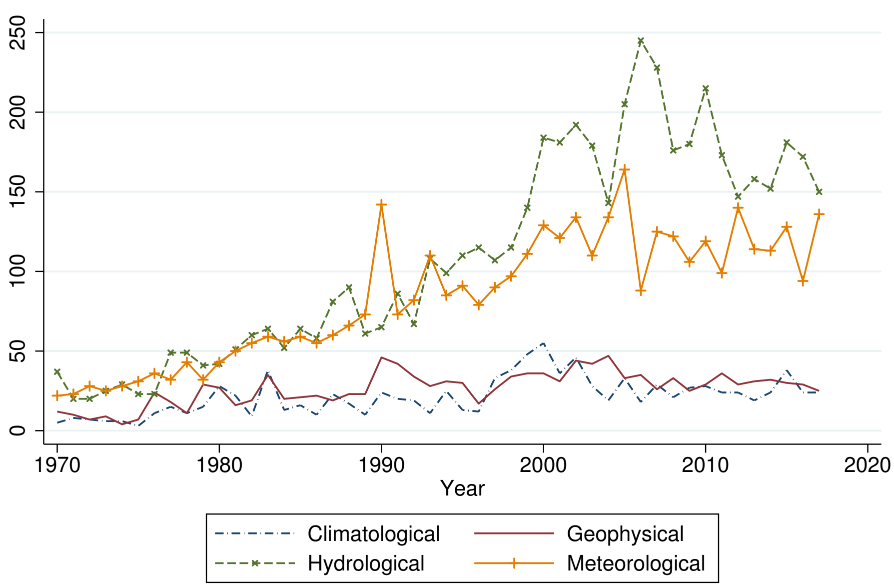
Supplemental Appendix – Warming with Borders: Forced Climate Migration and Carbon Pricing

Maria Alsina-Pujols

Online Appendix

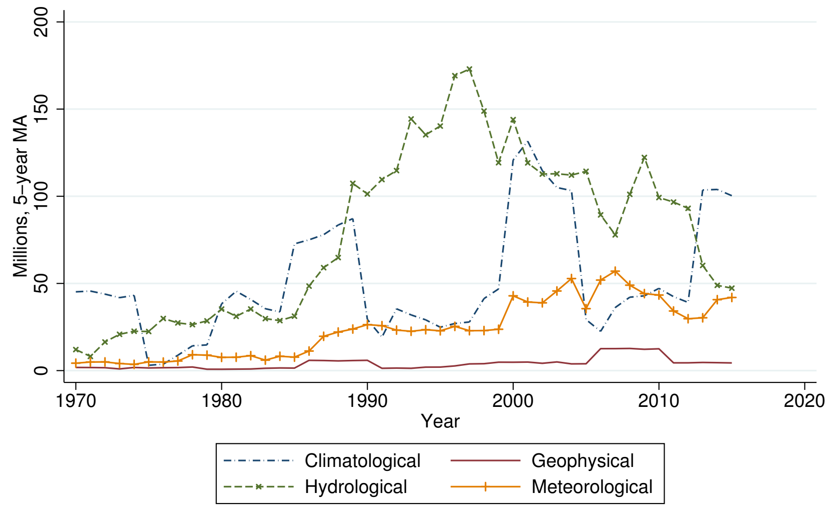
A Empirical Analysis: Figures

Figure A.1: Frequency of natural disasters by group (1970–2017)



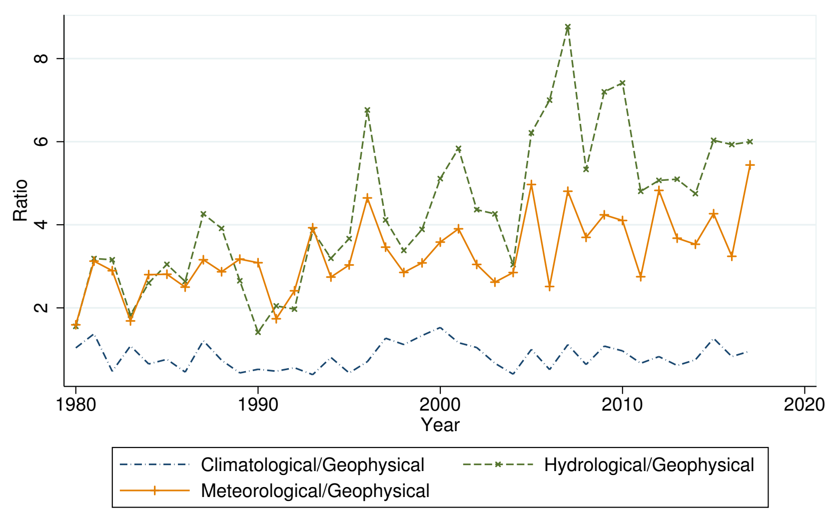
Note: This graph illustrates the evolution of natural disasters since 1970. The frequency variable in the y-axis represents the total number of shocks in a year. *Source:* Author, based on EM-DAT database.

Figure A.2: Total number of people affected by disaster group (1970–2017)



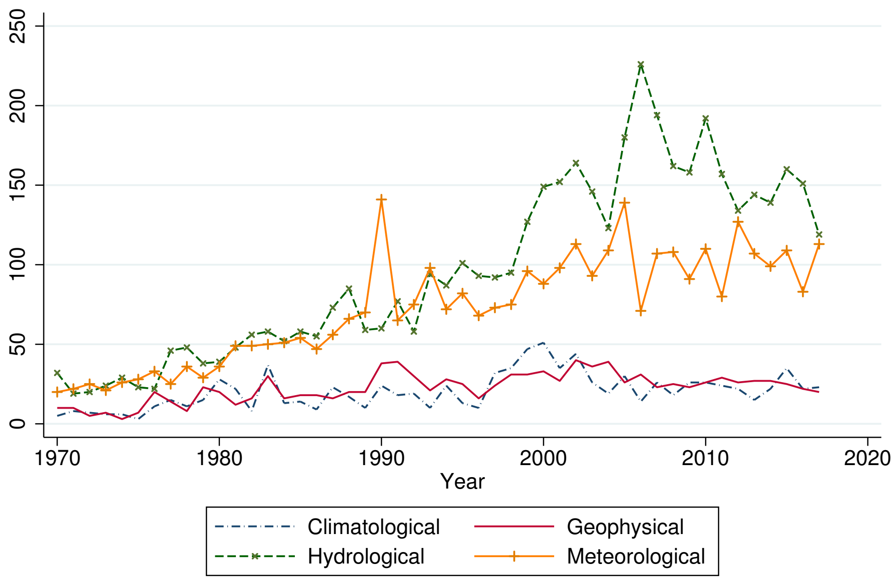
Note: This graph shows the evolution of people affected by natural disasters worldwide. Units are in millions and data points are five-year moving averages. *Source:* Author, based on EM-DAT database.

