Warming with Borders: Climate Refugees and Carbon Pricing

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Abstract

As climate changes and natural disasters intensify, the threat of large and sudden human displacement increases. This paper explores how carbon should be taxed in the presence of international displacement caused by climate change. It first provides empirical evidence on the migration response to natural disasters from developing to developed countries. Second, it introduces climate refugees into a climate-economy growth model and theoretically characterizes global and unilateral optimal carbon prices taking into account the economic and social impact of climate refugees. Third, it quantifies global and unilateral carbon prices in a North-South calibration. The main finding is that forced migration enhances the incentives of host regions to fight climate change—with a 26% increase in the unilateral carbon price, more so if political conflict is taken into account. This stands in contrast to the global and the unilateral policy in origin regions, which barely change in magnitude after accounting for the presence of climate refugees.

Keywords: Climate change; Climate refugees; Optimal policy; Unilateral policy; Carbon tax
JEL classification: E13; F22; F64; H23; O13; Q50

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1 Introduction

A large number of scientific studies have found that climate change increases the frequency and intensity of natural disasters (Fischer and Knutti 2015; Thomas and López 2015). For instance, record-breaking heatwaves will be between two to seven times more likely in the next thirty years according to recent projections (Fischer, Sippel, and Knutti 2021). Moreover, natural disasters affect people living in developing regions more severely (Closset et al. 2018), which makes them potential triggers for massive human displacement. Hence, displacement ought to be accounted for as an economic impact of global warming. The economic literature, however, has ignored climate refugees in assessing optimal environmental policies.

In this context, this paper makes three contributions. First, it empirically documents the effect of natural disasters on forced migration from developing to developed countries. Second, it theoretically analyzes the impact of such displacement on optimal carbon policies within different settings. Third, it calibrates each setting and quantifies global and unilateral carbon prices. I demonstrate that taking into account climate refugees strongly affects the incentives of developed countries to fight climate change. In other words, developed countries should selfishly pursue greener unilateral policies when facing potential inflows of population. This stands in contrast to the global policy, which does not change much in magnitude after accounting for the presence of climate refugees. In what follows, I discuss these contributions in detail.

Although the term climate refugee does not exist in international law, I use it to refer to individuals that are forced to move internationally due to natural disasters.[1] In order to document this phenomenon, I use historical country data on population flows and natural disasters. I find a strong positive effect of natural shocks on contemporaneous migration from developing to developed countries, with a semi-elasticity of 3%. The novelty of this result is twofold. First, existing studies typically target general climate migration, that is, migration as a response to slow and progressive changes in climate such as temperature, and they identify it using an intermediate trigger, generally agriculture deterioration.[2] Instead, I analyze displacement as a consequence of warming-induced natural disasters, which provides new insights on unavoidable and forced migration. Second, to the best of my knowledge, this is the first study that uses a global yearly panel and focuses on migration flows from developing to developed countries.

Motivated by the empirical findings, I examine the effects of climate refugees on carbon policies by introducing climate displacement into an integrated assessment model (IAM) a la Golosov et al. (2014) (GHKT). The model features multiple regions that are grouped in host and origin regions. The use of a dirty energy resource contributes to climate change, which more severely affects origin regions. Following an increase in global carbon concentrations, some individuals from origin regions

[1] In contrast, the term climate migrant is substantially broader as it includes both national and international migrants that either choose or are forced to move for any environmental reason (IOM 2007). The Report of the United Nations High Commissioner for Refugees, reissued in 2018, recognizes that "climate, environmental degradation and disasters increasingly interact with the drivers of refugee movements" ((UNHCR) 1997, p.2). Due to the lack of data on climate-forced international displacement, the existence and magnitude of climate refugees is still an open empirical question.

[2] In the long-run, adaptation to climate change can mitigate this type of migration.

are forced to move to host regions. Hence, energy emissions are the source of two distinct externalities: they directly damage production and generate population flows. Because these externalities originate from the same source, a unique policy instrument is enough to correct for them. This framework can also consider another aspect of migration. Recent electoral outcomes in Europe and the United States suggest that citizens sometimes have negative views of immigrants.[3] As far back as the 1990s, the first Intergovernmental Panel for Climate Change (IPCC)[4] report highlighted that future flows of climate migrants could have social impacts in the form of political conflict or social instability. This social cost of immigration—or anti-immigrant sentiment—is the source of a third externality to the use of emissions that can vary in intensity, if any. In order to analyze its impact on carbon prices, my model accounts for it in a reduced-form way, as a direct utility cost.

My theoretical findings include analytical expressions of optimal carbon prices under three different settings: i. when only developed countries undertake climate action unilaterally, ii. when a global agreement is in place, and iii. under a Nash equilibrium with multiple countries. I first focus on the setting with unilateral climate action in host regions and show that climate refugees lead to a more stringent unilateral policy. That is, the existence of forced displacement impacts the welfare of host regions negatively, and thus governments are more willing to abate emissions, for three reasons. First, emissions per capita are usually higher in developed regions; hence, migration increases emissions and environmental damages. Second, a larger population lowers per capita consumption as it reduces the per capita availability of the environmental good, which is finite and deteriorates with pollution. The same dilution happens with capital, which cannot be adjusted immediately. Third, there may be some direct utility cost of immigration.

In my quantitative analysis I find that without climate refugees the unilateral price for host regions is around USD 44 per ton of carbon, which is in line with existing studies. However, in the presence of climate refugees, host countries should be willing to increase their carbon price by at least 26%. In fact, this is only a lower bound. If one is willing to consider the direct utility cost of immigration, the optimal carbon price should be boosted further. Specifically, I calibrate such a utility cost using three different measures: i. the European Union's (EU) "pay to go programs", ii. the EU-Turkey agreement on refugees, and iii. a survey on the willingness to pay to reduce immigration conducted in the United Kingdom after the 2016 Brexit referendum. I find the carbon price can increase up to fivefold, depending on which measure of the disutility from immigration is used. This indicates that countries with strong anti-immigrant sentiment would benefit from more-stringent environmental action.

I then derive analytical expressions and quantify the globally optimal social cost of carbon[5] (SCC) and the non-cooperative carbon prices under a Nash equilibrium. I show that the theoretical characterization of the globally optimal carbon tax changes compared to the standard one that does not account for climate refugees. In particular, the global planner internalizes any potential benefit

[3]For instance, the former United States president Donald Trump obtained 48.5% of the popular vote in November 2020 with a clear anti-immigration electoral agenda. Müller and Schwarz (2020) document that the 2015 inflow of refugees into Germany combined with antirefugee sentiment on Facebook predicts hate crimes against against refugees.

[4]The IPCC, is the United Nations body in charge of assessing scientific knowledge related to climate change.

[5]The SCC is the monetary value of current and future damages caused by a marginal increase in emissions.

of reallocating refugees to less vulnerable areas, as well as any potential economic—and social—cost suffered by individuals in origin and destination countries as a consequence of refugees. In the quantitative exercise, I find that, in the presence of a global agreement, the first-best policy increases with climate migration only slightly, as long as there is not a large disutility cost of migration. The increase is only temporary and due to the fact that per capita emissions in developed regions are higher. Hence, if population moves to more developed and polluting areas, the carbon policy should be slightly more stringent at the beginning. However, in the longer run, this is no longer the case because the benefits of reallocating population to low vulnerable areas dominate. In the Nash equilibrium exercise, I show that host and origin regions are affected by climate refugees in opposite ways. Before accounting for climate refugees, the unilateral carbon price is almost two times higher in origin regions because those regions are more vulnerable to climate change and more populated. However, once I account for climate refugees, there is some degree of convergence, that is, the unilateral price increases in host regions and slightly decreases in origin regions.

Instead of analyzing the more general phenomenon of climate migration, this paper deliberately focuses on climate refugees. I do so to provide a well-identified quantification of carbon policies with climate-induced migration. By looking at the contemporaneous migration effect of natural disasters, I ensure that my empirical estimates capture migration responses to climate change only. On the contrary, identifying the migration response to slow and progressive changes in climate is challenging because when individuals decide to migrate, they are typically motivated by multiple reasons. Hence, by taking this approach, I provide a lower bound, yet properly identified, quantification of the effects of climate migration on environmental policy.

In the main extension to this model, host countries have the possibility of investing in border control as a way to stop the inflows of migrants. I find that this partially offsets the effects of refugees on regional policies only when deportation costs are low enough. Hence, host countries may prefer to use border control instead of climate policies to mitigate the effects of climate refugees, but that is only the case when the cost of implementing border control is very low.

The analysis further relates to the literature in the following ways. On the theoretical side, this paper contributes to the literature on optimal carbon policies and integrated assessment models (IAMs), which has abstracted so far from forced climate migration. There is a very recent strand of literature that analyzes the interaction of long-run climate change and migration without looking at optimal and unilateral carbon policies. Cruz Alvarez and Rossi-Hansberg (2021), Bretschger and Xepapadeas (2021) and Beneviste, Oppenheimer, and Fleurbaey (2020) employ dynamic gravity models with global warming and provide interesting insights of long-term projections of welfare and population reallocation. Although these are the most closely related to this study, other papers also look at the phenomenon of climate migration. Burzynski et al. (2019) account for internal and international migration in a non-IAM dynamic overlapping generations model, considering a rich set of exogenous scenarios of climate change. Mason (2017) working paper also builds a non-IAM dynamic model with climate migration and analyzes theoretically the abatement incentives of host regions. Shayegh (2017) looks at how exogenous carbon concentrations affect climate migration

and the living conditions of those who cannot migrate and find that since stayers may change their fertility and education decisions as a consequence of population outflows, their welfare conditions may improve. I complement this literature by analyzing global and unilateral carbon policies, both theoretically and quantitatively, and by focusing on climate refugees. I also contribute to the literature on unilateral policies, represented by Elliott and Fullerton (2014), among others, which commonly analyze the emissions leakage effect of unilateralism.

