	0.63	8.595	14.539
India	–141.948	–1.25	3.658	7.641
MiddEast	36.824	0.57	14.204	21.049
Africa	–394.583	–3.22	3.509	7.337
LatAme	16.098	0.12	11.508	19.262
OHI	63.323	1.00	35.146	46.513
OthAsia	–108.800	–0.96	3.828	8.336

NOTE: Income is measured as gross firm revenues plus net income from capital minus the net payment for emission permits $Income_j=[p\kappa_j(K_j(p,\mathrm{c}))^{\gamma}]+[r(\bar{K}_j-K_j(p,\mathrm{c}))]-[cE_j(p,c)-a_jcE]$. Population is the average population in 2016-2055.

SOURCE: Own elaboration.

4. Conclusion

The model we have presented has much less detail in it than many of the models in the climate-change literature. We have presented this reduced form because our analysis focuses on showing that if nations agree to cooperate, there are mechanisms leading to a satisfactory solution to the massive challenge we all face. In that sense, the global unanimity equilibrium presents a mechanism that contrasts with regimes of punishments that would support a Nash (non-cooperative) equilibrium among nations. We believe that the COP meetings, and in particular COP21 that led to the signing of the Paris Agreement in 2015 Paris, exhibit both the desire and the feasibility for nations to cooperate. A key practical question is the applicability of large cross-border financial transfers. As shown in Figure 2, in our calibration, net financial flows across countries exceed 500 billion $ per year. While this is a large number, COP26 led to commitments of 100 billion US$ of annual climate finance to be provided to middle and lower income countries. Our proposal is, therefore, within the ballpark of the latest climate policy negotiations in the real world. However, our analysis does not pretend to offer a solution to the problem of achieving a deeper global cooperation, except in so far as the attractiveness of the global unanimity equilibrium is an advertisement for the cooperation that could bring it about. However, we think that research in climate economics continues to have a direct bearing on climate policy and that, as Karp and Sakamoto (2021) show, economic insights affect beliefs, which in turn matter for the possibility of climate cooperation in the real world.

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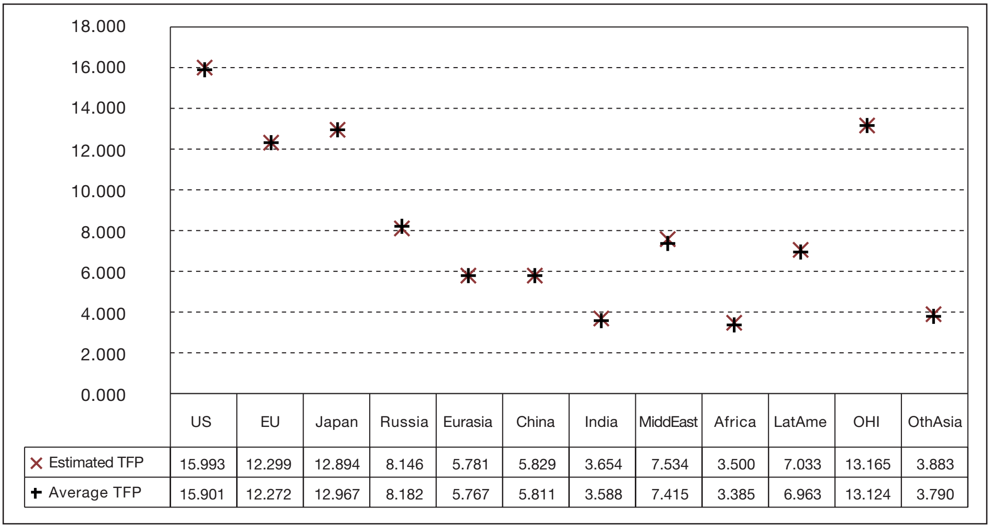
APPENDIX

A.1. Estimated total factor productivity

Figure A1 shows that our estimated values of total factor productivity are very similar to total factor productivity when averaging the values for 2016-2055 reported in the baseline run of RICE-2010.