Figure A.3: Frequency of natural disasters relative to geophysical events (1980–2017)



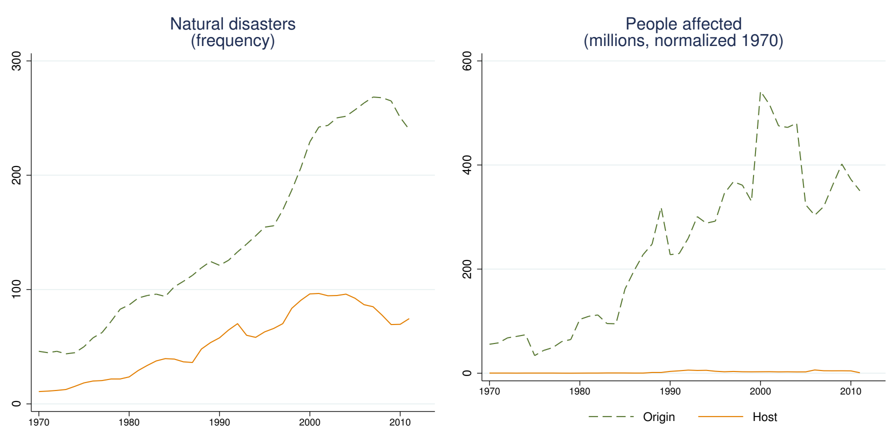
Note: This graph checks for reporting bias (unreported events) in early periods. Given that reporting bias might be orthogonal to disaster type and geophysical events are unrelated to climate change, the ratio between each disaster type and geophysical events should cancel any potential bias. The graph shows that this ratio presents the same trends as Figure A.1, indicating that the increasing pattern of disasters is not attributable to reporting bias. *Source:* Author, based on EM-DAT database.

Figure A.4: Frequency of large disasters by group (1970–2017) (Large disaster: $\geq$ 1,000 people affected or $\geq$ 100 deaths)



Note: This graph shows the evolution of large natural disasters, namely those events that have caused at least 100 deaths or directly affected at least 1,000 people. The pattern is very similar to Figure A.1, indicating that the increase is not driven by small disasters that are potentially more likely to suffer from reporting bias. *Source:* Author, based on EM-DAT database.

Figure A.5: Host–origin comparison (1970–2014)



Note: This graphs shows the evolution of disasters and the number of people affected in host and origin countries, excluding geophysical events. The number of people affected is normalized by 1970 population. Y-axes variables are five-year moving averages. *Source:* Author, based on EM-DAT database.

B Empirical Analysis: Alternative Specifications and Robustness Checks

This section presents alternative specifications and robustness checks to the empirical analysis. To address the presence of zero values in the dependent variable, column (1) in Table B.1 presents the results under a zero inflated negative binomial (ZINB) model specification.[1] The main estimate of interest remains positive and significant. Columns (2) and (3) examine bilateral migration flows, with the dependent variable defined as I_{ijt}, where i corresponds to the country of origin and j to the destination country. The main conclusions hold true under bilateral flows, both in logarithmic form and under a ZINB framework.[2] While not explicitly visible in the table, this pattern remains consistent after controlling for country time trends[3].

It is interesting to compare the migration response between poor and middle-income countries. Previous studies on international climate (non-forced) migration have found a greater migration response among higher income countries, suggesting that migration costs render it unaffordable for the very poor (Cattaneo and Peri 2016, among others). To investigate whether forced climate migrants respond differently than overall climate migrants, column (4) of Table B.1 introduces an interaction term between the frequency of natural disasters and a dummy variable denoting poor countries.[4] The estimate of the interaction term is positive and significant, indicating that poorer countries affected by natural disasters exhibit a stronger migration response. Hence, unlike general climate migration, the migration response to natural disasters does not seem to be driven by middle-income countries, i.e., migration costs are less relevant when the reason for migrating is a natural disaster.

The baseline log-log specification transforms the main independent variable following log(1+#ND). This avoids losing observations as a result of the logarithmic transformation of zero values. However, given that the mean value of observations is low, this could raise a concern of creating a large bias in the estimates. To assess this, Table B.2 presents regression estimates for three-year non-overlapping windows. This reduces the number of observations with a zero value in the independent variable and it more than doubles its

[1] Still, the share of zeros in the dependent variable is low enough to be non-problematic.

[2] With bilateral flows, the dependent variable exhibits a larger share of zeros. This requires the use of a ZINB model, which accommodates the excess of zeros generating them with a different process.

[3] Accounting for the time trends of recipient countries addresses the possibility that their level of receptiveness may vary overtime.

[4] The specification follows Cattaneo and Peri (2016), which considers poor countries those in the bottom quartile of the GDP per capita distribution in 1990.

Table B.1: Alternative Specifications and Income Heterogeneity

	Bilateral flows			
	zinb	log(#mig+1)	zinb	Income
	(1)	(2)	(3)	(4)
Nat. Disasters (#)	0.012		0.134	
	(0.006)		(0.009)	
log(Nat. Disasters (#))		0.163		0.025
		(0.010)		(0.053)
log(Nat. Disasters (#))*Poor				0.298
				(0.110)
FE (C, T)	Y	Y	Y	Y
Population_{t-1}, pcGDP_{t-1}	Y	Y	Y	Y
Observations	4731	92445	93976	4667
Countries	156	199	199	164

Notes: Standard errors, in parentheses, are clustered at the country level. Main sources: UN migration data, EM-DAT disaster data. Sample period: 1980-2013. Columns (1) and (3) use a zero inflated negative binomial (ZINB) specification, with the dependent variable in levels. Column (2) controls for origin-destination fixed effects. Column (4) adds an interaction between natural disasters and a dummy for poor countries (i.e., countries in bottom quartile of the GDP per capita distribution in 1990) and the dummy itself.

mean. The estimated coefficients increase more than twofold.

Table B.2: Regressions with 3-year periods

Dep var: log(# migrants)	(1)	(2)	(3)	(4)
log(Nat. Disasters (#))	0.204	0.207		
	(0.06)	(0.07)		
log(Affected (#))			0.022	0.023
			(0.01)	(0.01)
FE (C, T)	Y	Y	Y	Y
Population_{t-1}, pcGDP_{t-1}	N	Y	N	Y
Observations	1754	1608	1754	1608
Countries	165	165	165	165

Notes: Standard errors, in parentheses, are clustered at the country level. Main sources: UN migration data, EM-DAT disaster data. Sample period: 1981–2013. This table reproduces some regressions in Table 1 for natural disasters and people affected by them, but using three-year observations instead of yearly observations. The sample size is smaller with controls due to missing observations for some countries.

Table B.3 checks that results are robust to alternative variable transformations and are not driven by a few countries. Column (1) replicates the main log-log regression using the logarithm of per capita migration as the dependent variable. Column (2) uses the inverse hyperbolic sinus (IHS) transformation of the dependent variable, which is particularly useful to deal with zeros in the dependent variable. China and India are the largest countries in the origin group, which might display differentiated response patterns to weather shocks. To check for that, column (3) excludes China and India and rules out that results are only driven by these two countries. Note that following the Kyoto Protocol criteria, South Korea and Singapore are considered origin countries. However, one could reasonably argue that they respond differently than other origin countries due to their socioeconomic characteristics. Excluding them from the sample does not change the main results (column 4), reassuring that these countries are not driving the results.

