

International climate finance and emission reduction: what do the last twenty years tell us?

Claire Gavard^{1,*} and Niklas Schoch ²

¹ ZEW Mannheim, L7 1, 68161 Mannheim, Germany.

² Sciences Po, 27 Rue Saint-Guillaume, 75007 Paris, France.

*Corresponding author: claire.gavard@gmail.com

ONLINE APPENDIX

Online Appendix: International Climate Finance and Emission Reductions

Appendix A: Descriptive statistics

List of recipient countries included in the analysis

Afghanistan, Albania, Algeria, Andorra, Angola, Antigua and Barbuda, Argentina, Armenia, Aruba, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belize, Benin, Bermuda, Bhutan, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Bulgaria, Burkina Faso, Burundi, Cabo Verde, Cambodia, Cameroon, Cayman Islands, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo Dem. Rep., Congo Rep., Cook Islands, Costa Rica, Cote d'Ivoire, Croatia, Cuba, Djibouti, Cyprus, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Greenland, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Islamic Republic of Iran, Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kiribati, Kosovo, Kuwait, Kyrgyzstan, Laos, Lebanon, Lesotho, Liberia, Libya, Macao, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Marshall Islands, Mauritania, Mauritius, Mexico, Micronesia, Moldova, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nauru, Nepal, Nicaragua, Niger, Nigeria, Niue, North Korea, Oman, Pakistan, Palau, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Puerto Rico, Qatar, Romania, Russia, Rwanda, Samoa, San Marino, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Syria, Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Tuvalu, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, West Bank and Gaza, Yemen, Zambia, Zimbabwe.

Panel descriptives

Table A1: Panel descriptives

		Mean	Std. Dev.	Min	Max	N/n/T-bar
Emissions (yearly)	overall	105.9879	624.1254	0	9838.754	2952
	between	.	596.1777	.0069455	7259.999	164
	within	.	190.1374	-3804.716	2684.743	18
CDM Inflow	overall	.1770596	2.04078	0	67.20989	2916
	between	.	1.194126	0	14.12999	162
	within	.	1.657457	-13.95293	53.25695	18
RIO Adaptation Inflow	overall	.0333016	.1128646	0	2.265868	2934
	between	.	.0548512	0	.3999572	163
	within	.	.0987279	-.3666557	1.899212	18
RIO Mitigation Inflow	overall	.0738312	.2804853	0	5.410978	2934
	between	.	.1845791	0	1.887475	163
	within	.	.2116601	-1.784903	3.597334	18
Population	overall	3.46e+07	1.42e+08	0	1.39e+09	2952
	between	.	1.42e+08	10365.17	1.33e+09	164
	within	.	8206631	-1.13e+08	1.69e+08	18
GDP	overall	123.4005	539.3534	0	10131.87	2950
	between	.	499.9389	0	5589.827	164
	within	.	205.5304	-3234.28	4665.439	17.9878
Industry Share	overall	27.33416	14.40977	2.073173	87.79689	2703
	between	.	14.4528	6.31905	77.09931	160
	within	.	4.467502	-14.87371	58.44316	16.89375
Vulnerability	overall	.4762952	.0857174	.3317106	.7090511	2646
	between	.	.0854805	.3357233	.6844649	147
	within	.	.0093551	.443616	.5400377	18

Table A2: Sectoral distribution of RIO mitigation flows

Transport & Storage	16.334%
Energy generation, renewable sources	12.946%
General Environment Protection	11.774%
Water Supply & Sanitation	9.664%
Agriculture	8.067%
Energy distribution	6.223%
Other Multisector	6.007%
Energy Policy	4.390%
Unallocated / Unspecified	6.261%
Banking & Financial Services	2.985%
Energy generation, non-renewable sources	2.579%
Forestry	2.227%
Disaster Prevention & Preparedness	1.656%
Industry	1.566%
Other Social Infrastructure & Services	1.344%
Government & Civil Society-general	1.218%
Developmental Food Aid/Food Security Assistance	0.750%
Emergency Response	0.496%
Reconstruction Relief & Rehabilitation	0.462%
Mineral Resources & Mining	0.378%
Basic Health	0.361%
Fishing	0.359%
Business & Other Services	0.318%
Trade Policies & Regulations	0.312%
Post-Secondary Education	0.199%
Health, General	0.180%
Education, Level Unspecified	0.172%
Tourism	0.123%
Population Policies/Programmes & Reproductive Health	0.119%
Construction	0.115%
Basic Education	0.101%
Conflict, Peace & Security	0.098%
Secondary Education	0.080%
Communications	0.077%
Hybrid energy plants	0.044%
General Budget Support	0.007%
Nuclear energy plants	0.006%
Action Relating to Debt	0.002%
Administrative Costs of Donors	0.001%
Other Commodity Assistance	0.000%