FIGURE A1

AVERAGE 2015-2055 TOTAL FACTOR PRODUCTIVITY IN RICE-2010 (TFP), AND ESTIMATED TOTAL FACTOR PRODUCTIVITY (eTFP)



	US	EU	Japan	Russia	Eurasia	China	India	MiddEast	Africa	LatAme	OHI	OthAsia
× Estimated TFP	15.993	12.299	12.894	8.146	5.781	5.829	3.654	7.534	3.500	7.033	13.165	3.883
+ Average TFP	15.901	12.272	12.967	8.182	5.767	5.811	3.588	7.415	3.385	6.963	13.124	3.790

SOURCE: Own elaboration.

A.2. Temperature change and climate change damages in RICE-2010

Table A1 reports temperature increases and the associated climate change damages as reported in the baseline run of RICE-2010.

TABLE A1
CLIMATE CHANGE DAMAGES (IN TRILLIONS OF INTERNATIONAL $) AND TEMPERATURE CHANGE (IN °C WITH RESPECT TO 1850) IN NORDHAUS' RICE-2010 MODEL

		Annual climate change damages (trillions of international $ per annum)											
Year	**Temperature Change (ºC)**	**US**	**EU**	**Japan**	**Russia**	**Eurasia**	**China**	**India**	**MiddEast**	**Africa**	**LatAme**	**OHI**	**OthAsia**
2005	0.73070	0.00935	0.01173	0.00334	0.00104	0.00086	0.00663	0.00994	0.00554	0.00746	0.00529	0.00278	0.00571
2015	0.94387	0.02021	0.04350	0.00694	0.00230	0.00198	0.05589	0.02590	0.01397	0.02321	0.01262	0.01269	0.01340
2025	1.20613	0.04275	0.08144	0.01310	0.00461	0.00443	0.11603	0.05726	0.02905	0.05599	0.02786	0.02381	0.03226
2035	1.49926	0.08173	0.14601	0.02251	0.00835	0.00886	0.21457	0.11373	0.05521	0.12313	0.05556	0.04273	0.07008
2045	1.80860	0.14257	0.24230	0.03468	0.01394	0.01609	0.36262	0.20658	0.09644	0.24630	0.10035	0.07029	0.13798
2055	2.12340	0.22888	0.37414	0.05178	0.02174	0.02681	0.56957	0.34241	0.15431	0.43964	0.16554	0.10706	0.24547
2065	2.43529	0.34364	0.54447	0.07454	0.03195	0.04173	0.85110	0.52974	0.23210	0.71822	0.25557	0.15344	0.40420
2075	2.73901	0.49175	0.75753	0.10223	0.04455	0.06139	1.21812	0.78225	0.33548	1.11831	0.37518	0.21066	0.63192
2085	3.03226	0.67684	1.01552	0.13472	0.05954	0.08622	1.67934	1.11025	0.46909	1.67328	0.52815	0.27922	0.94567
2095	3.31449	0.90387	1.33649	0.17220	0.07684	0.11661	2.29977	1.52496	0.64049	2.44189	0.71828	0.36502	1.37078
2105	3.58611	1.17354	1.73935	0.21926	0.09920	0.15535	3.11989	2.03508	0.83575	3.37014	0.95002	0.47306	1.91334
2115	3.84052	1.48180	2.24197	0.27819	0.12807	0.20397	4.20694	2.64044	1.04171	4.39468	1.22266	0.60890	2.57415
2125	4.08099	1.82910	2.82489	0.34466	0.16105	0.26050	5.54053	3.34469	1.27361	5.57047	1.53693	0.76794	3.38989
2135	4.30983	2.24344	3.51536	0.42419	0.20161	0.32873	7.13854	4.16637	1.52997	6.95919	1.89814	0.95238	4.34411
2145	4.52899	2.69988	4.29612	0.51156	0.24680	0.40564	9.03139	5.09463	1.81019	8.52319	2.30084	1.16177	5.48729
2155	4.73957	3.20350	5.17183	0.60746	0.29706	0.49174	11.24380	6.13336	2.11460	10.26080	2.74639	1.39769	6.84170
2165	4.94229	3.75892	6.14886	0.71250	0.35278	0.58736	13.79650	7.28525	2.44322	12.17060	3.23556	1.66184	8.42941
2175	5.13764	4.37029	7.23282	0.82715	0.41424	0.69272	16.70780	8.55200	2.79579	14.24810	3.76866	1.95579	10.27340
2185	5.32595	5.04153	8.42873	0.95179	0.48172	0.80796	19.99370	9.93456	3.17187	16.48650	4.34563	2.28099	12.39750
2195	5.50748	5.77645	9.74115	1.08672	0.55541	0.93309	23.66830	11.43330	3.57083	18.87690	4.96610	2.63881	14.82580
2205	5.68233	6.57305	11.18160	1.23266	0.63481	1.07006	27.79340	13.12190	4.01303	21.53380	5.65569	3.03141	17.67680
2215	5.85083	7.43195	12.76010	1.39022	0.71966	1.22012	32.42670	15.05060	4.51102	24.53710	6.43059	3.46086	21.05990