Table B.3: Additional robustness checks I

	Per capita	IHSin	w/o C, I	w/o S, SK
Dep var: log(# migrants)	(1)	(2)	(3)	(4)
log(Nat. Disasters (#))	0.077	0.131	0.091	0.094
	(0.04)	(0.06)	(0.04)	(0.04)
FE (C, T)	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	Y	Y	Y	Y
Observations	4575	4621	4508	4509
Countries	156	156	154	154

Notes: Standard errors, in parentheses, are clustered at the country level. Main sources: UN immigration data, EM-DAT disaster data. Sample period: 1980–2013. This table presents robustness checks. Column (1) presents results for the log-log specification and migration per capita. Column (2) uses the inverse hyperbolic sin transformation of the dependent variable. Column (3) reproduces the main log log regression excluding China and India. Column (4) excludes Singapore and South Korea.

Table B.4 checks that results are robust to alternative model specifications. Column (1) controls for conflict to rule out that results were driven by the relationship between climate change and conflict. I use the number of battle-related deaths from the World Bank database to proxy for conflict. Column (2) controls for the climate vulnerability index in (Closset et al., 2018). Column (3) controls for the second lag of the independent variable. From the coefficient of the second lag we can see that after two years of being hit by a natural disasters, there is still a some migration response. This shows that this paper takes a conservative approach when measuring climate migration, since it deliberately accounts only for the contemporaneous effect of natural disaster. Column (4) uses a polynomial regression, including the square of the occurrence variable. Results suggest there is no acceleration, but the estimate shows some concavity. Finally, column (5) uses a Poisson model. Results are robust to all these alternative specifications.

Table B.5 shows the log-log specification results for each disaster group. Every group presents positive estimates, with hydrological disasters having higher and significant magnitudes.

Table B.4: Additional robustness checks II

			Control 2nd lag	Polinomial	Poisson
Dep var: log(# migrants)	(1)	(2)	(3)	(4)	(5)
log(Nat. Disasters (#))	0.106	0.076	0.077	0.257	0.007
	(0.05)	(0.05)	(0.04)	(0.07)	(0.00)
Conflict (log)	0.059				
	(0.02)				
Climate Vulnerability		0.105			
		(0.00)			
log(Nat. Disasters (#))^2				-0.115	
				(0.03)	
log(Nat. Disasters (#))$_{t-2}$			0.112		
			(0.03)		
FE (C, T)	Y	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	N	Y	Y	Y	Y
Observations	750	4299	4469	4576	4576
Countries	85	144	156	156	

Notes: Standard errors, in parentheses, are clustered at the country level. Main sources: UN immigration data, EM-DAT disaster data. Sample period: 1980–2013. This table presents additional robustness checks. Column (1) controls for conflict, defined as the number of battle-related deaths from the World Bank database. Column (2) controls for the climate vulnerability index in (Closset et al., 2018). Column (3) controls for the second lag of the independent variable. Column (4) uses a second-order polynomial regression. Column (5) uses a Poisson model.

Table B.5: Regressions by Disaster Group

	Climatological	Hydrological	Meteorological
Dep var: log(# migrants)	(1)	(2)	(3)
log(Nat. Disasters (#))	0.047	0.165	0.009
	(0.06)	(0.05)	(0.05)
FE (C, T)	Y	Y	Y
Observations	5368	5368	5368
Countries	165	165	165

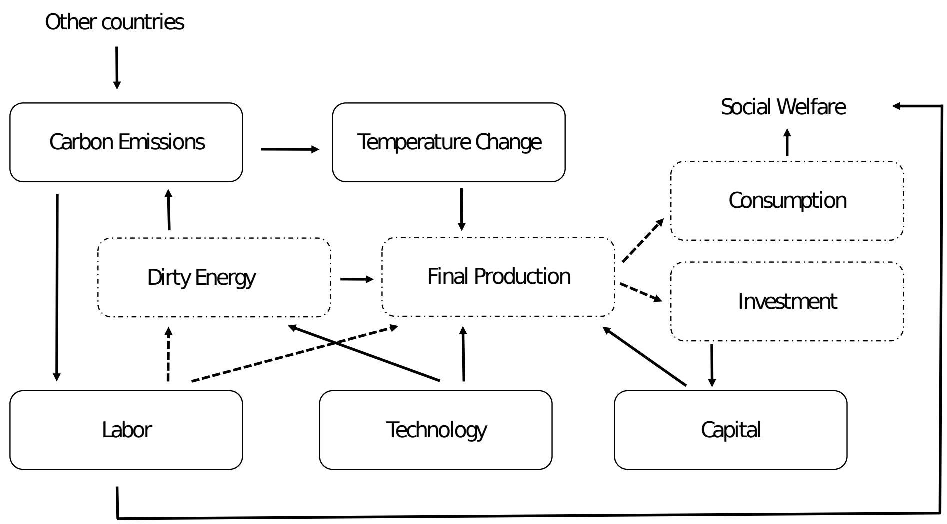
Notes: Standard errors, in parentheses, are clustered at the country level. Main sources: UN immigration data, EM-DAT disaster data. Sample period: 1980–2013. The table presents the relationship between disasters and migration to host regions by disaster subgroup.

C Theoretical model and mathematical derivations

C.1. Structure of the theoretical model

Figure C.1 depicts the main variables of the model and their interrelationships.

Figure C.1: Structure of the theoretical model



Note: Solid boxes characterize the state variables of the model. Dashed boxes represent flow variables. Dashed arrows represent choice variables.

C.5. The global planner solution. Proof of equation (13) and Proposition 2

The global planning problem is given by:

$$\max_{K_{rt+1},E_{rt}} \sum_{t=0}^{\infty} \beta^t \left[log \left(\sum_{r\in H} (P_{r0} + (P_{rt} - P_{r0})(1-\eta_{rt}))\, c_{rt} + \sum_{r\in O} P_{rt}c_{rt} - \sum_{r\in H} P_{r0}\gamma_r h_r I \right) \right]$$

subject to

$c_{rt} = \frac{Y_{rt} - K_{rt+1}}{P_{rt}}$

$Y_{rt} = \Omega_r(z_t) A_{rt} K_{rt}^{\alpha} \left(L_{rt}^{Y}\right)^{\upsilon} E_{rt}^{1-\alpha-\upsilon}$

$z_t = f(E_1, E_2, ..., E_t)$

$E_t = \sum_r E_{rt}$

$P_{rt} = P_{rt-1} + h_r i(\Delta z_{t-1})\, if\, r \in H$
$P_{rt} = P_{rt-1} - o_r i(\Delta z_{t-1})\, if\, r \in O$
$L^e_{rt} + L^Y_{rt} \leq L_{rt}$
$E_{rt} = A^e_{rt} L^e_{rt}$
$P_{rt} = L_{rt}$, since I assume $\kappa = 1$

To build the Lagrangian, let λ^{GSP}_{rt} be the shadow value of final outputs (Y_{rt}), ω^{GSP}_t of carbon concentrations (z_t) and μ^{GSPh}_{rt}, μ^{GSPo}_{rt} of population evolution in the host and in the origin regions, respectively. One can substitute the resource constraint into the objective function and E_t into z_t . The labor inequality is fulfilled in equality for every region. To simplify notation, I remove L^e_{rt} by solving E_{rt} for L^e_{rt} and plugging it into the production functions. The same applies for the labor clearing constraints. I assume $\kappa = 1$. Once again, I take a conservative approach and assume that immigration is only a function of the previous period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$. Let's also define $\Theta_{rt} \equiv P_{r0} + (P_{rt} - P_{r0})(1 - \eta_{rt})$.