Table A3: Sectoral distribution of RIO adaptation flows

Water Supply & Sanitation	20.37%
Agriculture	19.28%
General Environment Protection	16.80%
Other Multisector	9.93%
Transport & Storage	5.67%
Disaster Prevention & Preparedness	4.35%
Government & Civil Society-general	2.48%
Forestry	2.05%
Developmental Food Aid/Food Security Assistance	2.04%
Energy generation, renewable sources	1.97%
Banking & Financial Services	1.54%
Other Social Infrastructure & Services	1.52%
Emergency Response	1.28%
Energy Policy	1.26%
Reconstruction Relief & Rehabilitation	1.21%
Unallocated / Unspecified	1.95%
Industry	0.91%
Basic Health	0.76%
Fishing	0.71%
Energy distribution	0.57%
Trade Policies & Regulations	0.49%
Business & Other Services	0.49%
Population Policies/Programmes & Reproductive Health	0.30%
Education, Level Unspecified	0.26%
Post-Secondary Education	0.26%
Basic Education	0.24%
Conflict, Peace & Security	0.24%
Health, General	0.23%
Energy generation, non-renewable sources	0.21%
Tourism	0.14%
Communications	0.14%
Secondary Education	0.14%
Mineral Resources & Mining	0.10%
Hybrid energy plants	0.07%
General Budget Support	0.01%
Construction	0.01%
Nuclear energy plants	0.00%
Action Relating to Debt	0.00%
Administrative Costs of Donors	0.00%
Other Commodity Assistance	0.00%

Appendix B: Further Robustness Checks

Table B1: Impact of Transfers on Emissions - Additional Controls

Dependent Variable: Logarithmic emissions of recipient countries

	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00477 (0.0736)			-0.00764 (0.0748)
L(2).CDM inflow	0.0293 (0.0712)			0.00225 (0.0567)
L(3).CDM inflow	0.0753 (0.0744)			0.0439 (0.0574)
L(4).CDM inflow	0.0338 (0.0784)			0.00371 (0.0639)
L(5).CDM inflow	-0.333 (0.907)			-0.449 (0.893)
L(6).CDM inflow	-1.793 (0.836)			-2.083 (0.894)
L.Mitigation inflow		0.307 (0.279)		0.214 (0.289)
L(2).Mitigation inflow		0.605 (0.343)		0.444 (0.341)
L(3).Mitigation inflow		0.889 (0.319)		0.521 (0.356)
L(4).Mitigation inflow		1.065 (0.364)		0.733 (0.354)
L(5).Mitigation inflow		0.512 (0.386)		0.223 (0.417)
L(6).Mitigation inflow		0.607 (0.309)		0.446 (0.310)
L.Adaptation inflow			0.349 (0.367)	0.254 (0.358)
L(2).Adaptation inflow			0.545 (0.391)	0.249 (0.377)
L(3).Adaptation inflow			1.050 (0.413)	0.778 (0.391)
L(4).Adaptation inflow			1.131 (0.930)	0.846 (0.974)
L(5).Adaptation inflow			1.365 (0.498)	1.381 (0.501)
L(6).Adaptation inflow			3.163 (1.317)	2.875 (1.426)
Controls				
ln(Population)	0.963 (0.199)	0.952 (0.193)	0.943 (0.190)	0.941 (0.189)
ln(GDP)	0.465 (0.119)	0.465 (0.119)	0.465 (0.119)	0.468 (0.120)
Industry share in value added	0.000750 (0.00111)	0.000665 (0.00113)	0.000571 (0.00110)	0.000531 (0.00112)
Vulnerability	-1.500 (1.030)	-1.480 (1.045)	-1.505 (1.031)	-1.515 (1.048)
Political Stability Indicator	-0.0113 (0.0118)	-0.0112 (0.0117)	-0.00951 (0.0115)	-0.0100 (0.0115)
Forest area	-0.00894 (0.00775)	-0.00901 (0.00759)	-0.00800 (0.00740)	-0.00877 (0.00747)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1485	1485	1485	1485
MSE	0.0121	0.0121	0.0121	0.0121

Standard errors in parentheses.