This paper also sheds light on the causal relationship between climate change and climate refugees. Although there has been substantial research on the impacts of climate change on migration (see Kaczan and Orgill-Meyer (2020) for a recent review), studies on forced migration are almost nonexistent. My paper contributes to this literature by conducting a worldwide analysis and providing strong evidence that natural shocks cause international displacement from developing to developed countries. In addition, contrary to the literature on general climate migration, I find that the response is not driven by middle-income countries. Among the existing studies on general migration, most focus on internal migration (Gröger and Zylberberg 2016; Partridge, Feng, and Rembert 2017; Peri and Sasahara 2019). A smaller, but growing, literature analyzes international migration (Coniglio and Pesce 2015; Cai et al. 2016). This literature usually identifies an intermediate trigger for migration such as agricultural deterioration (Cattaneo and Peri 2016), wages (Beine and Parsons 2017) or conflict (Burke, Hsiang, and Miguel 2015; Bosetti, Cattaneo, and Peri 2020). Although some of these studies provide evidence of a link between slow-onset climate change and international migration, with high variation in the magnitudes, results are oftentimes inconclusive. Overall, a consensus on the appropriate empirical methodology is still lacking and natural disasters are either not accounted for or used as second-order covariates (Beine and Parsons 2017). In this paper, I identify forced migration as the migration response to natural shocks. The limited number of existing studies that analyze the effect of natural disasters either focus on internal migration (Bohra-Mishra, Oppenheimer, and Hsiang 2014) or on a small subset of contiguous countries (Naudé 2010) and find either a small or no migration response to short-term shocks. Alexeev and Reuveny (2018) also use a global panel. However, their empirical approach is substantially different to the one in this paper, since they focus on bilateral flows, include non-weather disasters and account for over fifty additional explanatory variables.

The rest of the paper is organized as follows. Section 2 presents empirical evidence on climate-forced migration. The theoretical model is described in Section 3. Section 4 presents the theoretical results, calibration, and simulation results under a host-origin region setting with climate action in the host region only. Section 5 presents the globally optimal and the Nash equilibrium settings. Section 6 contains the model extensions. Finally, Section 7 concludes.

2 Empirical Evidence on Climate Refugees

Identifying the causal relationship between global warming and forced international migration is complex because individuals' reasons for leaving their homes can be multiple and have different

natures. This section presents an empirical approach to address this challenge by exploiting the randomness of natural disasters. The analysis serves three main purposes: i) it motivates the paper; ii) it provides evidence of the existence and magnitude of climate refugees; iii) it allows me to calibrate an important parameter of the theoretical model, namely, the relationship between climate refugees and global warming.

2.1 Data

A. Natural disasters

I use natural disasters data from the Emergency Events Database (EM-DAT).[6] As pointed out by Thomas and López 2015, the total number of recorded natural disasters has increased drastically in recent decades, from 363 between 1970 and 1974 to over 1,600 between 2010 and 2014. The sharp increase has been mostly driven by hydrological events (floods, landslides, coastal flooding) and meteorological events (storms, heatwaves)—see Figure 1.[7] Climatological events (droughts, wildfires) and geophysical events (earthquakes, volcanic eruptions) have experienced a lower increase. Given that geophysical events are not related with climate change, they will be excluded from the empirical analysis.

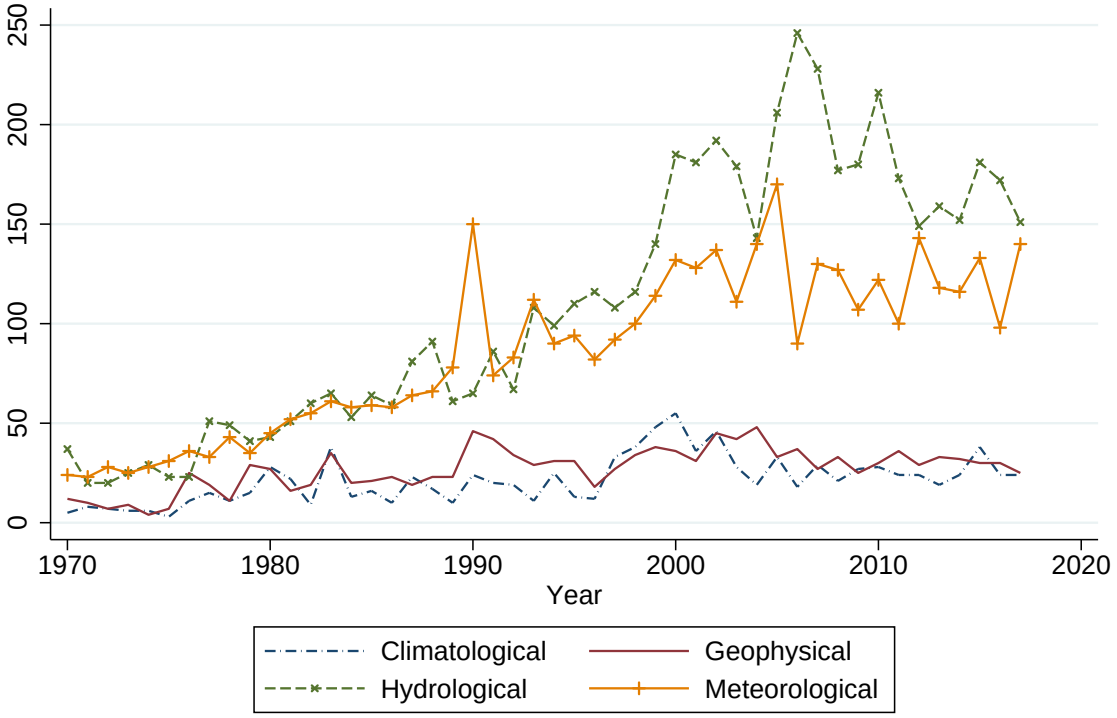
In line with the evolution of natural disasters, the number of people affected by these shocks has also increased, especially during the 1980s and 1990s (see Figures A1 and A2 in the Appendix). The increase is not driven by a mechanical effect of population growth because after normalizing the number of people affected by the country population in 1970, the variable presents a very similar evolution for all types of disasters (see Figure A3 in the Appendix).

One potential threat is that these positive trends are due to reporting bias, that is, the systematic underrecording of events happening earlier in the sample period. I check whether reporting bias is present in the EM-DAT data set using three different approaches. First, I exploit the non climate change-related nature of geophysical events. It is reasonable to assume that if reporting bias is present, it must be orthogonal to the disaster type. In other words, it is unlikely that some disaster types are subject to underrecording while others are not. Therefore, by taking the ratio of a warming-related disaster type to a non warming related type one can cancel the reporting bias, if any. Figure A4 in the Appendix plots the ratio between the frequency of each disaster type and geophysical disasters. It shows a clear upward trend for hydrological and meteorological ratios, enhancing the evidence that the pattern in Figure 1 is not driven by reporting bias but by global warming. Second, I follow Thomas and Lopez (2015) and exclude the events that have caused less

[6] The EM-DAT database is provided by the Center for Research on the Epidemiology of Disasters (CRED) of the Université Catholique de Louvain. It contains all the events since 1900 that have caused at least 10 deaths, have affected at least 100 people, or have prompted a declaration of a state of emergency or a call for international assistance.

[7] The evolution presents a slowdown around the mid-200s. This is consistent with natural disasters being related to temperature increases because it has been documented that temperatures increased substantially due to human activity between 1970 and 2000; there was a respite after 2000, but in recent years, temperatures have begun to increase again (Partridge, Feng, and Rembert 2017).

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



Note: This graph displays the evolution of natural disasters by disaster group since 1970. The variable frequency is defined as the total number of natural shocks in a year. *Source:* Author, based on data from EM-DAT database.

than 100 deaths or that directly affected less than 1,000 people, as these events are more likely to have suffered from reporting bias. Figure A5 in the Appendix shows that the pattern is almost identical once small events are excluded. Third, I use an alternative data set of natural disasters. While the first two approaches can exclude the existence of reporting bias in earlier periods, they could still underperform in detecting persistent underrecording in poorer areas.[8] To check for that, I replicate the empirical analysis using a different natural disasters data set, called GEOMET, which specifically takes this into account; the pattern persists. More details about this data set are provided in the robustness checks section.

B. Migration

I use international migration data from the United Nations (UN) migration flows tables. This data set reports the annual flows of international migrants as recorded by 43 destination countries—including most OECD countries—and it specifies immigrant's country of origin. I group world countries into potential host (destination) and potential origin countries based on the Annex I Parties of the Kyoto Protocol. The host group includes most European countries, the United

[8]Felbermayr and Gröschl (2014, p. 93) find that "the likelihood of some disaster with given physical magnitude being reported in EMDAT depends strongly on the affected country's GDP per capita."

States, Canada, Australia, and New Zealand.[9] These countries are merged and treated as a unique destination region. The rest of the world, that is, the origin regions, is kept unpooled in order to exploit the variation in the number of local natural disasters.

Natural disasters affect host and origin countries differently, both in terms of their frequency and severity. Figure 2 shows the evolution of natural disasters and the number of people affected by disasters, for each group of countries.[10] Even though the frequency of natural disasters has increased substantially over time in both groups, origin countries present a higher trend. Moreover, the vast majority of people affected by natural disasters live in an origin country. Figure A6 in the Appendix shows the number of deaths. Although they are higher in origin countries, the number of deaths has decreased significantly since the 1970s. The contemporaneous correlation between out migration and natural disasters is positive and substantial for many countries—see Figures A7 and A8 in the Appendix. All figures exclude geophysical events.

Figure 2: Host–origin comparison (1970–2017)

Note: These graphs show the evolution of natural disasters and the number of people affected by them for host and origin countries. The number of people affected is normalized by the 1970 population. Data points are five-year moving averages. *Source:* Author, based on data from the EM-DAT database.

[9]These countries belong to the Kyoto Protocol Annex I, that is, they committed themselves to binding targets for green-house gas emissions. More concretely, the host group includes: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, the Russian Federation, San Marino, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, the United Kingdom, and the United States. France, Andorra (Not Kyoto Annex I), Malta, Monaco, and Japan are excluded due to lack of detailed migration flow data. The United States signed the Annex I of the Kyoto Protocol, but has not ratified it. Canada withdrew from it in 2012. Turkey is not included in the host group since it joined Kyoto later.