The first order conditions (FOCs) of the planner problem are:

$[Y_{rt}]$:

$$\beta^t u'_t \frac{\Theta_{rt}}{P_{rt}} - \lambda^{GSP}_{rt} = 0\, if\, r \in H,$$

$$\beta^t u'_t - \lambda^{GSP}_{rt} = 0\, if\, r \in O.$$

$[K_{rt+1}]$:

$$-\beta^t u'_t \frac{\Theta_{rt}}{P_{rt}} + \lambda^{GSP}_{rt+1} \alpha \frac{Y_{rt+1}}{K_{rt+1}} = 0\, if\, r \in H,$$

$$-\beta^t u'_t + \lambda^{GSP}_{rt+1} \alpha \frac{Y_{rt+1}}{K_{rt+1}} = 0\, if\, r \in O.$$

$[z_t]$:

$$\sum_r \lambda^{GSP}_{rt} \overbrace{\frac{\partial Y_{rt}}{\partial z_t}}^{=\frac{\partial \Omega_{rt}}{\partial z_t}\overline{Y_{rt}}} - \omega^{GSP}_t = 0,$$

which implies that the shadow value of carbon concentrations at time t in the optimum equals the marginal utility loss generated by a lower production due to time t concentrations.

$[P_{ht}]$ for $r \in H$:

$$\beta^t u_t' \left((1-\eta_{rt}) \frac{Y_{rt} - K_{rt+1}}{P_{rt}} - \Theta_{rt} \frac{Y_{rt} - K_{rt+1}}{P_{rt}^2} \right) + \lambda_{rt}^{GSP} \overbrace{\frac{\partial Y_{rt}}{\partial P_{rt}}}^{= \upsilon \frac{Y_{ht}}{L_{rt} - \frac{E_{rt}}{A_{rt}^e}}} - \mu_{rt}^{GSPh} + \mu_{rt+1}^{GSPh} = 0.$$

Solving for μ_t, solving recursively and finally plugging in for λ_{t+j}^{GSP}:

$$\mu_{rt}^{GSPh} = \sum_{j=0}^{\infty} \left(\beta^{t+j} u_{t+j}' \left[-\frac{P_{r0}}{P_{rt+j}} \eta_{rt+j} \frac{Y_{rt+j} - K_{rt+1+j}}{P_{rt+j}} + \frac{\Theta_{rt+j}}{P_{rt+j}} \frac{\partial Y_{rt+j}}{\partial P_{rt+j}} \right] \right).$$

$[P_{ot}]$ for $r \in O$:

$$\lambda_{rt}^{GSP} \frac{\partial Y_{rt}}{\partial P_{rt}} - \mu_{rt}^{GSPo} + \mu_{rt+1}^{GSPo} = 0.$$

Plugging in for λ_{rt}^{GSP}, solving for μ_{rt}^{GSPo} and solving recursively yields:

$$\mu_t^{GSPo} = \sum_{j=0}^{\infty} \beta^{t+j} u_{t+j}' \frac{\partial Y_{rt+j}}{\partial P_{rt}}.$$

One has now obtained closed solutions for the shadow values λ, ω and μ's.

$[E_{rt}]$, under the assumption $i(\Delta z_{t-1}) = i^*(E_t)$:

$$\begin{aligned} & -\beta^{t+1} u_{t+1}' \sum_{r \in H} P_{r0} \gamma_r h_r \frac{\partial i(\Delta z_t)}{\partial E_{dt}} + \lambda_{rt}^{GSP} \overbrace{\frac{\partial Y_{rt}}{\partial E_{rt}}}^{= -\upsilon \frac{Y_{rt}}{P_{rt} - \frac{E_{rt}}{A_{rt}^e}} \frac{1}{A_{rt}^e} + (1-\alpha-\upsilon) \frac{Y_{rt}}{E_{rt}} \equiv NMPE_{rt}} \\ & + \sum_{j=0}^{\infty} \omega_{t+j}^{GSP} \frac{\partial f_{t+j}()}{\partial E_{rt}} + \sum_{r \in H} \mu_{t+1}^{GSPh} h_r \frac{\partial i(\Delta z_t)}{\partial E_t} - \sum_{r \in O} \mu_{t+1}^{GSPo} o_r \frac{\partial i(\Delta z_t)}{\partial E_t} \\ & = 0. \end{aligned}$$

This corresponds to equation (13), after solving for $\frac{\partial Y_{rt}}{\partial E_{rt}} \equiv NMPE_{rt}$. Proposition 2 follows from it.

C.6. The Nash equilibrium solution–host. Proof of equation (14) and Proposition 3

The local planning problem in a host region is:

$$\max_{K_{ht+1},E_{ht}} \sum_{t=0}^{\infty} \beta^t \left[log\left(P_{h0}c_{ht} - P_{h0}\gamma_h h_h I\right)\right]$$

subject to

$c_{ht} = \frac{Y_{ht}-K_{ht+1}}{P_{ht}}$

$Y_{ht} = \Omega_h(z_t)A_{ht}K_{ht}^{\alpha}\left(L_{ht}^{Y}\right)^{\upsilon}E_{ht}^{1-\alpha-\upsilon}$

$z_t = f(E_1, E_2, ..., E_t)$

$E_t = \sum_r E_{rt}$

$P_{rt} = P_{rt-1} + h_r i(\Delta z_{t-1})\, if\, r \in H$

$L_{ht}^{e} + L_{ht}^{Y} \leq L_{ht}$

$E_{ht} = A_{ht}^{e}L_{ht}^{e}$

$P_{ht} = L_{ht}$, since I assume $\kappa = 1$

To build the Lagrangian, let λ_t^{NEh} be the shadow value of final output (Y_{ht}), ω_t^{NEh} of carbon concentrations (z_t) and μ_t^{NEh} of labor evolution in the host (L_{ht}). One can substitute the resource constraint into the objective function and E_t into z_t . The labor inequality is fulfilled in equality. To simplify notation, I remove L_{ht}^{e} by solving E_{ht} for L_{ht}^{e} and plugging it into the production function. The same applies for the labor clearing constraint. I take a conservative approach and assume that immigration is only a function of the previous period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$.

The FOCs are:

$[Y_{ht}]$: $\quad \beta^t u_t' \frac{P_{h0}}{P_{ht}} - \lambda_t^{NEh} = 0.$

$[K_{ht+1}]$: $\quad -\beta^t u_t' \frac{P_{h0}}{P_{ht}} + \lambda_{t+1}^{NEh}\alpha\frac{Y_{ht+1}}{K_{ht+1}} = 0.$

$$[z_t]: \quad \lambda_t^{NEh} \overbrace{\frac{\partial Y_{ht}}{\partial z_t}}^{=\frac{\partial \Omega_{ht}}{\partial z_t}\overline{Y_{ht}}} - \omega_t^{NEh} = 0,$$

which implies that the shadow value of carbon concentrations at time t in the optimum equals the marginal utility loss generated by a lower production due to time t concentration.

$$[P_{ht}]: \quad -\beta^t u_t' \frac{P_{h0}(Y_{ht}-K_{ht+1})}{P_{ht}^2} + \lambda_t^{NEh} \overbrace{\frac{\partial Y_{ht}}{\partial P_{ht}}}^{=\upsilon\frac{Y_{ht}}{L_{ht}-\frac{E_{ht}}{A_{ht}^{e}}}} - \mu_t^{NEh} + \mu_{t+1}^{NEh} = 0.$$

Solving for μ_t^{NEh}, solving recursively and plugging in for λ_{t+j}^{NEh}:

$$\mu_t^{NEh} = \sum_{j=0}^{\infty} \left(\beta^{t+j} u'_{t+j} \frac{P_{h0}}{P_{ht+j}} \left[- \frac{Y_{ht+j} - K_{ht+1+j}}{P_{ht+j}} + \frac{\partial Y_{ht+j}}{\partial P_{ht+j}} \right] \right).$$

Thus, the shadow value of labor in the host country is equal to the sum of all future wedges between marginal production and average consumption.