Table B2: Impact of Transfers on Emissions - Excluding China

Dependent Variable: Logarithmic emissions of recipient countries

	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00919 (0.0697)			-0.0118 (0.0709)
L(2).CDM inflow	0.0230 (0.0647)			-0.00334 (0.0507)
L(3).CDM inflow	0.0669 (0.0673)			0.0364 (0.0510)
L(4).CDM inflow	0.0250 (0.0723)			-0.00356 (0.0584)
L(5).CDM inflow	-0.271 (0.903)			-0.402 (0.890)
L(6).CDM inflow	-1.629 (0.842)			-1.942 (0.900)
L.Mitigation inflow		0.300 (0.278)		0.202 (0.291)
L(2).Mitigation inflow		0.603 (0.340)		0.433 (0.344)
L(3).Mitigation inflow		0.877 (0.317)		0.498 (0.354)
L(4).Mitigation inflow		1.042 (0.364)		0.694 (0.353)
L(5).Mitigation inflow		0.482 (0.385)		0.184 (0.415)
L(6).Mitigation inflow		0.542 (0.297)		0.376 (0.295)
L.Adaptation inflow			0.339 (0.370)	0.248 (0.364)
L(2).Adaptation inflow			0.573 (0.395)	0.296 (0.386)
L(3).Adaptation inflow			1.084 (0.418)	0.833 (0.403)
L(4).Adaptation inflow			1.149 (0.937)	0.868 (0.989)
L(5).Adaptation inflow			1.380 (0.507)	1.415 (0.516)
L(6).Adaptation inflow			3.224 (1.316)	2.970 (1.424)
Controls				
ln(Population)	0.999 (0.203)	0.990 (0.198)	0.978 (0.193)	0.980 (0.194)
ln(GDP)	0.456 (0.122)	0.456 (0.122)	0.457 (0.121)	0.459 (0.123)
Industry share in value added	0.000787 (0.00113)	0.000711 (0.00114)	0.000601 (0.00112)	0.000574 (0.00114)
Vulnerability	-1.461 (1.035)	-1.440 (1.050)	-1.473 (1.036)	-1.480 (1.053)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1474	1474	1474	1474
MSE	0.0122	0.0122	0.0122	0.0122

Standard errors in parentheses.

Table B3: Impact of Transfers on Emissions - Re-weighting Matrix

Dependent Variable: Logarithmic emissions of recipient countries				
	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00703 (0.0660)			-0.00699 (0.0692)
L(2).CDM inflow	0.0313 (0.0706)			0.00367 (0.0538)
L(3).CDM inflow	0.0722 (0.0804)			0.0376 (0.0583)
L(4).CDM inflow	0.0318 (0.0888)			-0.00378 (0.0674)
L(5).CDM inflow	-0.664 (0.734)			-0.800 (0.724)
L(6).CDM inflow	-2.087 (1.036)			-2.337 (1.080)
L.Mitigation inflow		0.277 (0.273)		0.149 (0.290)
L(2).Mitigation inflow		0.576 (0.333)		0.345 (0.349)
L(3).Mitigation inflow		0.801 (0.319)		0.337 (0.373)
L(4).Mitigation inflow		1.127 (0.374)		0.623 (0.387)
L(5).Mitigation inflow		0.401 (0.406)		-0.00479 (0.478)
L(6).Mitigation inflow		0.543 (0.304)		0.314 (0.327)
L.Adaptation inflow			0.315 (0.348)	0.251 (0.350)
L(2).Adaptation inflow			0.676 (0.405)	0.445 (0.407)
L(3).Adaptation inflow			1.081 (0.468)	0.898 (0.477)
L(4).Adaptation inflow			1.473 (1.004)	1.197 (1.082)
L(5).Adaptation inflow			1.563 (0.574)	1.645 (0.610)
L(6).Adaptation inflow			3.319 (1.392)	3.171 (1.537)
Controls				
ln(Population)	1.018 (0.189)	1.008 (0.184)	0.998 (0.179)	0.994 (0.179)
ln(GDP)	0.461 (0.116)	0.455 (0.115)	0.460 (0.115)	0.463 (0.116)
Industry share in value added	0.000637 (0.00105)	0.000581 (0.00106)	0.000441 (0.00104)	0.000414 (0.00105)
Vulnerability	-1.157 (1.046)	-1.144 (1.058)	-1.134 (1.039)	-1.187 (1.059)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1519	1519	1519	1519
MSE	0.0121	0.0121	0.0121	0.0120

Standard errors in parentheses.

Table B4: Impact of Transfers on Emissions - Additional Controls
(Re-weighting Matrix)

Dependent Variable: Logarithmic emissions of recipient countries

	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00338 (0.0696)			-0.00330 (0.0730)
L(2).CDM inflow	0.0366 (0.0764)			0.00914 (0.0595)
L(3).CDM inflow	0.0798 (0.0871)			0.0452 (0.0648)
L(4).CDM inflow	0.0401 (0.0946)			0.00402 (0.0730)
L(5).CDM inflow	-0.647 (0.738)			-0.777 (0.728)
L(6).CDM inflow	-2.130 (0.998)			-2.374 (1.047)
L.Mitigation inflow		0.278 (0.274)		0.158 (0.287)
L(2).Mitigation inflow		0.568 (0.337)		0.354 (0.348)
L(3).Mitigation inflow		0.804 (0.322)		0.364 (0.376)
L(4).Mitigation inflow		1.144 (0.376)		0.672 (0.390)
L(5).Mitigation inflow		0.432 (0.410)		0.0467 (0.481)
L(6).Mitigation inflow		0.607 (0.322)		0.386 (0.348)
L.Adaptation inflow			0.313 (0.347)	0.244 (0.346)
L(2).Adaptation inflow			0.631 (0.398)	0.381 (0.396)
L(3).Adaptation inflow			1.029 (0.459)	0.828 (0.463)
L(4).Adaptation inflow			1.439 (0.993)	1.156 (1.061)
L(5).Adaptation inflow			1.524 (0.556)	1.582 (0.582)
L(6).Adaptation inflow			3.218 (1.386)	3.027 (1.526)
Controls				
ln(Population)	0.970 (0.187)	0.959 (0.182)	0.955 (0.178)	0.948 (0.178)
ln(GDP)	0.471 (0.115)	0.466 (0.114)	0.469 (0.114)	0.473 (0.115)
Industry share in value added	0.000583 (0.00104)	0.000520 (0.00105)	0.000399 (0.00103)	0.000363 (0.00104)
Vulnerability	-1.176 (1.042)	-1.165 (1.054)	-1.148 (1.036)	-1.201 (1.056)
Political Stability Indicator	-0.0118 (0.0119)	-0.0119 (0.0119)	-0.0100 (0.0115)	-0.0104 (0.0116)
Forest area	-0.00961 (0.00778)	-0.00963 (0.00757)	-0.00841 (0.00737)	-0.00919 (0.00745)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1519	1519	1519	1519
MSE	0.0121	0.0121	0.0121	0.0120