[10]This figure uses five-year moving averages of the variables in the y-axis. Figure A6 in the Appendix presents the host-origin comparison with yearly data.

2.2 Empirical specification and regression results

To identify the impact of natural disasters on migration flows from origin to host countries, I use the following model specification:

$$I_{it} = \beta_0 + \beta_1 ND_{it} + \beta_2 X_{it} + \alpha_i + \delta_t + u_{it}, \tag{1}$$

where I_{it} stands for the unilateral migration flow from origin country i to the group of host countries at time t. The dependent variable has a small share of zero values because the destination of migrants comprises a large group of countries. ND_{it} stands for the frequency of natural disasters in origin country i at time t. X_{it} includes controls such as population, conflict or GDP per capita. α and δ capture country and year fixed effects, respectively. The randomness associated with natural disasters makes this independent variable plausibly exogenous. In addition, including fixed effects enhances the confidence that β_1 captures a causal relationship.

Table 1 provides an overview of the main results. Throughout I use the natural logarithm transformation of the dependent variable. The main independent variable is in levels in column (1) and in logarithms in columns (2)–(5). I deal with zeros in the independent variable in two different ways: i) columns (2) and (3) add a constant equal to 1 before the logarithmic transformation ($log(1 + \#natural\,disasters)$); and ii) columns (4) and (5) replace all zeros by one and include a dummy that takes the unity value whenever the initial value of the independent variable is larger than zero. Columns (3) and (5) control for the first lag of population, to rule out that results are mechanically driven by the increase in population in origin countries[11], and GDP per capita.[12] Column (6) reproduces column (3) using, instead, the number of people affected by natural disasters as the main independent variable.

As Table 1 shows, there is a strong positive relationship between weather shocks in origin countries and migration to host countries (columns 1–5). In particular, a unit increase in the occurrence of natural disasters is related to a 3% increase of population inflows in host regions (column 1).[13] This relationship remains positive and statistically significant after controlling for GDP per capita and population (column 3). Columns (4) and (5) show the relevance of the extensive margin because the dummy coefficient is positive and strongly significant, which implies that whenever a country is hit by at least one natural disaster, out-migration increases. Column (6) shows a very similar pattern for the migration response to the number of people affected by natural disasters, which strengthens the plausibility of migration as a response to the effects of climate shocks. In addition to the effect of natural disasters on international migration, in the robustness checks I show that disasters also increase internal migration (see Table B.6 in the Appendix).

[11] Controlling merely for time-invariant origin country fixed effects would not take into account the importance of demographic pressures on immigration.

[12] Contemporaneous data on GDP and population is considered to be a potentially endogenous control because natural disasters can reduce GDP and affect population. To account for this, I use the first lag of these control variables. This does not substantially change the point estimates or the significance levels.

[13] Because the observational unit is at the year level, it could be that disasters happening at the end of the year had an effect on the next period. I check for that and find that the results in Table 1 do not change significantly if I assign natural disasters that happened in November or December in period t to the next period $t + 1$.

Table 1: Main Results

Dep var: log(# migrants)	(1)	(2)	(3)	(4)	(5)	(6)
Nat. Disasters (#)	0.031**					
	(0.01)					
Dummy (>0 Nat. Dis)				0.186***	0.133***	
				(0.04)	(0.05)	
log(Nat. Disasters (#))		0.190***	0.104**	0.067	0.004	
		(0.05)	(0.05)	(0.05)	(0.05)	
log(People Affected (#))						0.011***
						(0.00)
FE (C, T)	Y	Y	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	N	N	Y	N	Y	Y
Observations	5,344	5,344	4,184	5,344	4,184	4,184
Adj. R^2	0.883	0.883	0.874	0.884	0.874	0.874
Dep. var. mean	7.086	7.086	7.688	7.086	7.688	7.688
Countries	180	180	156	180	156	156

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. Main data sets: UN migration flows tables and EMDAT. Sample period: 1980–2013. Columns (1)–(5) use the number of natural disasters as the main independent variable, while column (6) uses the number of people affected by natural disasters. Columns (2), (3) and (6) use a logarithmic transformation of the independent variable adding a constant equal to one—log(x+1). Columns (4) and (5) use a logarithmic transformation of the independent variable after replacing all zeros by one and include a dummy in the regression that takes a value of one for observations with a positive number of natural disasters and a value of zero for observations with zero natural disasters. Column (3), (5) and (6) control for the first lag of population and GDP per capita. The sample size with controls is smaller because of missing data on population and GDP for some countries.

Table 2 presents alternative model specifications. To account for the presence of zeros in the dependent variable, column (1) presents the results under a zero inflated negative binomial (ZINB) model specification.[14] The main estimate of interest remains positive and significant. Columns (2) and (3) consider bilateral migration flows (origin-destination) and the dependent variable is now defined as I_{ijt}, where i corresponds to the country of origin and j to the destination country. Once again, the conclusions hold under a bilateral flows specification, both using a logarithm and a ZINB specification.[15] Although it cannot be seen in the table, the pattern does not change if one controls for country time trends[16] or uses net flows.

It is interesting to compare the migration response in poor versus middle-income countries. What

[14]Still, the number of zeros in the dependent variable is low enough to be non-problematic; it corresponds to 2% of the observations.

[15]In the case of bilateral flows, the share of zeros in the dependent variable is 65%, which clearly justifies the use of a model specification that accounts for the excess zeros being generated by a different process from the count values.

[16]The significant positive relationship prevails after controlling for recipient countries' time trends, which accounts for the fact that some recipient countries could be more or less welcoming over time.

Table 2: Alternative Specifications and Income Heterogeneity

		Bilateral flows			
	zinb	log(#mig+1)	zinb	Income	Large disasters
	(1)	(2)	(3)	(4)	(5)
Nat. Disasters (#)	0.242***		0.710***		
	(0.019)		(0.064)		
log(Nat. Disasters (#))		0.314***		0.124**	0.137**
		(0.020)		(0.06)	(0.06)
log(Nat. Disasters (#))*				0.295**	
Poor				(0.12)	
FE (C, T)	Y	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	Y	Y	Y	N	Y
Observations	4,225	144,096	144,092	5,344	4,184
Adj. R^2		0.067		0.884	0.874
Dep. var. mean	12,918	1.671	408	7.086	7.688
Countries		156		180	156

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. Main data sets: UN immigration data, EMDAT disaster data. Sample period: 1980-2013. The table presents alternative specifications to the main regression. 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, defined as countries in the bottom quartile of the GDP per capita distribution in 1990. It also controls for the poor countries' dummy. Column (5) includes only large disasters in the regression ($\geq$ 1,000 people affected or $\geq$ 100 deaths).

stands out in Table 1 is that the inclusion of GDP per capita as a control reduces the point estimates of the main regressor only slightly.[17] This suggests that income levels in origin regions do not explain much of the variation in the outflows from these areas. However, existing studies on international climate (non-forced) migration find the opposite (Cattaneo and Peri 2016, among others) and argue that the existence of migration costs make migration unaffordable for very poor people. To further investigate whether climate refugees respond differently than climate migrants, column (4) of Table 2 includes an interaction between the frequency of natural disasters and a dummy variable on poor countries.[18] The estimate of the interaction term is positive and significant, which indicates that poorer countries affected by natural disasters present a higher migration response. Hence, unlike general climate migration, the migration response to natural disasters is not driven by middle-income countries. In other words, migration costs are less relevant when the reason for migrating is a natural disaster.

Finally, column (5) in Table 2 reproduces column (3) of Table 1 and includes only the largest

[17] In addition, the estimates for GDP per capita in Table 1 are insignificant.

[18] The specification follows Cattaneo and Peri 2016, which classifies as poor countries those in the bottom quartile of the GDP per capita distribution in 1990.

natural disasters, defined as disasters that have affected at least 1,000 people or caused at least 100 deaths. Unsurprisingly, the migration response is higher for more-severe disasters.

Section B in the Appendix provides several additional robustness checks.

3 A Climate-economy Model with Climate Refugees

This section introduces the economic model, the characterization of climate refugees, and the climate system. The analysis of optimal carbon policies requires a general equilibrium structure to account for the interactions between pollution, climate refugees and the economy. Hence, I build a neoclassical growth model with a climate module (IAM), which features multiple countries and allows for climate refugees. Time is discrete and runs to infinity. Throughout, the terms refugees and migrants are used interchangeably.

As depicted in Figure 3, each country produces a final good using a combination of capital, labor, and dirty energy. There is an intermediate sector that produces energy using labor. Hence, a share of total labor is used in fossil fuel extraction. Energy use causes emissions that accumulate in the atmosphere and increase the global mean temperature, that is, it causes climate change. Changes in temperature affect the economy by damaging final production. In addition, temperature changes increase the frequency and intensity of natural disasters which, consistent with my empirical findings, force people to migrate to less-affected regions[19] and modify countries' labor forces. Social welfare depends on individuals' consumption and is also affected by climate refugees. In particular, refugees affect welfare in two different ways: i. host countries' natives bear a social cost from newly arrived individuals[20]; and ii. refugees must pay a migration cost. Every region is in semi-autarky because final goods and capital are non-movable across countries.

3.1 Preferences, production, and capital accumulation

The world comprises $R > 1$ regions indexed by $r \in \{1, ..., R\}$.[21] Regions are similar in their fundamental mechanisms but differ parametrically by size, technological level, and climate change vulnerability. They are grouped in host and origin regions, $r \in \{H, O\}$. Host regions are inhabited by natives and climate refugees, while origin regions are inhabited by natives only.