Assuming $i(\Delta z_{t-1}) = i^*(E_t)$, the FOC with respect to $[E_{ht}]$ is:

$$\begin{aligned} & - \beta^{t+1} u'_{t+1} P_{h0} \gamma_r h_r \frac{\partial i(\Delta z_t)}{\partial E_{ht}} + \beta^t u'_t \frac{P_{h0}}{P_{ht}} \overbrace{\frac{\partial Y_{ht}}{\partial E_{ht}}}^{= -\upsilon \frac{Y_t}{L_t - \frac{E_t}{A^e_{ht}}} \frac{1}{A^e_{ht}} + (1-\alpha-\upsilon) \frac{Y_{ht}}{E_{ht}} \equiv NMPE_{ht}} \\ & \sum_{j=0}^{\infty} \omega_{t+j}^{NEh} \frac{\partial f_{t+j}()}{\partial E_{ht}} + \mu_{t+1}^{NEh} \frac{\partial i(\Delta z_t)}{\partial E_{ht}} \\ & = 0. \end{aligned}$$

As before, this corresponds to equation (14). Proposition 3 follows from it.

C.7. Nash equilibrium solution–origin. Proof of equation (15) and Proposition Proposition 4

The local planning problem in an origin region is:

$$\max_{K_{ot+1}, E_{ot}} W_{ot} = \sum_{t=0}^{\infty} \beta^t log \left[P_{ot} c_{ot} + \sum_{l \in H} \left(c_{lt} \left(1 - \eta_{rt} \right) \sum_{m=0}^{t\text{-}1} h_l o_o I_{t-m} \right) \right]$$

subject to

$c_{rt} = \frac{Y_{rt} - K_{rt+1}}{P_{rt}}$

$Y_{rt} = \Omega_r(z_t) A_{rt} K_{rt}^{\alpha} \left(L_{rt}^Y \right)^{\upsilon} E_{rt}^{1-\alpha-\upsilon}$

$z_t = f(E_1, E_2, ..., E_t)$

$E_t = \sum_r E_{rt}$

$P_{ht} = P_{ht-1} + h_h i(\Delta z_{t-1}) \, for \, r \in H$

$P_{ot} = P_{ot-1} - o_o i(\Delta z_{t-1}) \, for \, r \in O$

$L_{rt}^e + L_{rt}^Y \leq L_{rt}$

$E_{ot} = A_{ot}^e L_{ot}^e$

To build the Lagrangian, let λ_t^{NEo} be the shadow value of final output, ω_t of carbon concentrations and μ_t^{NEho}, μ_t^{NEo} of labor evolution in the host (P_{ht}) and in the origin region

(P_{ot}), respectively. One can substitute the resource constraint into the objective function and E_t into z_t. The labor inequality is fulfilled in equality. To simplify notation, I remove L^e_{rt} by solving E_{rt} for L^e_{rt} and plugging it into the production function. The same applies for the labor clearing constraint. I take a conservative approach and assume that immigration is only a function of the previous period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$.

The FOCs are:

$[Y_{ot}]$:

$\beta^t u'_t - \lambda^{NEo}_{ot} = 0 \, for \, r \in O,$

$\beta^t u'_t \frac{1}{P_{rt}} (1 - \eta_{rt}) \sum_{m=0}^{t\text{-}1} h_l o_o I_{t-m} - \lambda^{NEo}_{rt} = 0 \, for \, r \in H.$

$[K_{ot+1}]: \quad -\beta^t u'_t + \lambda^{NEo}_{ot+1} \alpha \frac{Y_{ht+1}}{K_{ht+1}} = 0.$

$$[z_t]: \quad \lambda^{NEo}_{ot} \overbrace{\frac{\partial Y_{ot}}{\partial z_t}}^{=\frac{\partial \Omega_{ot}}{\partial z_t}\overline{Y_{ot}}} + \sum_{r \in H} \lambda^{NEo}_{rt} \overbrace{\frac{\partial Y_{rt}}{\partial z_t}}^{=\frac{\partial \Omega_{rt}}{\partial z_t}\overline{Y_{rt}}} - \omega^{NEo}_t = 0,$$

which adds up all the climate damages occurring to its own region plus the ones occurring in host regions, since origin natives have migrated there.

$$[P_{ot}]: \quad +\lambda^{NEo}_{ot} \overbrace{\frac{\partial Y_{ot}}{\partial P_{ot}}}^{=\upsilon \frac{Y_{ot}}{P_{ot} - \frac{E_{ot}}{A^e_{ot}}}} - \mu^{NEo}_t + \mu^{NEo}_{t+1} = 0.$$

Solving for μ_t, solving recursively and plugging in for λ_{t+j}:

$$\mu^{NEo}_t = \sum_{j=0}^{\infty} \beta^{t+j} u'_{t+j} \frac{\partial Y_{ot+j}}{\partial P_{ot+j}}.$$

$[P_{ht}]$:

$\beta^t u'_t \left[\sum_{l \in H} \left(-\frac{Y_{lt} - K_{lt+1}}{P^2_{lt}} (1 - \eta_{rt}) \sum_{m=0}^{t\text{-}1} h_l o_o I_{t-m} \right) \right] + \sum_{l \in H} \lambda^{NEo}_t \frac{\partial Y_{lt}}{\partial P_{lt}} - \mu^{NEoh}_t + \mu^{NEoh}_{t+1} = 0.$

Plugging in for ω_t, solving for μ^o_t and solving recursively yields:

$$\mu^{NEoh}_t = \sum_{j=0}^{\infty} \left(\beta^{t+j} u'_{t+j} \sum_{l \in H} \left[\left(\frac{\partial Y_{ht+j}}{\partial L_{ht+j}} \frac{1}{P_{lt+j}} - \frac{Y_{lt+j} - K_{lt+1+j}}{P^2_{lt+j}} \right) (1 - \eta_{rt+j}) \sum_{m=0}^{t\text{-}1\text{+}j} h_l o_o I_{t-m} \right] \right).$$

Assuming $i(\Delta z_{t-1}) = i^*(E_t)$, the FOC with respect to $[E_{ht}]$ is:

$$\lambda_{ot}^{NEo} \overbrace{\frac{\partial Y_{ot}}{\partial E_{ot}}}^{=-\upsilon \frac{Y_{ot}}{P_{ot}-\frac{E_{ot}}{A_{ot}^{e}}}\frac{1}{A_{ot}^{e}}+(1-\alpha-\upsilon)\frac{Y_{ot}}{E_{ot}}\equiv NMPE_{ot}} + \sum_{j=0}^{\infty} \omega_{t+j}^{NEo} \frac{\partial f_{t+j}()}{\partial E_{ot}} + \mu_{t+1}^{NEoh} \frac{\partial i(\Delta z_t)}{\partial E_{ot}}$$

$$- \mu_{t+1}^{NEo} \frac{\partial i(\Delta z_t)}{\partial E_{ot}} + \sum_{j=1}^{\infty} \beta^{t+j} u'_{t+j} \left(\sum_{l \in H} \left(c_{lt+j} \left(1 - \eta_{rt}\right) h_l \frac{\partial i(\Delta z_t)}{\partial E_{ot}} \right) \right)$$

$$= 0.$$

As before, this corresponds to equation (15). Proposition 4 follows from it.