Standard errors in parentheses.

Table B5: Impact of Transfers on Emissions - Additional Lag Dynamics
(Re-weighting Matrix)

Dependent Variable: Logarithmic emissions of recipient countries

	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00504 (0.0663)			-0.00651 (0.0682)
L(2).CDM inflow	0.0345 (0.0738)			0.00649 (0.0570)
L(3).CDM inflow	0.0838 (0.0865)			0.0496 (0.0646)
L(4).CDM inflow	0.0512 (0.0962)			0.0156 (0.0750)
L(5).CDM inflow	-0.567 (0.766)			-0.689 (0.755)
L(6).CDM inflow	-1.963 (0.904)			-2.205 (0.959)
L.Mitigation inflow		0.304 (0.282)		0.195 (0.295)
L(2).Mitigation inflow		0.600 (0.361)		0.402 (0.369)
L(3).Mitigation inflow		0.817 (0.333)		0.402 (0.387)
L(4).Mitigation inflow		1.146 (0.369)		0.703 (0.374)
L(5).Mitigation inflow		0.457 (0.395)		0.0858 (0.459)
L(6).Mitigation inflow		0.568 (0.316)		0.361 (0.348)
L.Adaptation inflow			0.317 (0.364)	0.237 (0.365)
L(2).Adaptation inflow			0.615 (0.402)	0.350 (0.395)
L(3).Adaptation inflow			1.011 (0.468)	0.793 (0.463)
L(4).Adaptation inflow			1.455 (0.994)	1.153 (1.056)
L(5).Adaptation inflow			1.606 (0.545)	1.655 (0.568)
L(6).Adaptation inflow			3.061 (1.352)	2.834 (1.492)
Controls				
ln(Population)	1.026 (0.201)	1.016 (0.197)	1.011 (0.193)	1.005 (0.193)
ln(GDP)	0.485 (0.122)	0.481 (0.121)	0.483 (0.121)	0.486 (0.122)
Industry share in value added	0.000641 (0.00106)	0.000591 (0.00107)	0.000474 (0.00106)	0.000443 (0.00107)
Vulnerability	-1.252 (1.025)	-1.238 (1.040)	-1.234 (1.021)	-1.273 (1.041)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1518	1518	1518	1518
MSE	0.0120	0.0120	0.0120	0.0119

Standard errors in parentheses.

Table B6: Impact of Transfers on Emissions - Excluding China
(Re-weighting Matrix)

Dependent Variable: Logarithmic emissions of recipient countries

	(1)	(2)	(3)	(4)
Transfers				
L.CDM inflow	-0.00808 (0.0658)			-0.00772 (0.0692)
L(2).CDM inflow	0.0302 (0.0705)			0.00311 (0.0539)
L(3).CDM inflow	0.0712 (0.0805)			0.0374 (0.0587)
L(4).CDM inflow	0.0310 (0.0891)			-0.00376 (0.0679)
L(5).CDM inflow	-0.617 (0.738)			-0.763 (0.728)
L(6).CDM inflow	-2.007 (1.026)			-2.275 (1.074)
L.Mitigation inflow		0.274 (0.272)		0.149 (0.289)
L(2).Mitigation inflow		0.570 (0.333)		0.344 (0.349)
L(3).Mitigation inflow		0.792 (0.319)		0.335 (0.372)
L(4).Mitigation inflow		1.117 (0.373)		0.622 (0.386)
L(5).Mitigation inflow		0.392 (0.406)		-0.00764 (0.478)
L(6).Mitigation inflow		0.536 (0.303)		0.311 (0.327)
L.Adaptation inflow			0.311 (0.348)	0.248 (0.350)
L(2).Adaptation inflow			0.667 (0.404)	0.438 (0.406)
L(3).Adaptation inflow			1.068 (0.469)	0.887 (0.477)
L(4).Adaptation inflow			1.459 (1.003)	1.184 (1.080)
L(5).Adaptation inflow			1.547 (0.571)	1.634 (0.607)
L(6).Adaptation inflow			3.302 (1.388)	3.153 (1.532)
Controls				
ln(Population)	1.015 (0.191)	1.005 (0.186)	0.995 (0.181)	0.992 (0.181)
ln(GDP)	0.462 (0.118)	0.456 (0.117)	0.461 (0.117)	0.463 (0.118)
Industry share in value added	0.000627 (0.00105)	0.000572 (0.00106)	0.000435 (0.00105)	0.000411 (0.00106)
Vulnerability	-1.149 (1.047)	-1.137 (1.059)	-1.127 (1.041)	-1.179 (1.061)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1508	1508	1508	1508
MSE	0.0122	0.0122	0.0121	0.0121