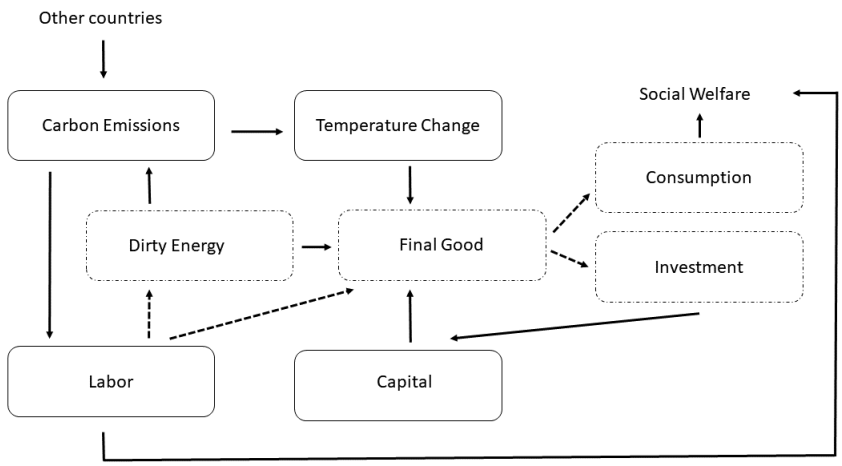
The instantaneous utility, v, of natives and refugees living in region r is given by

[19] I do not distinguish between regions that are less affected by climate change and regions that are more adapted to it.

[20] Although ethically questionable, this is in line with recent electoral outcomes in Europe and the United States. There are several channels through which immigration can create opposition from locals, for instance, cultural prejudice. Although here I do not model explicitly the mechanisms of this aversion, I account for it estimating some reduced-form measures.

[21] I use the term region and country interchangeably, but a region can be understood either as a country or a group of countries.

Figure 3: **Structure of the IAM**. Solid boxes characterize the state variables of the model. Dashed boxes represent flow variables. Dashed arrows represent choice variables.



$$v_{r,t} = \begin{cases} c_{rt} - \gamma_r h_r I_t & if\, r \in H\, and\, is\, native \\ (1-\eta_{rt})c_{rt} & if\, r \in H\, and\, is\, refugee \\ c_{rt} & if\, r \in O \end{cases},$$

where c_r is per capita consumption in region r and $h_r I_t$ stands for the number of refugees entering the host region in period t; section 3.2 provides more details. γ represents the marginal social cost of immigration and η is a (destination) country-specific migration cost that migrants must bear forever.

The social cost of immigration lasts for one period. Hence, only newly arrived immigrants affect natives' utility directly. This assumption on the timespan of the social cost of immigration is consistent with empirical studies showing that hostility to immigrants decreases with contact. For instance, Kaufmann (2014) finds evidence that white British people "habituate to both East European and non-European immigrants after a ten-year period." In my quantitative exercise, one period corresponds to ten natural years, which is aligned with the evidence.

In every region, the allocation of consumption must satisfy the feasibility constraint in the final goods sector

$$C_{rt} + K_{rt+1} = Y_{rt}, \tag{2}$$

where capital letters represent total values, that is, $C_{rt} \equiv c_{rt} P_{rt}$, with P_{rt} denoting regional population. K_{rt} and Y_{rt} stand for, respectively, capital and final output net of climate damage. Note that (2) assumes that there is full capital depreciation. This would be a strong abstraction if time steps were short because full depreciation requires a larger investment effort in every period, which lowers output and mechanically leads to a lower level of the carbon price. However, in my analysis, I use

long time steps—10 years—, which substantially offsets this effect.

Final output production, gross of climate damages, follows a Cobb-Douglas technology

$$\overline{Y}_{rt} = A_{rt} K_{rt}^{\alpha} \left(L_{rt}^{Y}\right)^{\upsilon} E_{rt}^{1-\alpha-\upsilon}, \tag{3}$$

where $\alpha, \upsilon \in (0,1)$ and K_{rt}, L_{rt}^{Y}, E_{rt}, and A_{rt} denote capital, final output labor, energy, and total factor productivity, respectively. The bar, $\overline{Y}$, indicates that output is gross of climate damages. Total factor productivity, A_{rt}, is exogenous and can vary over time.

I now turn to the production of the energy input. An intermediate good sector produces energy using labor,[22] L_{rt}^{e}, and is subject to a specific energy production technology, G, and productivity level, A_{rt}^{e}

$$E_{rt} = G(A_{rt}^{e}, L_{rt}^{e}). \tag{4}$$

E_{rt} is measured in terms of its carbon content; hence, energy and emissions are equivalent. In this model, E_{rt} should be interpreted as coal. The extraction costs of coal are, unlike other fossil fuels, non-negligible. In addition, coal is considered to be the main driver of future climate change (GHKT). According to recent estimates from the US Energy Information Administration (EIA), the amount of coal reserves worldwide could last over 3.5 centuries. Consistent with this evidence, I assume an unlimited supply of energy, which further implies that the the model does not have a scarcity rent.[23] This approach is also consistent with Casey (2019), who shows that there is an inconsistency between empirical evidence and a model in which increasing energy prices are a result of scarcity rents. The author suggests that aggregate data are aligned instead with increasing extraction costs. In the quantitative exercise I assume energy is produced at constant returns to labor: $E_{rt} = A_{rt}^{e} L_{rt}^{e}$.

Finally, I assume that labor is perfectly mobile across sectors and the labor-clearing condition is satisfied in each region

$$L_{rt} = L_{rt}^{Y} + L_{rt}^{e}, \tag{5}$$

which indicates that regional labor is either used to produce final output or energy input. Note that total regional labor, L_{rt}, does not necessarily coincide with total regional population, P_{rt}, as explained below.

3.2 Climate refugees: Population flows and the size of the labor force

The following characterizes the forced migration response to climate change. Given that origin regions are morevulnerable to climate change and are hit by natural disasters more intensely, climate refugees migrate from origin to host regions. In the baseline model, I assume that hosting regions

[22] The energy resource is extracted using labor; thus, abatement is achieved by allocating fewer workers to energy production.

[23] In other words, the model abstracts from the Hotelling problem of optimal extraction of a finite resource

cannot restrict immigration, but this is relaxed in extension 6.1.

Global population, P, is constant over time. However, regional population, P_{rt}, evolves as a result of refugee flows. Total migration at time t, I_t, is a function of the increase in concentrations, Δz_{t-1}[24]

$$I_t \equiv i(\Delta z_{t-1}),$$

where i is increasing in Δz_{t-1}. Whenever $\Delta z_{t-1} \leq 0$ there is no migration in period t. Note that the change in carbon concentration is independent of the emitting country, which reflects the fact that local emissions spread globally. Note also that in this paper, I account only for climate refugees, that is, individuals who are forced to migrate as a consequence of warming-related natural disasters. However, global warming can also affect climate migration in general. In other words, it can influence individuals' decisions to migrate. Although this additional relationship is omitted in this paper, its inclusion would presumably increase I_t. Hence, results provided in this analysis can be considered conservative.

Each origin region contributes to total migration according to an exogenous share o_r that depends on its climate vulnerability. Each host country receives a share h_r of total migrants. Hence, the law of motion of P_{rt} is

$$P_{rt} = \begin{cases} P_{rt-1} + h_r i\left(\Delta z_{t-1}\right) & if\, r \in H \\ P_{rt-1} - o_r i\left(\Delta z_{t-1}\right) & if\, r \in O \end{cases}, \tag{6}$$

where o_r and h_r add up to one, i.e., $\sum_{r \in H} h_r = 1$ and $\sum_{r \in O} o_r = 1$.

In every period a new generation of individuals is born in the region their immediate ascendant was living in. Individuals supply one unit of labor inelastically with no disutility. Following a well-established consensus in the literature, I assume that newly arrived immigrants have a lower labor productivity. Thus, the effective labor force, L_{rt}, in a host region given by

$$L_{rt} = P_{rt-1} + \kappa(P_{rt} - P_{rt-1})\, if\, r \in H \tag{7}$$

where $\kappa \leq 1$ is a parameter that controls the native–immigrant wage differential.[25] After one period of their arrival, immigrants are naturalized and have the same productivity as natives. Given that origin regions do not receive immigration, total regional labor coincides with total regional population: $L_{rt} = P_{rt}\, if\, r \in O$.

[24] I model migration—refugees—as a function of concentration flow instead of concentration stock to reflect the fact that migration is permanent. Once someone is hit by a natural disaster and is forced to migrate, he or she will move to a low vulnerability area and will not be hit by a disaster again, that is, will not be a climate refugee again. In an extension, I use a different specification of climate refugees based on the stock of carbon concentrations.

[25] In the initial period, labor force, L_{r0}, is equal to population, P_{r0}, because there are no immigrants.

3.3 Climate module and climate damages

I follow the characterization of the climate system and climate damages from GHKO. Intuitively, global carbon emissions E_t increase the amount of carbon concentrations in the atmosphere, which increase global temperature[26] and, as a consequence, a fraction Ω_{rt} of output is destroyed.[27]

Let z_t denote a function of the history of global emissions, E, at time t

$$z_t = f(E_1, E_2, ..., E_t), \tag{8}$$

where time goes back to pre-industrial times, and E_t is the sum of regional emissions, E_{rt}, that is, $E_t = \sum_r E_{rt} \, \forall t$. The variable z_t summarizes the level of carbon concentration in the atmosphere and is characterized as the sum of permanent and non-permanent concentrations–$z_{1,t}$ and $z_{2,t}$, respectively, that is, $z_t = z_{1,t} + z_{2,t}$. The evolution of permanent concentrations is given by $z_{1,t} = z_{1,t-1} + \phi_L E_t$, which represents that a share $\phi_L \in (0, 1)$ of time t emissions will remain in the atmosphere forever. Non-permanent concentrations will eventually decay following the law of motion: $z_{2,t} = (1-\phi)z_{2,t-1} + (1-\phi_L)\phi_0 E_t$. This implies that a share $(1-\phi_0)$ of time t emissions disappear within a decade while a fraction $(1-\phi_L)$ of the remaining emissions will disappear later. Accumulated emissions decay at a constant rate ϕ.

Carbon concentrations determine the extent of climate damages to output through a damage function denoted by $1 - \Omega_r(z_t)$. Following GHKT, $\Omega_r(z_t)$ takes the exponential form

$$\Omega_r(z_t) = exp\left(-\theta_r\left(z_t - \overline{z}\right)\right), \tag{9}$$

where θ scales the damage function and $\overline{z}$ denotes the pre-industrial level of carbon in the atmosphere. Unlike GHKT, the damage function is country-specific, hence, θ is indexed by r.