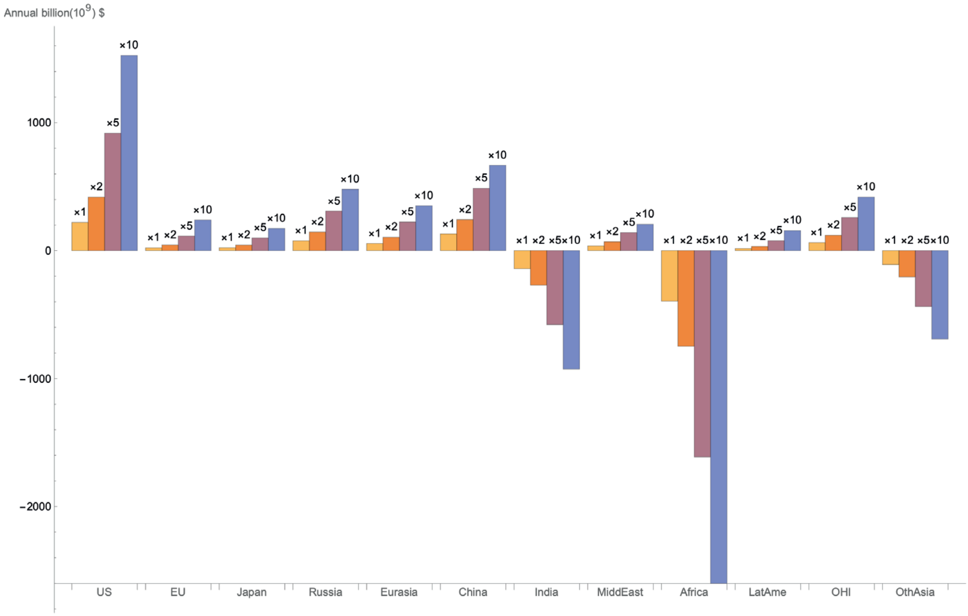
SOURCE: RICE-2010 Excel spreadsheet version 4.012510-baselin run.

A.3. Sensitivity analyses to climate damages

Climate damages in RICE are almost surely underestimated. We repeat the analysis for a range of much larger damages, finding a similar pattern in the allocation of net recipients, with magnitudes increasing with the cost of climate change. Figure A2 shows net contributions for a range of much larger damages. In particular, we study allocations for damages 2, 5, and 10-fold those used in RICE-2010 (that is, we consider $2\times\alpha_{1j}$, $5\times\alpha_{1j}$ and $10\alpha_{1j}$ in equation [16]). These allocations show a similar pattern to our main calibrated model. If anything, differences between net recipients and net contributors exacerbate with the increase in damages.

FIGURE A2

NET CONTRIBUTIONS AND RECIPIENTS AS INCREASES IN TEMPERATURE ENTAIL LARGER DAMAGES



NOTE: The bars shown correspond to the net contribution of each region for damages that are × 2, × 5 and × 10 those in RICE's baseline. A negative value means that the region is a net recipient of global carbon pricing revenue.

SOURCE: Own elaboration.