Standard errors in parentheses.

Appendix C: Conceptual framework

The theoretical academic literature has recognised the importance of equity and fairness in international climate negotiations, but it has mainly approached the role of climate finance in enabling emission reduction through the lens of coalition formation in public good games. It applies these game-theoretic approaches to forming and stabilising international environmental agreements (IEAs). Acknowledging the Westphalian sovereignty of states, the literature emphasises the necessity of self-enforcing agreements, since a country's decision to enter any international contract must be voluntary (Nordhaus, 2015; Treaty of Vienna, 1969). An issue of international cooperation in climate policy is to address the inherently strong free-riding incentives (Nordhaus, 2015).

The most widely discussed way to reduce free-riding incentives and facilitate stable coalition formation amongst the players is by sharing the cost of emission reductions via financial transfers. There are two common means to model financial transfers in international coalition formation: surplus sharing amongst coalition members or direct incentive payments. Studies of surplus sharing in global climate coalitions find that an appropriate design of transfer schemes can stabilise IEAs in global climate policy (Carraro et al., 2006; Finus et al., 2006; Lessmann et al., 2015; Nagashima et al., 2009; Tulkens & Chander, 1998; Weikard et al., 2006). Direct transfer payments, bribing other agents into coalition participation, can also constitute optimal behaviour for some agents and thereby help reduce global emissions below non-cooperative levels (Ansink et al., 2018; Carraro et al., 2006; Fuentes-Albero & Rubio, 2010).

The results of the theoretical literature indicate that financial transfers can play a role in incentivising participation in and contribution to IEAs, thereby reducing recipient countries' emissions.

The global emissions game

We model the global emissions game and incorporate financial transfers following two approaches supported by the current literature. The first approach assumes a global climate coalition with a surplus sharing agreement, whilst the second approach abstracts from the presence of international climate agreements and derives the role of transfers in emission reduction for ex-ante separated donor and recipient countries, behaving as individuals that maximise their utility. The objective of this framework is not to describe emissions trajectories but to give an insight into the impact to expect from financial transfers on cumulative emissions.

This conceptual framework extends the current theoretical literature by relaxing the focus on coalition formation and modelling a continuous choice of emissions by each country in the presence of transfers. We wish to thereby better reflect the current negotiations, in particular in the framework of the Paris Agreement, where nationally determined contributions (NDCs) are negotiated amongst membership parties.

No financial transfers

We start with the optimal emission choice of country i in the absence of financial transfers. Following Li and Rus (2019), the welfare of country i can be expressed as the benefits received from emissions minus climate-induced damages

$$W_i = B_i(e_i) - D_i\left(\sum_{j=1}^N e_j\right), \quad (1)$$

with $B_i(e_i)$ denoting the benefits country i receives from emitting e_i and $D_j\left(\sum_{j=1}^N e_j\right)$ the damages caused by global emissions $\sum_{j=1}^N e_j$ to country i .

Country i chooses its optimal emission level maximising its welfare with respect to emis-

sions. Its maximisation reads as

$$\max_{e_i} W_i(e_i) = B_i(e_i) - D_i \left(\sum_{j=1}^N e_j \right). \quad (2)$$

The first-order condition (FOC) of this maximisation problem is given by

$$\frac{\partial W_i(e_i)}{\partial e_i} = \frac{\partial B_i(e_i)}{\partial e_i} - \frac{\partial D_i \left(\sum_{j=1}^N e_j \right)}{\partial e_i} \stackrel{!}{=} 0. \quad (3)$$

The subsequent optimality condition is

$$\frac{\partial B_i(e_i)}{\partial e_i} = \frac{\partial D_i \left(\sum_{j=1}^N e_j \right)}{\partial e_i} \quad \forall i \in N. \quad (4)$$

As a country does not internalise the damages its emissions impose on other countries, the resulting emission level from individual maximisation is too high, and a reduction of emissions increases global welfare (Samuelson, 1954).