Final output net of climate damages, Y, is given by

$$Y_{rt} = \Omega_{rt}(z_t)\overline{Y}_{r,t}, \tag{10}$$

where $1 - \Omega_r(z_t)$ represent the share of output lost due to climate change.

4 Unilateral Climate Action in Host Region

I first examine optimal carbon pricing in the absence of a world agreement, assuming that only host regions undertake climate action—implement carbon taxes. For simplicity, I consider two regions, host and origin. The host is governed by a local planner that cares only about the welfare of its natives. The origin region is in laissez-faire.

[26] Carbon concentration is a key determinant of temperature, usually used as a sufficient statistic for climate change.

[27] This is a standard way to characterize how climate change affects the economy, used by Nordhaus and Boyer (2000) and Gerlagh and Liski (2018), among others.

4.1 Theoretical analysis

4.1.1 The economy in the origin region

The origin region does not implement climate action—is in laissez-faire, and its regional emissions are proportional to population

$$E_{ot} = \xi_t P_{ot}, \tag{11}$$

where $\xi_t \equiv \frac{1-\alpha-\upsilon}{1-\alpha} A^e_{ot}$ captures the carbon intensity of population in the origin country. It corresponds to the decentralized use of emissions, which does not account for climate change externalities (see Appendix C.1 for a detailed derivation of (11)).

The origin region affects the host in two different ways. First, origin emissions spread globally and contribute to climate damages. Second, population flows from origin to host as a result of global warming.

4.1.2 The host planner problem

I consider a utilitarian planner that maximizes the sum of discounted well-being across time for the native host population.[28] This is equivalent to conceiving the planner as a political entity seeking to maximize its support among the initial period voters. The planner aggregates welfare as follows

Assumption 1: *The planner aggregates natives' welfare. Her utility function, u, is concave and takes the logarithmic form.*

Assumptions 1 is common in the literature (for example, GHKO) and allows the derivation of closed-form solutions.

Assumption 2: *The social planner cannot individually distinguish (treat differently) natives and immigrants, but is aware of the number of natives at each point in time.*

This is a reasonable assumption in a long-term analysis that adds tractability to the model.[29] It implies that total consumption is equally distributed across the regional population—natives and refugees, if any.

Given the initial level of K_h, L_h, and z, the planner decides consumption—savings—and energy use to maximize the discounted lifetime utility of the native population, W_{ht},

[28] Given that the planner cares only about the initial period inhabitants' (i.e., natives') welfare, I call it the initial approach (IA). The aim of the IA is to obtain a social cost of carbon that neatly captures the effect of immigration on the policy. For that, I need to exclude the effects of a changing objective function and inequality.

[29] Immigrants cannot be distinguished by labor endowments or capital holdings, consistent with the naturalization assumption after 10 years and the empirical evidence on decreasing hostility. This would be a strong assumption if the goal was to compare welfare across citizens and countries. However, for the purpose of measuring the long-term social cost of carbon, it is not as much a concern.

$$\max_{K_{ht+1},E_{ht}} W_{ht} = \sum_{t=0}^{\infty} \beta^t u_{ht}(P_{h0} v(c_{ht}, I_{ht})),$$

subject to Assumptions 1 and 2 and equations (2)–(11). $\beta \in (0,1)$ is the discount factor.

4.1.3 The unilateral social cost of carbon in the host region

The social cost of carbon (SCC) is typically defined as the present value of the marginal damage caused by carbon emissions. It embodies the sum of all present and future discounted externalities that agents would not take into account in the market economy. In the planning problem, it corresponds to the wedge between the net marginal product and the marginal cost of emissions. In the current setting, I refer to it as the "unilateral SCC" or unilateral carbon price because the local planner accounts only for the externality that affects host natives' welfare.

Given the planner's problem defined above, one can theoretically characterize the unilateral carbon price. Let λ_t denote the Lagrange multiplier on the final production function (3). Additionally, let ω_t be the multiplier on the carbon concentrations equation (8) and μ_t^h and μ_t^o be the multipliers associated with the evolution of population in the host and the origin region, respectively, from equation (6). To simplify the expressions, I assume $\kappa = 1$, hence, $L_{ht} = P_{ht}$.

Proposition 1: *In a setting in which the origin region is environmentally inactive, the unilateral planner in the host region will increase pollution until the net marginal product of energy, $NMPE_{ht}$, equals the social cost of carbon, that is, $NMPE_{ht} = SCC_t^{Uh}$ where*

$$SCC_t^{Uh} \equiv \frac{1}{\lambda_t}\Bigg(\overbrace{\sum_{j=0}^{\infty} -\omega_{t+j} \frac{\partial f_{t+j}(.)}{\partial E_{ht}}}^{Standard\,Output\,Damages} - \overbrace{\mu_{t+1}^o(-1)\frac{\partial i(\Delta z_t)}{\partial E_t}}^{Emissions\,Reallocation} + \overbrace{\beta u'_{t+1} P_{h0} \gamma \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Social\,Cost\,of\,Immigration} + \overbrace{\mu_{t+1}^h(-1)\frac{\partial i(\Delta z_t)}{\partial E_t}}^{Labor\,Effect} \Bigg). \tag{12}$$

Hence, the unilaterally optimal use of energy in the host region can be achieved by implementing a carbon price equal to $\tau_{ht}^{Uh} = SCC_t^{Uh}$.

See Appendix C.1 for a detailed derivation of (12). Intuitively, under the carbon price in Proposition 1, energy use is such that private and public marginal consequences of polluting are equalized. Equation (12) summarizes the public consequences (SCC). The private consequences are captured by $NMPE_{ht}$, namely, the net marginal product of energy.[30]

[30] More specifically, $NMPE_{ht} \equiv \frac{\partial Y_{ht}}{\partial E_{ht}} + \frac{\partial Y_{ht}}{\partial L_{ht}^Y}\frac{\partial L_{ht}^Y}{\partial E_{ht}} = (1-\alpha-\upsilon)\frac{Y_{ht}}{E_{ht}} - \upsilon \frac{Y_{ht}}{L_{ht}-L_{ht}^d}\frac{1}{A_{ht}^e}$. Note that $NMPE_{ht}$ embeds a

From equation (12) one can see that the unilateral SCC consists of the sum of four components. Each component is multiplied by $\frac{1}{\lambda_t}$, where λ_t is the shadow value of one unit of final good production. Hence, each component is expressed in terms of the final good. In the optimum, λ_t equals the marginal utility of natives' consumption, $\lambda_t = \beta^t u'_t \frac{P_{h0}}{L_{ht}}$.[31]

The first component of the unilateral SCC, denoted *Standard Output Damages*, corresponds to the present discounted value of climate damages to final output, in utils. In the optimum, the shadow value of carbon concentrations, ω_t, equals the impact of concentrations on final production and is given by $\omega_t = \beta^t u'_t \frac{P_{h0}}{L_{ht}} \frac{\partial Y_{ht}}{\partial z_t}$. The term $\frac{\partial f_{t+j}(.)}{\partial E_{ht}}$ captures the impact of emissions on carbon concentrations. While this component is standard in most IAMs, the remaining three are novel.

The second component is denoted *Emissions Reallocation* because it captures the fact that as refugees move to host regions, emissions in origin regions decline. The reduction of emissions in origin regions benefits the host planner because it implies lower climate damages. Hence, it diminishes the overall price of carbon. In the optimum, the shadow value of the origin population, μ_t^o, equals the impact that the origin population has on host natives' present and future welfare, through environmental degradation. It is given by $\mu_t^o = \sum_{j=0}^{\infty} (j+1)\beta^{t+j} u'_{t+j} \frac{P_{h0}}{L_{ht+j}} \frac{\partial Y_{ht+j}}{\partial z_t} \frac{\partial f(.)}{\partial P_{ot}} \xi_{t+j}$. Intuitively, the effect of the origin population on host natives' welfare is decomposed into: i. the effect of the origin population on global carbon concentrations z_t, denoted by $\frac{\partial f(.)}{\partial P_{ot}}$; and ii. the effect of global carbon concentrations on climate damages to final output, denoted by $\frac{\partial Y_{ht+j}}{\partial z_t}$. Note also that the larger the emissions per capita in the origin region, ξ, the higher the damages. Finally, the term $\frac{\partial i(\Delta z_t)}{\partial E_t}$ reflects the number of refugees that are forced to migrate as a result of a marginal increase in energy use.

The third component, denoted *Immigration Social Cost*, represents the direct disutility of immigration borne by natives.[32] It captures the fact that societies with a strong opposition to immigration should be willing to tax carbon more stringently.

Finally, and perhaps more interestingly, the fourth element, denoted *Labor Effect*, captures the future discounted sum of both a welfare cost and a welfare benefit of climate refugees. μ_t^h is the shadow value of the host population, and it captures the contribution of host residents to present and future natives' welfare. In the optimum it is given by $\mu_t^h = \sum_{j=0}^{\infty} \left(\beta^{t+j} u'_{t+j} \frac{P_{h0}}{L_{ht+j}} \left[\frac{\partial Y_{ht+j}}{\partial L_{ht+j}} - \frac{Y_{ht+j} - K_{ht+1+j}}{L_{ht+j}} \right] \right)$. One can see that the sign and magnitude of μ_t^h depends on two different effects. On the one hand, the inflow of climate refugees increases labor input, which results in higher output. That is captured by the first element inside the square brackets and it constitutes a positive externality; hence, it reduces the carbon price—note that μ_t^h is multiplied by -1 in equation (12). On the other hand, climate migration reduces per capita consumption for two reasons. First, it reduces per capita final output net of climate damages because environmental resources are finite, that is, there is climate

private benefit and a private cost of using emissions. The private benefit, the first element of $NMPE_{ht}$, corresponds to the additional units of production. The private cost, the second element of $NMPE_{ht}$, consists of a lower amount of labor available to produce the final output.