D Calibration

D.1 Social cost of immigration

I calibrate the social cost of immigration using data on different programs and policies. I complement these with World Bank data on consumption and population. To find domestic population's willingness pay to reduce immigration, I use the share of consumption per capita that, according to each different program or policy, they are willing to sacrifice to reduce the current stock of immigration. I compare this to actual consumption and calculate the hypothetical cost that would make them indifferent in both situations. In other words, I obtain the value for the social cost parameter γ solving the expression: $ln((1-\rho)c) = ln(c - \gamma * immigrants)$, where ρ denotes the share of per capita consumption that natives are willing to forgo according to each program/policy.

Details on Pay to Go Programs: The European Commission provides data on 2015 Pay to Go expenditures from individual countries[5] and the EU as an institution. For the calibration of the disutility parameter I use the expenditures for the so-called "Assisted Voluntary Return Programs".

E Additional Results

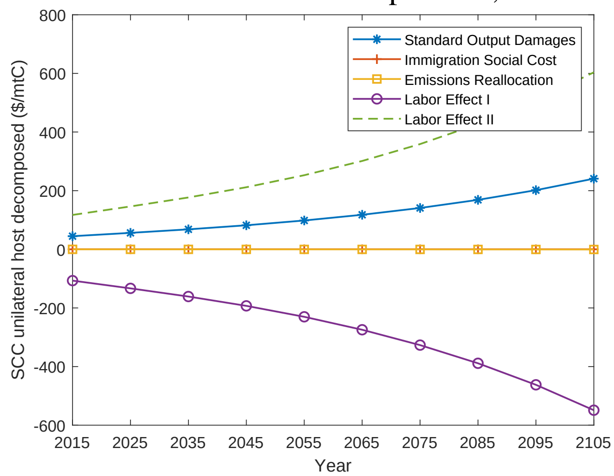
Unilateral SCC decomposition

Figure E.1 shows the decomposition of the unilateral host carbon price into the four components

[5]Individual countries include: Austria, Belgium, Bulgaria, Cyprus, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Malta, the Netherlands, Norway, Poland, Slovakia, Slovenia, Sweden and the United Kingdom.

presented in the main text. Note that the *Labor effect* component is disaggregated further into the positive and the negative externality originated by the increase in the population.

Figure E.1: Unilateral host SCC decomposition, without disutility

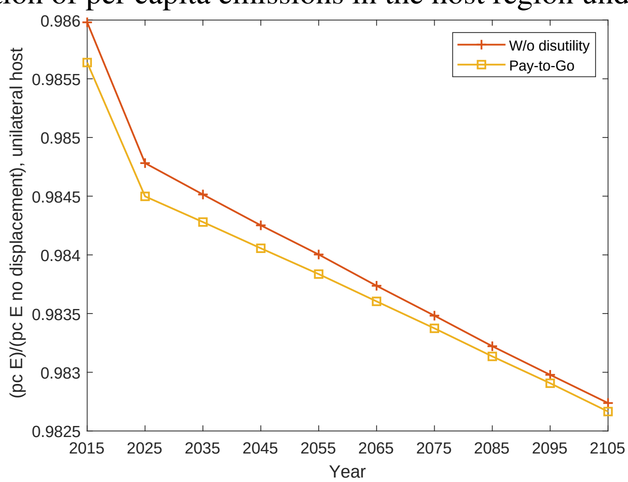


Notes: This figure shows the evolution of each component of the carbon price under the setting in which only the host country implements the carbon policy unilaterally. The disutility of immigration is zero.

Per capita emissions under the unilateral host policy scenario

Figure E.2 illustrates the evolution of per capita emissions in the host region for each scenario, relative to the scenario without forced climate migration.

Figure E.2: Evolution of per capita emissions in the host region under unilateral policy

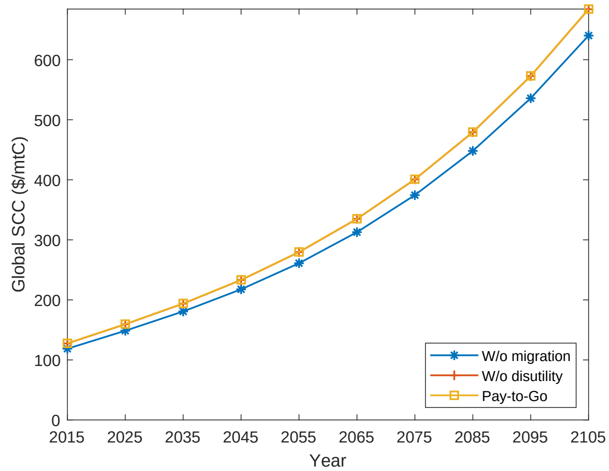


Evolution of the globally optimal carbon price

Figure E.3 illustrates the evolution of the globally optimal carbon price—equivalently, the global

SCC, under the three different scenarios detailed in the main text.

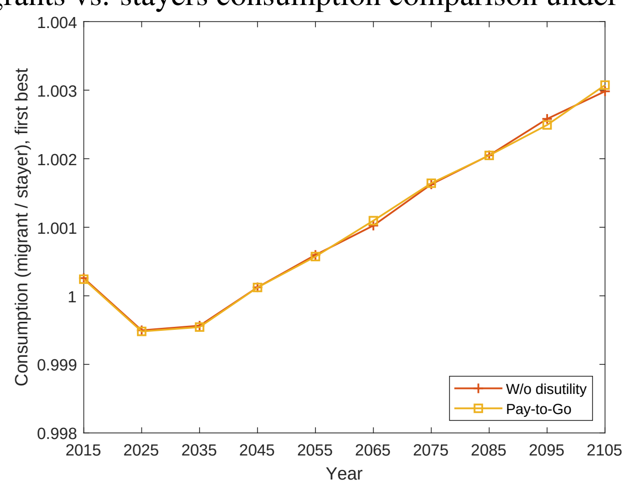
Figure E.3: Evolution of the first best carbon price



Consumption of forced climate migration

Figure E.4 shows that migrants experience only a minor consumption increase after a few decades.

Figure E.4: Migrants vs. stayers consumption comparison under first-best setting

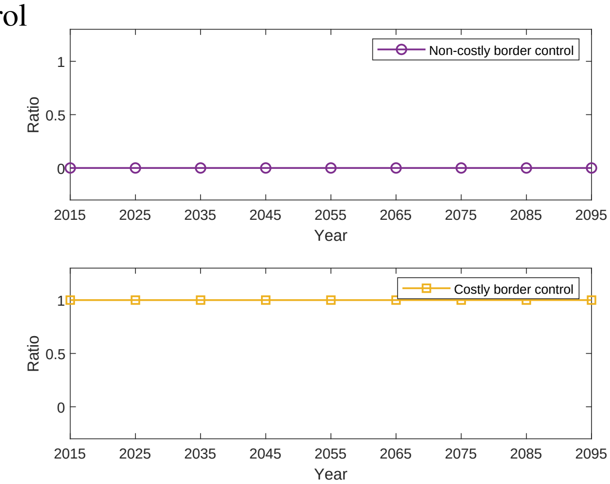


Notes: This figure shows migrants' consumption relative to origin stayers under the first best.