Transfers as surplus sharing

A large body of the literature on global emission reductions focuses on the implementation of international cooperation as a means to fix this problem. Global coalition formation in emission reduction can result in the internalisation of external damages from emissions. Countries engaging in international cooperation take into account the damage of their emissions on other coalition members and reduce their emissions (Vogt, 2016). This yields a global welfare surplus compared to the situation of individual maximisation. One can distribute this surplus amongst coalition members such that the new allocation achieves a Pareto improvement as compared to the non-cooperative emission behaviour.

In the existing coalition formation literature, countries usually face a dichotomous choice between joining an international coalition, or remaining non-signatory (Carraro et al., 2006; Finus et al., 2006; Tulkens & Chander, 1998; Vogt, 2016; Weikard et al., 2006). Transfers are then modelled as a redistribution of coalition surpluses in the emissions

game.¹ In contrast, we want to establish a surplus sharing scheme for a continuous emission choice. Our model describes a global emissions game, where countries are part of a global coalition with a pre-agreed transfer scheme, redistributing the welfare surpluses obtained from unilateral continuous emission reductions. To better see how the theoretical model reflects real negotiations, one can think of this transfer scheme as negotiating parties making further emission reductions conditional on extended financial commitments from the international community. As a result, the amount of transfer received is a function of the emission reductions of the recipient country.

We propose the following structure of the game to model this negotiation behaviour: There exists an exogenously given transfer scheme, granting each country a share of the welfare surplus resulting from its emission reduction. Countries then choose their optimal emission level, knowing the transfer scheme will be enforced.

From the Samuelson rule (Samuelson, 1954), we know that a reduction of emission below the non-cooperative level will yield a global welfare increase. The increase arises since, for any emissions above the globally optimal emission level,² the foregone benefits for country i when reducing its emissions are outweighed by the relieved damages to the other countries. The surplus of emission reduction is defined as the increase in global welfare arising from this emission reduction.

Mathematically, the global surplus induced by the reduction in emissions of country i from the non-cooperative level e'_i to e_i can be expressed as

$$SU = B_i(e_i) - B_i(e'_i) - \sum_{j=1}^N \left(D_j \left(e_i, \sum_{k \neq i}^N e_k \right) - D_j \left(e'_i, \sum_{k \neq i}^N e_k \right) \right). \quad (5)$$

¹(Harstad, 2008) shows that, for collective decisions with a large number of parties, the absence of transfers might make cooperation impossible.

²The global optimum is the emissions resulting from all countries incorporating all damages of their emissions on all other countries.

It holds that

$$SU > 0 \quad \forall \quad e'_i > e_i > e_i^*, \quad (6)$$

with e_i^* denoting the global optimum.

It follows that the surplus arises due to the prevented damages to all other countries. We define these global prevented damages (GPD) as

$$GPD = \sum_{j=1}^N \left(D_j \left(e'_i, \sum_{k \neq i}^N e_k \right) - D_j \left(e_i, \sum_{k \neq i}^N e_k \right) \right). \quad (7)$$

When choosing their optimal emission level, countries now take into account the transfer payment they receive for reducing their emissions. The magnitude of this transfer depends on the share of surplus λ each country receives. The simplest choice for λ is a Nash-bargaining solution, as described by Carraro et al. (2006). It implies equal shares for all. Other mechanisms are also possible (Sheriff, 2019). Our analysis below is valid for any arbitrary choice of the sharing vector $\lambda = (\lambda_1, \dots, \lambda_N)$, assigning each country i an individual λ_i .

Knowing about its individual share λ_i , which it will receive when reducing its emission below the non-cooperative level, the maximisation problem of country i reads as

$$\max_{e_i} W_i = B_i(e_i) - D_i \left(\sum_{j=1}^N e_j \right) + \lambda_i GPD. \quad (8)$$

The resulting FOC

$$\frac{\partial W_i(e_i)}{\partial e_i} = \frac{\partial B_i(e_i)}{\partial e_i} - \frac{\partial D_i \left(\sum_{j=1}^N e_j \right)}{\partial e_i} + \lambda_i \left(\frac{\partial GPD}{\partial e_i} \right) \stackrel{!}{=} 0 \quad \forall i \in N \quad (9)$$

yields the optimality condition

$$\frac{\partial B_i(e_i)}{\partial e_i} = \frac{\partial D_i \left(\sum_{j=1}^N e_j \right)}{\partial e_i} + \lambda_i \sum_{j=1}^N \left(\frac{\partial D_j \left(\sum_{k=1}^N e_k \right)}{\partial e_i} \right) \quad \forall i \in N. \quad (10)$$

We define the marginal transfer as the increase in transfer per unit of emission reduction and obtain

$$-\frac{\partial tr_i(e_i)}{\partial e_i} = -\lambda_i \left(\frac{\partial GPD}{\partial e_i} \right) = -\lambda_i \sum_{j=1}^N \left(\frac{\partial D_j \left(\sum_{k=1}^N e_k \right)}{\partial e_i} \right). \quad (11)$$