[31] It is multiplied by $\frac{P_{h0}}{L_{ht}}$ to adjust for the native population.

[32] It is multiplied by the discount parameter because current emissions result in immigration in the next period; hence, the cost is effective one period ahead.

degradation. Second, it dilutes capital because refugees migrate without capital. This is captured by the second element in the square brackets and constitutes a negative externality that increases the carbon price.

The next theoretical step is to evaluate the net impact of the *Labor Effect* on the unilateral carbon price. The following result summarizes it.

Result 1: *Under a Cobb-Douglas production function and multiplicative climate damages, the "Labor Effect" is a negative externality that increases the social cost of carbon.*

Proof: see Appendix C.2. Result 1 is a consequence of the decreasing returns to labor of the production function, driven by the existence of capital and climate damages. A larger population dilutes capital and net production; thus, it increases the cost of carbon.

To simplify notation, I have presented the price of carbon for the case in which $\kappa = 1$. However, it is straightforward to show the effect of a lower κ on the carbon tax. First note that under $\kappa < 1$, newly arrived immigrants are less productive than natives and longstanding immigrants. Thus, the labor supply is lower under $\kappa < 1$, which affects the price of carbon as stated in the following remark.

Remark 1: *The social cost of carbon is decreasing in κ.*

Proof: For $\kappa < 1$ expression (12) changes slightly. The positive externality element of the labor effect—that is, the first element of μ_t^h inside the square brackets—is multiplied by κ only when $j = 1$. Hence, the lower the κ, the lower the benefit of having additional labor. That applies only for one period since immigrants are naturalized in the second year after their arrival (recall that one period corresponds to ten years).

Taking stock, expression (12) shows that accounting for forced migration affects the unilateral carbon price more than the mere change in direct climate damages to the economy. The reallocation of population changes the labor force in all regions, it reallocates pollution, and it affects consumption per capita in host regions. On top of that, host natives may have some anti-immigration sentiment that diminishes their welfare. The magnitude of this change is a quantitative question that will be addressed below.

4.2 Quantification of impacts and calibration of the model

This section conducts an original empirical analysis of the impacts of climate change on refugees as well as the disutility cost of migration. The reminder of this section discusses the parameter selection.

4.2.1 Climate refugees' function

I disentangle the relationship between climate change and climate refugees using an elasticity decomposition methodology. I decompose the percentage change of migration as a consequence of changes in carbon concentrations, $\frac{\partial ln(Climate\,Refugees_t)}{\partial ln(CO_2\,Conc_t)}$, into two subelasticities

$$\frac{\partial ln(Climate\,Refugees_t)}{\partial ln(CO_2\,Conc_t)} = \frac{\partial ln(Climate\,Refugees_t)}{\partial ln(\#\,Disasters_t)} \frac{\partial ln(\#\,Disasters_t)}{\partial ln(Carbon\,Conc_t)}. \tag{13}$$

The first elasticity in (13) measures the changes in migration due to changes in the frequency of natural disasters. It is estimated using the data presented in the empirical section above and pooling countries into two regions: host and origin. I obtain a value of 0.88. The second elasticity captures the change of disasters due to changes in carbon concentrations.[33] To measure it, I conduct a cointegration analysis of the time-series relationship between carbon concentrations and natural disasters, following Thomas and López (2015).[34] While Thomas and López (2015) look at each disaster type separately, I analyze all disasters jointly and also exclude meteorological events since these present a weaker relationship with migration; see Table B.7 in the Appendix.[35] I find that the elasticity between atmospheric concentrations and the frequency of natural disasters is 13.49, or 6.74 when meteorological events are included. In other words, a 1% increase in the level of carbon concentrations results in a 13.49% increase in the number of climate disasters. Hence, the overall elasticity of interest is: $\frac{\partial ln(Climate\,Refugees_t)}{\partial ln(CO_2\,Conc_t)} = 0.88 \times 13.49 = 11.87$, or 5.93 including meteorological events.[36]

In the benchmark analysis, I assume migration is a linear function of the change in carbon concentrations

$$I_t = B\left(z_{t-1} - z_{t-2}\right),$$

[33]Scientific evidence tells us that human-induced carbon emissions contribute to the frequency and intensity of extreme weather events. According to the special report of Working Groups I and II of the fifth IPCC report (Seneviratne et al. (2012)), "A changing climate leads to changes in the frequency, intensity, spatial extent, ... of weather and climate extremes ...." In addition, "There is evidence that some (climate and weather) extremes have changed as a result of anthropogenic influences, including increases in atmospheric concentrations of greenhouse gases."

[34]In this paper the authors explore whether there is a "significant relationship between climate change and the global increase in the frequency of intense natural disasters." They admit that, even though the frequency of climate-related natural disasters is rising, the causal relationship between "climate change and natural disasters is not fully understood." The authors use EM-DAT disaster data from 1970 to 2013, for most countries. Their main empirical model regresses annual country frequency of disasters on global CO_2 concentrations and global sea temperature deviations from the trend. See their paper for further details.

[35]Although I include five more years in the analysis, my results do not differ substantially from those from Thomas and López (2015) when disaster types are analyzed separately.

[36]To intuitively understand this magnitude, the yearly average number of immigrants entering host countries between 1990 and 2013 was 4,832,294 (in 2010, for instance, it was 5,995,066). The current amount of carbon concentrations in the atmosphere is approximately 400 parts per million (ppm), and the average increase is 2 ppm per year (roughly 0.5% annually). This results in a 2.9% increase in immigrants, that is, 284,880 more immigrants per year on average. This magnitude is non-negligible especially if we compare it with political asylum applications. For instance, from 2008 to 2013, the European Union received on average 200.000 new refugee applications per year. https://ec.europa.eu/eurostat/statistics-explained/index.php/Asylum_statistics

where B captures the migration response to a marginal change in carbon concentrations. B is calibrated using the historic average increase in concentrations per decade (40 Gt of carbon), the elasticity of immigration to concentrations, and the average decade migration normalized by host population.[37] This leads to a value of $B = 5.76 \times 10^{-5}$ (2.88×10^{-5} with meteorological disasters).

4.2.2 Social cost of immigration

The theoretical model accounts for host natives' anti-immigration sentiment, or the social cost of immigration, through the parameter γ. It captures natives' willingness to pay (WTP) to prevent immigration. In economic terms, γ represents the consumption-equivalent loss of a marginal increase in immigration, more details are provided in Appendix D. Although the literature has made several attempts to measure the impact immigration on local population wages,[38] to the best of my knowledge there is no study that specifically targets γ. To shed some light on this, I calibrate it using three different approaches. The approaches are summarized below:

A: EU-Turkey Agreement. In 2015 the European Union (EU) saw an influx of almost 1 million refugees, mostly coming from Syria. This was accompanied by violent crimes committed against refugees. The vast majority entered through Turkey. Threatened by the fact that the migration crisis would persist, in March 2016 the EU authorities approved a deal with Turkey to control the entrance of population into the EU (European Commission 2016). Using data on the 2015 refugee crisis, the expenses of this particular European policy, and European consumption, the parameter γ takes a value of 7.3×10^3.[39]

B: "Pay to Go" programs. The so-called "Pay to Go" programs consist of immigration control policies that provide incentives to immigrants to return to their country of origin, usually through offering paid travel and financial help to cover their settling expenses. These incentives frequently required that the immigrant did not return during a specified period of time.[40] Using data on the European "Pay to Go" programs in 2015, the γ parameter takes a value of 7.1×10^3.

C: The Brexit Experiment: One of the main motivations for Brexit voters in the 2016 referendum was to reduce the number of Europeans entering the United Kingdom.[41] The majority of citizens were willing to undergo the costs of leaving the EU—which are uncertain but not negligible—in order to lower European immigration. To calibrate γ, I use data from a survey conducted by YouGov and Eric Kaufmann in which respondents were explicitly asked about their willingness to pay to reduce

[37] More specifically, on average there is an increase in 4 Gt of Carbon (approximately 2 ppm) per year, which represents roughly a 0.5% increase in concentrations (400 ppm). That implies a 5.9% increase in migrants per year (2.9% including meteorological events), that is, 286,796 (143,278 including meteorological events) immigrants per year. Finally, this corresponds to 2.3×10^{-4} (1.16×10^{-4}) billions of refugees, per 4 Gt a year.

[38] For instance, Aydede (2014) and Card and DiNardo (2000) quantify the effect of immigration on natives' dislocalization, providing contradicting results.

[39] This value reflects the amount evaluated in terms of final goods that a native is willing to pay to reduce migration by 1 billion.

[40] Germany implemented a "Pay to Go" program for the first time in 1974 and Belgium in 1984. Almost all European countries have implemented a similar program at least once, with Croatia being the only exception. Although it is more common in European countries, Canada has also implemented a softer version of such programs.

[41] In 2015, the United Kingdom had 185.000 new immigrants from the EU.

European immigration.[42] One could initially reason that this approach provides a comparatively low measure for the social cost of immigration, since the targeted immigrants—Europeans—are relatively similar to natives.[43] However, the survey was conducted when political and social tensions were abnormally high and immigration from other countries was already restricted in the United Kingdom. For that reason, I instead consider it as a comparatively high measure. Using Brexit survey data, γ takes the value 4.7×10^6.

Given the disparity in the different measures, I present the simulation results under the highest and lowest calibrations.

4.2.3 Technology, energy and other parameters

I take each period to be 10 years, with $t_0 = 2015$. The host region is calibrated to match Kyoto Annex I countries and the origin matches the rest of the world. Table 7 summarizes the calibration of the main parameters. Throughout I use the assumptions described in Section 3, which include logarithmic preferences -common in growth models and its curvature is appropriate for a period of 10 years-, Cobb Douglas production function of final goods and full depreciation. The discount factor is the most common in the literature, $\beta = 0.985$ (1.5% per year), but an alternative discount value is presented in the extensions. The technology parameters are taken from GHKO, $\alpha = 0.3$ and $1 - \alpha - \upsilon = 0.04$.