Displacement with border control

Figure E.5 shows the evolution of the number of forced migrants under a setting with border control policy, compared to the setting without border control.

Figure E.5: Number of migrants under border control relative to the number of migrants without border control



Notes: This figure presents the ratio between the number of migrants with border control and the number of migrants without border control for the first 100 years. The upper graph shows the case when border control is costless, while the lower graph shows the case when the cost of border control matches that in the United States.

Weaker decreasing marginal returns to labor

As detailed in the main text, the labor effect under the unilateral carbon policy scenario constitutes a cost because of: i. the inclusion of climate damages and; ii. capital depreciation. These two forces offset the benefit of having a larger labor force, hence the labor effect is a net cost.

The benchmark specification does not explicitly account for the benefits of population agglomeration (that is, doesn't present larger returns to labor). This, however, is not a concern because agglomeration forces have been found empirically meaningful when considering much smaller regions, such as cities, but not for groups of countries like in this study. Hence, the Cobb-Douglas specification is a sensible one. Still, in order to provide some intuition on how the main results would change if agglomeration forces were also present at a larger scale, Table E.1 presents the unilateral carbon taxes in the host country under a production function with weaker marginal returns to labor. More specifically, the following formulation has been used: $\tilde{Y_{ht}} = A_{ht} K_{ht}^{\alpha} \left(L_{ht}^{Y}\right)^{\upsilon} E_{ht}^{\varpi}$, where I set $\alpha = 0.3$, $\upsilon = 0.7$ and $\varpi = 0.04$, hence, $\alpha + \upsilon + \varpi > 1$.

Results, displayed in Table E.1, show that there is still an increase in the carbon tax after accounting for migration, yet lower. This is consistent with the fact that the costs of a larger population in the host region still offset the benefits, but now the benefits are larger in magnitude than under the benchmark scenario.

Alternative forced climate migration function

The benchmark model employs a conservative approach on the international displacement response

Table E.1: Unilateral carbon price in the host region, weaker marginal returns to labor

	Without FCM	With FCM	
		Without Disutility	With Disutility Pay to Go
	(1)	(2)	(3)
$ per ton of carbon	44.72	48.72	48.97

Notes: This table displays the unilateral carbon price in the Host region under weaker decreasing returns to labor. The calibration accounts for climatological and hydrological disasters.

to climate change. It assumes that only contemporaneous changes in concentrations lead to forced migration, disregarding any delayed effect of concentrations on natural disasters and its consequent migration response. In what follows, I relax this rigidity by introducing a migration response to the accumulated amount of carbon. More specifically, migrants are now determined by the change in concentrations with respect to the initial period. This means that current emissions contribute to future periods' migration as long as they have not fully dissipated. In the analytical expression for the carbon tax, this is captured by the fact that the migration increase due to a marginal increase in emissions, $\frac{\partial I_{t+1}}{\partial E_{ht}}$, now becomes $\sum_{q=1}^{j} \frac{\partial I_{t+q}}{\partial E_{ht}}$, that is, emissions today create new migrants in the following j years. Table E.2 presents the unilateral carbon prices in the host region, with an inactive origin region. As previously mentioned, under this alternative migration function, carbon prices increase more when considering migration compared to the benchmark—and more conservative—specification.

Table E.2: Unilateral carbon price in the host region, alternative migration function

	Without FCM	With FCM	
		Without disutility	With disutility
			Pay to Go
$ per ton of carbon	(1)	(2)	(3)
	44.72	56.96	57.21

Notes: This table presents the host region unilateral carbon prices with an inactive origin region, under an alternative forced climate migration function where emissions today cause migration in the future as long as they are not fully dissipated. The migration response to climate change is calibrated using climatological and hydrological disasters.

Alternative discounting, higher climate damages, and Negishi weights

Following Nordhau's approach, I assume an annual discount factor, β, of 0.958. However, economists have long debated the appropriate value of this factor to quantify the effects of climate change, leading to significant disagreement. Stern (2007), among others, advocates for a 0.1% discount rate arguing that future losses are as worrying as losses today, so there should be almost no discounting. Panel B of Table E.3 displays the unilateral host carbon prices under Stern discounting, and Panel A reproduces the results under the Nordhaus discounting for comparison. As expected, carbon prices under Stern discounting are higher. Still, the main message of this paper remains unchanged.

IAMs use a damage function to integrate the climate into an economic growth model. However, we are uncertain about the right characterization of this function due to our limited understanding of the true economic impacts of climate change. In this paper, I borrow the functional form and calibration from GHKT.[6] Some scientists and economists have argued that this function leads to implausibly low damages. To account for this concern, I redo the quantitative analysis under a more severe consideration of climate damages. Panel C in Table E.3 presents carbon prices when the likelihood of "catastrophic" damages is three times higher than in GHKT's consideration. In particular, I use Nordhau's calibration for "catastrophic" damages. One can see that carbon prices increase twofold but, once again, the main message of this paper remain unchanged.

The first-best setting does not consider the distribution of consumption across countries. I now introduce the optimal global policy when the planner is concerned about consumption distribution. Specifically, the planner's objective is a weighted sum of the utilities of individuals based on their country of origin:

$$\max_{K_{rt+1},E_{rt}} W_t^{GSP^w} = \sum_{t=0}^{\infty} \beta^t \left[\sum_{r\in H} \Upsilon_r U\left(P_{r0}c_{rt} - P_{r0}\gamma_r h_r I_t\right) + \sum_{r\in O} \Upsilon_r U\left(P_{rt}c_{rt} + \sum_{l\in H} \left((1-\eta_{lt}) \left(\sum_{m=0}^{t\text{-}1} h_l o_r I_{t-m} \right) c_{lt} \right) \right) \right]$$

where Υ_r is a vector of constant regional weights, with $\sum_r \Upsilon_r = 1$. Weights are determined as the inverse of each region's marginal utility of consumption in the initial period.[7] Hence, individuals who originally come from poorer regions receive lower weights. This is similar to the commonly used approach based on Negishi weights (Stanton, 2011). The goal is to ensure that the initial distribution of consumption is preserved and results reflect the intention of addressing climate-

[6]The main parameter is θ, which scales the damage function. It is calibrated as a weighted average between a "moderate" damage and a "catastrophic" damage scenario.

[7]Regional weights are calculated as $\Upsilon_r = \frac{\frac{1}{U'_r}}{\sum_r \frac{1}{U'_r}}$.

Table E.3: Unilateral carbon price in the host region

	Without FCM	With FCM	
		Without disutility	With disutility
			Pay to Go
$ per ton of carbon	(1)	(2)	(3)
Panel A: Benchmark			
	44.72	54.95	55.17
Panel B: Stern discounting			
	147.48	160.07	160.35
Panel C: Higher climate damages			
	87.92	98.32	98.57

Notes: This table presents some sensitivity analysis of the short-term unilateral carbon prices for the host region. The migration response to climate change is calibrated using climatological and hydrological disasters. Panel A reproduces the benchmark results to facilitate the comparisons. Panel B presents the results under Stern discounting. Panel C presents the results under higher climate damages.

related issues.[8] Table E.4 presents the first-best carbon prices using regional weights. The main message of this paper remains unchanged.