Please note that the transfer received by country i decreases in its emissions:

$$\frac{\partial tr_i(e_i)}{\partial e_i} < 0. \quad (12)$$

Equation 10 can thus be expressed as

$$\frac{\partial B_i(e_i)}{\partial e_i} = \frac{\partial D_i \left(\sum_{j=1}^N e_j \right)}{\partial e_i} - \frac{\partial tr_{j,i}(e_i)}{\partial e_i} \quad \forall i \in N. \quad (13)$$

In (4), the benefits for country i to emit an additional unit must only compensate the resulting damage to itself. In contrast, in (10), the additional benefits must also compensate for the damages to all other countries, represented by the transfer received. Equation (13) shows that this means it also accounts for the reduced transfer when emitting an additional unit. The second term on the right-hand side shows by how much the transfer increases with an additional unit of emission reduction, which is how we defined the marginal transfer in (11). The marginal benefit in optimum in (10) or (13) is then higher than in (4).

Assuming concave benefit and convex damage functions is a standard assumption in the literature, e.g. in Li and Rus (2019). This means transfers decrease the amount of emissions. Intuitively, when receiving a larger share of the surplus (meaning a larger transfer), a country incorporates a larger share of the avoided damages caused by its emissions to other countries into its maximization. This results in a reduction of the optimal emission level. We examine the optimality condition (9) further when deriving analytic expressions for a country's optimal emission choice.

Transfers as direct incentive payments

We now present direct incentive payments as an alternative way to consider financial transfers. In this case, we assume that there is no international climate coalition and that countries behave as individual utility maximisers. The reader may raise the concern that there are existing international environmental agreements in place. However, following Nordhaus (2007) or Murdoch and Sandler (1997), one can consider that these agreements simply codify the emission levels observed in a non-cooperative Nash equilibrium. We develop an emissions game with donor and recipient countries.³ The donor countries choose to pay recipient countries transfers, where the transfer amount depends on the recipient's emission choice. This approach is inspired by Ansink et al. (2018), where donor countries incentivise recipient countries to join a coalition. They show that there exists a Nash equilibrium with a positive number of supporters who find it optimal to directly incentivise the behaviour of recipient countries with financial transfers. We adapt their approach in order to model a continuous emission choice of the recipient countries.

The structure of the game is as follows: there are N donor countries and M recipient countries. Each donor chooses to pay transfers to the recipients to incentivise emission reductions. To do so, each donor sets a transfer scheme, where the transfer paid depends on the recipient's final emissions. Given the structure of the transfer scheme, each recipient chooses its optimal emission level.

The maximisation problem of a donor country j is now

$$\max_{e_j, \sum_{i=N+1}^{N+M} tr_{j,i}} W_j^D = B_j^D(e_j) - D_j^D\left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k)\right) - \sum_{j=N+1}^{N+M} tr_{j,i}(e_j), \quad (14)$$

where W_j^D denotes the welfare of donor j , consisting of the benefits of emissions $B_j^D(e_j)$ depending on its own emissions e_j , the damages from global emissions $D_j^D\left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k)\right)$,

³As we consider financial flows from OECD to non-OECD countries, we find this ex-ante definition of recipient and donor groups is consistent with the political landscape in the context of our study.

the transfers $tr_{j,i}$ paid to recipient i by donor j , and the total amount of transfers recipient i receives from the N donors $tr_i = \sum_{j=1}^N tr_{j,i}$.

We first model how a donor sets an incentive-compatible transfer scheme. To derive this optimal transfer scheme, we adapt the approach developed by Habla and Winkler (2013). The transfer scheme has to satisfy the following conditions:

- The donor cannot be worse-off when paying the transfer as opposed to not offering it. The reduced damage due to e_j has to compensate for the transfer.
- The recipient has to find it optimal to reduce its emissions and receive a transfer, as opposed to unilaterally choosing its emissions.
- The donor pays the minimal necessary transfer to convince the recipient to reduce its emissions and receive the transfer.

We propose the following transfer scheme

$$tr_{j,i}(e_i) = \max[0, W_j^{D*}(e_i) - \bar{W}_j^D], \quad (15)$$

with W_j^{D*} being the realised welfare of donor j depending on the emissions of recipient i , net of all transfers

$$W_j^{D*} = B_j^D(e_j) - D_j^D \left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k) \right) \quad (16)$$

and $\bar{W}_j^D$ some fixed reference welfare with

$$\bar{W}_j^D \geq W_j^{D'}, \quad (17)$$

where $W_j^{D'}$ denotes the donor's welfare under unilateral maximisation of all countries. Condition (17) states that $\bar{W}_j^D$ is at least as high as the donor's welfare in case of non-cooperative emissions and ensures the donor is not worse-off through the transfers.