The GDP in the calibration year 2015 is obtained from the Penn World Tables.. Initial capital stock is calibrated to match a net rate of return on capital of 5% as in, for instance, the DICE model[44] and GHKO. To obtain the capital stock for Kyoto (and non-Kyoto) Annex I countries, I use the GDP relationship between OECD and Kyoto countries, according to which Kyoto countries represent 0.95% of OECD GDP. Initial emissions, E_0^{Host} and E_0^{Origin}, are obtained from OECD data on carbon dioxide emissions embodied in final domestic demand[45] and, as with capital, they are imputed to Kyoto–non Kyoto Annex I countries. I calibrate the initial share of labor devoted to final output assuming the economies are initially in laissez-faire; hence, a constant share of labor is allocated to final output. Initial period total factor productivities, A_{r0}, are calibrated using the definition of the standard neoclassical growth model, $TFP = \frac{Y}{\Omega K^{\alpha}(L^Y)^{\upsilon}E^{1-\upsilon-\alpha}}$. Their growth rate is taken from GHKO. Energy productivities are analogously calibrated using the share of labor devoted to energy production and assuming a linear energy production function. The initial population for the host country is normalized to 1, and the origin population is calculated to maintain the current

[42] This allows me to obtain a measure of United Kingdom natives' valuation of immigrants based on contingent valuation. Contingent valuation, sometimes called stated preferences, is a method to determine the value of goods by simply asking people directly about their value of that good. This method carries the problem of hypothetical bias, which implies that the respondent's answer may differ from his or her actual behavior.

[43] Compared to other origin regions like Africa, Asia, or South America, it is reasonable to assume that, immigrants arriving from the EU are substantially more like the native United Kingdom population.

[44] The dynamic integrated climate change (DICE) model, developed by William Nordhaus, is one of the main IAMs used to provide estimates of the SCC.

[45] OECD statistics report global CO_2 emissions of 32 Gt of CO_2-equivalent in 2015 (this corresponds to 8.7 Gt of Carbon), 13 Gt of which is imputed to OECD countries (1 ton Carbon = 3.67 tons CO_2).

Table 3: Calibrated Parameters

Parameter	Value	Source
I. *Preferences and technology*		
β	0.985	Literature
α	0.3	GHKT
1-$\alpha - \upsilon$	0.04	GHKT
II. *Initial values*		
Y_0^{Host}	52,380 Billion USD per year	Penn World Tables (2015)
Y_0^{Origin}	60,365 Billion USD per year	Penn World Tables (2015)
E_0^{Host}	3.325 GtC per year (2015)	OECD (2015) & calibrated
E_0^{Origin}	5.275 GtC per year (2015)	OECD (2015) & calibrated
K_0^{Host}	96,470 Billion USD	Calibrated
K_0^{Origin}	111,180 Billion USD	Calibrated
$\frac{L_{r0}-L_{r0}^d}{L_{r0}}$	$1 - \frac{1-\alpha-\nu}{1-\alpha} = 0.94$	Calibrated
$A_0^{Host}(g_{A_0^H})$	15,211 (1.3% per year)	Calibrated (GHKT)
$A_0^{Origin}(g_{A_0^O})$	5,719 (1.3% per year)	Calibrated (GHKT)
$A_0^{e_{Host}}(g_{A_0^{eH}})$	581	Calibrated
$A_0^{e_{Origin}}(g_{A_0^{eO}})$	183	Calibrated
θ^{Host}	2.4×10^{-5}	HKOR
θ^{Origin}	5×10^{-5}	HKOR
L_0^{Host}	1	Normalized
L_0^{Origin}	5.02	Calibrated to match L_0^{Host}
III. *Other parameters*		
κ	0.8	Card (2014)

Note: This table summarizes the calibrated parameters.

share in origin regions relative to host regions.[46]

Finally, the parameters and functional forms defining the damage function and the climate model adopt the specifications and calibration from GHKT. The scale parameter θ^r is region-specific and is calibrated using Hassler, Olovsson, and Reiter (2019) (HKOR). For host countries (θ^{Host}) I use the average value for the United States and Europe, weighted by GDP. For origin countries (θ^{Host}) I use the average of India and Africa, weighted by GDP.

4.3 Quantitative results

This section quantifies the unilateral policy in the host region, that is, the unilateral SCC, when the origin region is environmentally inactive. I present model results across four scenarios:

1. "Without climate refugees": To relate my results to existing studies, I first present the calibration results without displacement.

2. "Without disutility": This scenario accounts for climate refugees, but assumes there is no social cost of immigration.

3. "Pay to Go": This scenario accounts for climate refugees and assumes that the social cost of immigration is calibrated based on Pay to Go programs, the lowest value among the different calibration approaches considered.

4. "Brexit": This scenario accounts for climate refugees and assumes that the social cost of immigration is calibrated based on Brexit survey data, the highest value obtained among the approaches considered.

I also present the results under two different calibrations of the migration response to natural disasters, first including climatological and hydrological events only (C&H disasters) and then adding meteorological events (C&H&M disasters).

To approximate the planner's infinite-horizon problem, I simulate the economy for 30 periods, that is, 300 years. Due to discounting, increasing the simulation period does not change my results. I solve the problem using direct optimization. The choice variables are the savings rate and the labor share devoted to energy production. The extensions of the model require additional choice variables.

Table 4 presents the near-term unilateral carbon prices for the host country under each scenario. The optimal price of carbon without human displacement is roughly USD 45 per ton of carbon (column 1), which is very close to most estimates for the United States.[47] This adds confidence that the benchmark model is of a comparable order of magnitude with respect to existing studies. Under displacement (column 2), the optimal price increases by around 26% (13% if meteorological events are included). Unsurprisingly, accounting for the social cost of immigration increases the price of carbon even further and its magnitude depends strongly on the calibration of the social cost of immigration parameter. The increase is low under the Pay to Go calibration (column 3)

[46] In 2017, population in the host group was 1,244,177,792 and in the origin group 6,243,034,112.

[47] Appendix F presents a different comparison scenario in which origin regions suffer from a direct utility cost of natural disasters.

but substantial under the Brexit calibration (column 4). More knowledge on the real value of the social cost of immigration would be necessary to make more accurate quantitative statements when the social cost of migration is accounted for. Still, these results show that the more a society is "anti-immigrant", the more it should be willing to tax carbon.

Table 4: Unilateral Climate Price in Host Region, SCC^{Uh}

	W/o Climate Refugees	W Climate Refugees		
		W/o Disutility	W Disutility	
			Pay to Go	Brexit
$ per ton of carbon	(1)	(2)	(3)	(4)
C&H disasters	44.72	56.14	56.45	247.43
C&H&M disasters		50.73	50.87	149.12

Notes: This table presents short-term unilateral carbon prices for the host region under the different scenarios and calibrations of the migration response to different types of natural disasters ("C&H disasters" includes only climatological and hydrological disasters. "C&H disasters" includes also Meteoroglogical disasters).

Figure 4 plots the evolution of carbon prices for the next 100 years. The forced migration response to climate change is calibrated using climatological and hydrological disasters. The figure shows that prices are persistently larger under migration and increasing over time due to exogenous total factor productivity growth.

Figure 4: Evolution of the unilateral carbon price in host region

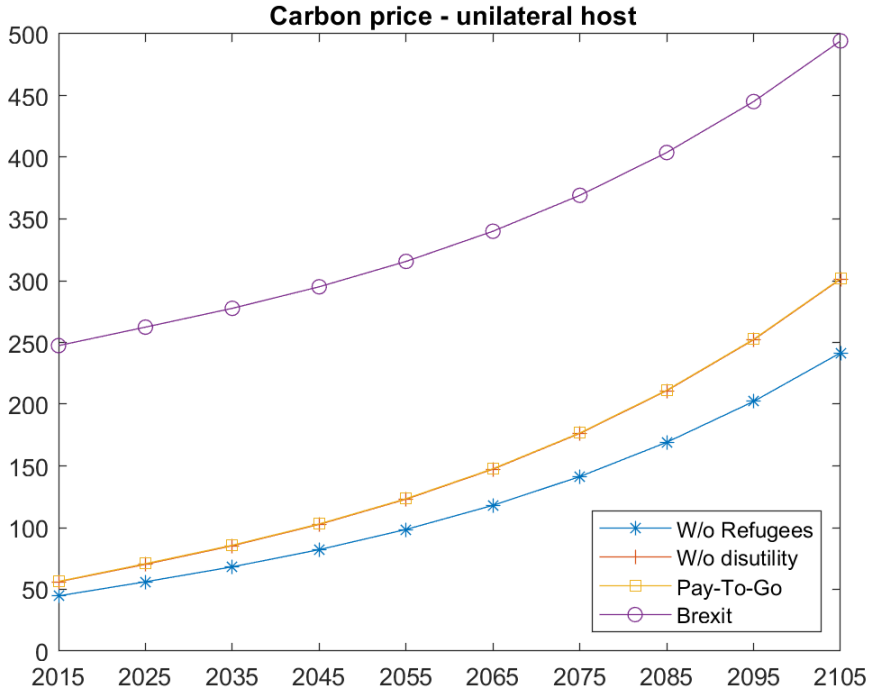


Figure E.1 in the Appendix shows the decomposition of the carbon price for each component—*Standard Climate Damages*, *Emissions Reallocation* and *Labor Effect*. It corresponds to the scenario "without disutility", that is, when $\gamma = 0$. For this reason, the *Social Cost of Immigration*—or disutility—component is zero. As population is forced to migrate to host regions, emissions in the rest of the world are mechanically reduced. This represents a positive externality that corresponds to the so called "*Emissions Reallocation*" component of the carbon price. It is low but negative since it reduces the SCC. At the same time, standard damages to the economy increase because population in the host region is larger. Although it cannot be seen from this figure, the net effect of these two components is such that it reduces the carbon tax slightly. In other words, if one would only account for the effect that forced migration has on emissions reallocation and output damages, ignoring the consequences on the labor market, displacement would be found to be beneficial for host regions because the host planner benefits from having a larger population under its control. Note also that in the laissez-faire, without climate action in the host country, total emissions would be larger under displacement since developed countries have higher emissions per capita.