[8] In other words, adding weights implies that the initial level of inequality is considered to be optimal within the planner's objective function.

Table E.4: First-best carbon prices with regional weights

	Without FCM	With FCM	
		Without disutility	With disutility
			Pay to Go
$ per ton of carbon	(1)	(2)	(3)
	118.23	126.26	126.51

Notes: This table presents the globally optimal carbon prices with regional Negishi weights. Individuals' utility is weighted based on their country of origin's initial consumption. The migration response to climate change is calibrated using climatological and hydrological disasters.

Labor differentiated by skill

I extend the model to accommodate high- and low-skilled labor in each region denoted L_{rt}^H and L_{rt}^L, respectively, with low-skilled being less productive. I use parameter $\rho_o^H \in (0,1)$ to represent the share of total emigrants from origin o that are high skilled (H). This parameters governs the fact that migration can be a function of skill. For instance, if $\rho_o^H = 1$ only high skilled individuals migrate from origin to host countries. In the unilateral policies setting, the analytical characterization of carbon taxes differs from the baseline model in one key aspect: the labor effect now distinguishes between the impact of each type of labor, that is:

$$Labor\ effect\ Unilateral\ host = \mu_{t+1}^{NEhH}(-1)\rho_o^H \frac{\partial i(E_t)}{\partial E_{ht}} + \mu_{t+1}^{NEhL}(-1)(1-\rho_o^H)\frac{\partial i(E_t)}{\partial E_{ht}},$$

where μ_{t+1}^{NEhH} is the shadow value of high-skilled population in the host country and μ_{t+1}^{NEhL} of low-skilled labor.

Based on Gottlieb, Poschke and Tueting (2024), I assume that in the host region 80% of the population is high-skilled, while in the origin region only 30% is high-skilled. The quantitative results under the unilateral (Nash equilibrium) policy case show three interesting results. First, when migrants move proportionally (only 30% of migrants are high-skilled), the host's carbon tax rises substantially more than in the baseline model, while the origin's remains almost unchanged. This means that the host suffers from receiving an inflow of mainly low-skilled. Second, in the more extreme case where only high-skilled workers migrate, the host's carbon tax increases but less than in the original setting, while the origin's carbon tax becomes larger than without migration. Third, if only low-skilled workers migrate, the host's carbon tax rises the most, while the origin's falls slightly compared to no migration. In this last case, this apparent "gain" for the origin, however, occurs only in the implausible case where exclusively low-skilled workers leave, since in reality high-skilled individuals are more likely to migrate (Docquier, 2014).

Mobile capital

The model can be extended to accommodate capital mobility. In the global planner setting, this requires an additional decision variable that captures the share of world capital allocated to each region, as well as an additional constraint, namely that global capital stock, K_t^W, cannot exceed the sum of regional capital stocks, i.e., $K_t^W \leq \sum_r K_{rt}$. Capital flows to the regions where it is most productive, so that in equilibrium the marginal products of capital (MPK_r) equalize across regions. Hence, the optimality condition for capital allocation in the global planner's problem is

$$\frac{\Theta_{ht}}{P_{ht}} MPK_{host,t} = MPK_{origin,t}$$

In the unilateral case, each country decides how much capital to borrow or lend in each period. The world interest rate r_t is determined endogenously. The new regional budget constraint is: $C_{rt} = Y_{rt} - K_{rt+1} - (1 + r_t)K_{rt}^{ROW}$, where K_{rt}^{ROW} is the amount of capital that region r borrows from the rest of the world in period t. In equilibrium, capital borrowing and lending satisfy:

$$(1 + r_t) = MPK_{r,t}.$$

That is, each region borrows or lends until its marginal product of capital equals the world interest rate. This condition pins down the world interest rate.

Theoretically, carbon taxes remain unchanged. Quantitatively, the unilateral carbon taxes are almost unchanged to the original setting. The same applies to the the globally optimal carbon taxes, as long as one neutralizes the incentives to correct for capital misallocations that are common in models of this type.

Time-inconsistent planners

Suppose that, instead of local planners, the economy is planned by local governments seeking to maximize the welfare of their resident population. In this case, host governments care about both natives and migrants, while origin governments care only about stayers. Such set-up leads to a time inconsistency, since governments would wish to re-optimize the maximization problem in each period as their resident population changes.

Allowing for time inconsistency does not substantially alter the quantitative results, though it does lead to slightly higher taxes over time. This is because climate damages become more salient and, with larger resident populations, host governments have stronger incentives to curb emissions.

F Extension with micro-founded migration

The model can be modified to include micro-founded migration, allowing individuals to make migration decisions based on economic factors. This reduces analytical tractability, making it impossible to derive closed-form solutions for carbon taxes. The following outlines the key modifications to the model and the main results for the setting with unilateral action in the host region only.

The economic setting remains the same, featuring one host and one more vulnerable and less economically developed origin region that does not take any climate action. However, instead of being forced to migrate due to climate change-induced disasters, individuals in the origin now base their migration decisions on the current per capita consumption in each region.[9] More specifically, at the end of each period, agents decide the location of their offspring based on per capita consumption in each region and the migration cost, η_{ot}. Agents are myopic, and can only observe current total consumptions in each region, which they take as given, and current population levels. Individuals will move from the origin to the host until per capita consumption equalizes. Hence, in equilibrium, the following must hold:

$$\frac{C_{ht}(1-\eta_{ot})}{P_{ht}+MigFlow_t}=\frac{C_{ot}}{P_{ot}-MigFlow_t},$$

where $Migflow_t$ stands for the migration flow from origin to host at time t . This leads to a per period migration flow of: $MigFlow_t=\frac{C_{ht}(1-\eta_{ot})P_{ot}-C_{ot}P_{ht}}{C_{ht}(1-\eta_{ot})+C_{ot}}$.

The origin region is in the laissez faire and it is straightforward to show that will save a constant fraction of output, given by $s=\beta\alpha$. Together with the characterization of origin regional emissions in (11), this allows for determining the migration flow in each period. The migration costs are calculated such that, absent climate change, individuals in the origin region have no incentives to migrate to the origin regions. Hence, the micro-founded migration flows are climate-related.

In the optimum, the host planner will allocate energy use such that the private marginal product of energy ($NMPE_h$) equals the social cost of energy use. For that reason, I estimate the carbon tax following the expression: $\tau_{ht}=NMPE_{ht}$.

Table F.1 shows the main results. One can see that the carbon tax is higher with micro-founded migration. This indicates that the efforts to mitigate climate change would be higher if all climate-related migration was accounted for.

[9] Production, and consumption, are affected by climate change as in the baseline model.

Table F.1: Comparison cases: no migration, forced climate migration and micro-founded climate migration

	Without migration	Forced climate migration	Micro-founded migration
$ per ton of carbon	(1)	(2)	(3)
	44.72	54.92	75.80

Notes: This table presents the host region unilateral carbon prices with an inactive origin region, without migration, with forced climate migration and with micro-founded climate migration only.

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