From (15), we obtain the marginal transfer, as defined in (11):

$$-\frac{\partial tr_{j,i}(e_i)}{\partial e_i} = -\frac{\partial W_j^{D*}(e_j)}{\partial e_i} = \frac{\partial D_j^D(e_j)}{\partial e_i}. \quad (18)$$

The resulting mechanism of the transfer scheme is as follows: by conditioning the amount on some reference welfare $\bar{W}_i^D$ satisfying $\bar{W}_j^D \geq W_j^{D'}$, the donor ensures to never be worse-off under the transfer scheme. But since $\bar{W}_j^D$ is fixed, the marginal transfer is unaffected by $\bar{W}_j^D$ and equals the marginal effect of the recipient's emission on the donor. Thus, the donor country sets the marginal transfer to exactly equal the relieved damages if a recipient decreases its emissions. This property ensures full internalisation of the external damages on the donor by the recipient.

Knowing this transfer scheme, the recipient maximises

$$\max_{e_i} W_i^R = B_i^R(e_i) - D_i^R \left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k) \right) + \theta_i \sum_{j=1}^N tr_{j,i}(e_i), \quad (19)$$

with W_i^R denoting the welfare of recipient country i , consisting of the benefits of emissions $B_i^R(e_i)$ depending on its own emissions e_i , the damages from global emissions $D_i^R \left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k) \right)$, the transfers $tr_{j,i}$ paid to recipient i by donor j , and a recipient-specific scaling factor θ_i , indicating how much the transfer is valued.

The resulting FOC

$$\frac{\partial W_i^R}{\partial e_i} = \frac{\partial B_i^R(e_i)}{\partial e_i} - \frac{\partial D_i^R \left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k) \right)}{\partial e_i} + \theta_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i} \stackrel{!}{=} 0 \quad (20)$$

yields the optimality condition

$$\frac{\partial B_i^R(e_i)}{\partial e_i} = \frac{\partial D_i^R \left(\sum_{j=1}^N e_j, \sum_{k=N+1}^{N+M} e_k(tr_k) \right)}{\partial e_i} - \theta_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i}. \quad (21)$$

The marginal benefits of emissions are now equated to the own marginal damages plus the sum of the marginal transfers from all donor countries. In comparison to Equation

(4), the marginal benefits are higher as they include the transfers. They hence incentivise an emission reduction. Note that this framework does not yield a global optimum since donor countries do not internalise the damages they impose on recipient countries and the damages imposed on each other.

Introducing functional forms for the benefit and damage functions

To deduce an equation for the empirical estimations, we impose functional forms on the benefits and damages. In a first step, we wish to abstract from strategic interactions in the optimal emission setting and impose a linear marginal damage function. Current emissions of a single country are always small compared to global cumulative emissions. This means that mapping emissions to damages via a linear specification is a good approximation. It is also consistent with the current literature (Habla & Winkler, 2018; Holtsmark & Weitzman, 2020).

Using the definition employed by Habla and Winkler (2018), we propose the following structural forms for the benefit and damage functions. We define the benefit function as

$$B_i(e_i) = \frac{1}{\phi_i} e_i \left(\epsilon_i - \frac{1}{2} e_i \right) \quad \text{with } e_i \in (0, \epsilon_i), \quad (22)$$

where ϵ_i denotes the maximal emissions, which are the emissions a country would choose in the absence of any damages, e_i the realised emissions of country i and ϕ_i a country-specific scaling of the marginal benefits.

This specification exhibits diminishing marginal benefits:

$$B'_i(e_i) = \frac{\epsilon_i - e_i}{\phi_i} \geq 0 \quad \forall \quad e_i \leq \epsilon_i \quad (23)$$

$$B''_i(e_i) = -\frac{1}{\phi_i} < 0. \quad (24)$$

We define the damage function as

$$D_i(E) = \delta_i E, \quad (25)$$

where E denotes the global emissions and δ_i country-specific marginal damages.

This specification exhibits constant marginal damages:

$$D'_i(E) = \delta_i \quad (26)$$

$$D''_i(E) = 0. \quad (27)$$

We use the definitions (22) and (25) to obtain the equation describing the optimal emission choice under the two transfer schemes from (10) and (21).

Transfers as a surplus sharing

In the approach considering transfers as surplus sharing, we obtain

$$\frac{\epsilon_i - e_i}{\phi_i} = \delta_i - \lambda_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i} \quad (28)$$

$$e_i = \epsilon_i - \phi_i \delta_i + \phi_i \lambda_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i}. \quad (29)$$

Transfers as direct incentive payments

In the approach considering transfers as direct incentives, we obtain

$$\frac{\epsilon_i - e_i}{\phi_i} = \delta_i - \theta_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i} \quad (30)$$

$$e_i = \epsilon_i - \phi_i \delta_i + \phi_i \theta_i \sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i}. \quad (31)$$

In both cases, e_i negatively depends on the marginal damages, δ_i , and the sum of the marginal received transfers per emission reduction, $\sum_{j=1}^N \frac{\partial tr_{j,i}(e_i)}{\partial e_i}$. Equations (29) and

(31) give rise to the testable implication that transfer payments from donor countries can incentivize emission reductions in recipient countries.

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