Despite the benefit of controlling a larger population, the cost of the *Labor Effect* dominates since the carbon price is larger under displacement even when there is no social cost of immigration. Throughout the simulation period the *Labor Effect* adds to the SCC. In other words, the benefit of having additional labor is offset by the reduction in per capita consumption. This is in line with the theoretical results (result 1).

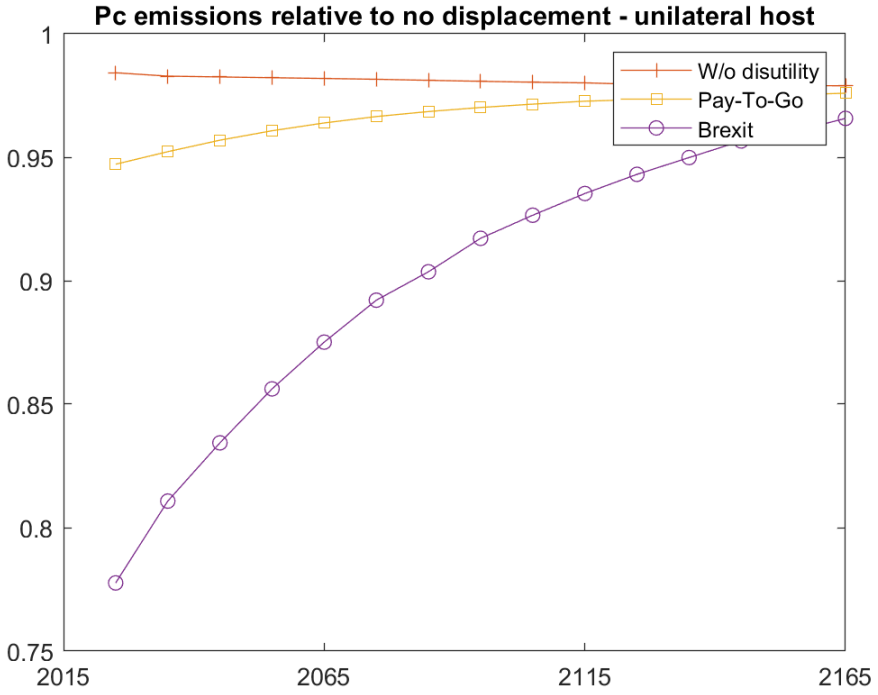
Figure 5 shows the evolution of per capita emissions in the host region under each scenario, relative to the no displacement scenario. Emissions per capita are persistently lower under forced displacement relative to no displacement. This is in line with having higher carbon prices under displacement, which reflects a stronger will to control pollution.

These results show that ignoring the effects of climate change on displacement results in an underestimation of the unilateral SCC. If host countries are willing to implement policies to tackle climate change unilaterally, they ought to consider the economic effects of climate refugees. Additionally, countries with strong social aversion to immigration should fight climate change to a greater extent. These results are obtained using a very standard economic setting—IAM—that is frequently used by the literature, international organizations, and governments. Assuming the economic setting is adequate, the policy recommendation for host regions is to increase carbon prices, that is, undergo more-stringent climate action.

5 Optimal Policy Under a Global Agreement (First-best) and Unilateral Policies (Nash Equilibrium)

This section characterizes the first-best and the Nash equilibrium solutions of the model. It first provides analytical expressions for the carbon prices under each setting. Then, it details the additional calibration that these settings require. Finally, it presents the quantitative results.

Figure 5: Evolution of per capita emissions in the host region under unilateral policy



5.1 The global social cost of carbon: first-best solution

The first-best solution mirrors a situation with full cooperation across countries and features a global social planner that cares about global welfare. In a multi-region model, there is no unique choice of the planner's objective function. How the planner aggregates welfare in each country, that is, how the social welfare function is constructed, needs to be determined. On that matter, I assume the planner cares only about the intertemporal aspect and does not have any preferences over distribution within each period—this is relaxed in the extensions (Section 6.3).[48] The main functional forms and capital depreciation mimic the unilateral host setting presented above.

Since migration is forced by climate change, the only channel through which individuals are reallocated is pollution. Given the current differences in per capita consumption across countries, the reallocation of population to more-developed regions may constitute a direct gain from the perspective of a global planner as well as a local origin planner. Hence, the global planner could strategically use emissions to induce population flows to richer and less-vulnerable areas, leading to unrealistic policy recommendations that would encourage pollution. To rule this out, migration costs are calibrated such that in the absence of climate change, individuals are equally well-off if they migrate or stay. This ensures almost fully that energy use balances emissions costs and benefits and does not respond to the will of modifying the spatial distribution of the population.

[48] Given that I do not consider inequality, the planner cannot distinguish between immigrants and natives. Thus, it is irrelevant who is paying the migration cost. What matters, instead, is the amount of immigrants, that is, the number of individuals bearing the cost.

In the first-best, the planner maximizes global welfare and takes into account that emitting in a specific region has local and global implications. The planning problem is given by[49]

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

subject to Assumptions 1 and 2, equations (3)–(11) and the regional budget constraints

$$(C_{rt} \equiv)\, P_{rt} c_{rt} = Y_{rt} - K_{rt+1}.$$

The first element in the objective function aggregates consumption in host regions, taking into account that there are two types of residents: natives (P_{r0}) and immigrants ($P_{rt} - P_{r0}$). Immigrants living in host regions must bear a migration cost, η_{rt}. To simplify notation, I define $\Theta \equiv P_{r0} + (P_{rt} - P_{r0})(1-\eta_{rt})$.

Following the procedure in the previous setting, one can find an analytical expression for the global SCC. Let λ_{rt}^{GSP} be the shadow value of regions' final output (3), ω_t^{GSP} of carbon concentrations (8), and μ_{rt}^{GSPh} and μ_{rt}^{GSPo} of population evolution in the host and in the origin regions (6), respectively. Once again assume $\kappa = 1$ to simplify; hence, $L_{rt} = P_{rt}$, $\forall r \in (H, O)$.

Proposition 2: *In the first-best setting, the global planner will increase pollution until the net marginal product of energy, $NMPE_{rt}$, equals the global social cost of carbon, that is, $NMPE_{rt} = SCC_t^{GSP}$ where*

$$SCC_t^{GSP} \equiv \frac{1}{\lambda_{rt}^{GSP}} \Bigg(\overbrace{\sum_{j=0}^{\infty} -\omega_{t+j}^{GSP} \frac{\partial f_{t+j}(.)}{\partial E_{rt}}}^{Standard\,Global\,Output\,Damages} + \overbrace{\beta^{t+1} u'_{t+1} \sum_{r\in H} P_{r0}\gamma_r h_r \frac{\partial i(\Delta z_t)}{\partial E_{dt}}}^{Social\,Cost\,of\,Immigration}$$
$$+ \overbrace{\sum_{r\in H} \mu_{t+1}^{GSPh} (-1) h_r \frac{\partial i(\Delta z_t)}{\partial E_t} + \sum_{r\in O} \mu_{t+1}^{GSPo} o_r \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Global\,Labor\,Effect} \Bigg). \tag{14}$$

Hence, the globally optimal use of energy can be achieved by implementing a carbon price equal to $\tau_t^{GSP} = SCC_t^{GSP}$.

See Appendix C.4 for a detailed derivation of (14).[50] The global SCC is given by (14), and it internalizes all the externalities associated with the use of carbon, regardless of where the emissions or damages occur.

[49] The objective function constitutes a proper social welfare function only under the assumption that individuals are one-period lived. Individuals' country of origin is determined by their ancestors (dynasty).

[50] It shows that the first-order condition of the global planner problem with respect to energy summarizes all the costs and benefits of energy use.

Proposition 2 shows that the globally optimal carbon price consists of the sum of three components. Each one is multiplied by $\frac{1}{\lambda_{rt}^{GSP}}$, the shadow value of one additional unit of final good in region r, which in the optimum equals the marginal utility gain of the final good, $\lambda_{rt}^{GSP} = \beta^t u_t' \frac{\Theta_{rt}}{P_{rt}}$. Hence, again, the carbon price is expressed in terms of the final good.

The first component of (14) embodies the present discounted value of climate damages to final output and is similar to the carbon price formulas in GHKO and Gerlagh and Liski (2018), for instance. ω_{t+j}^{GSP} is the social value of one unit of concentrations and in the optimum it is given by $\omega_t^{GSP} = \sum_r \lambda_{rt}^{GSP} \frac{\partial Y_{rt}}{\partial z_t}$. It aggregates host and origin regions damages. The second component in (14) captures the social cost of immigration that originates from time t emissions, borne by host natives.

Finally, the third component of (14), called the *Global Labor Effec*t, captures the welfare implications of having a larger population in host regions (first element) and a lower population in origin regions (second element). μ_{rt}^{GSPh} equals $\sum_{j=0}^{\infty} \left(\beta^{t+j} u_{t+j}' \left[\frac{\Theta_{rt+j}}{P_{rt+j}} \frac{\partial Y_{rt+j}}{\partial P_{rt+j}} - \frac{P_{r0}}{P_{rt+j}} \eta_{rt+j} c_{rt+j} \right] \right)$ in the optimum and determines the magnitude of the first element. This element accounts for several things: i. consumption per capita in the host region is lower due to the inflow of refugees (this corresponds to the labor effect, as seen in the unilateral host setting); ii. refugees now consume in the host—more developed—region; and iii. refugees must bear some migration costs. The second element of the *Global Labor Effect* captures the effect of population outflows on origin regions' final production. In the optimum, $\mu_{rt}^{GSPo} = \sum_{j=0}^{\infty} \beta^{t+j} u_{t+j}' \frac{\partial Y_{rt+j}}{\partial P_{rt}}$. Note that in a situation in which migration costs are zero, κ is high enough, and host regions are more productive, the overall *Global Labor Effect* is negative, and hence, it is a positive externality. This is because the decrease in production in origin regions would be offset by larger production in host regions and, thus, global welfare would be higher. However, this is not necessarily the case with positive migration costs.

Taking stock, the main difference between the global SCC and the unilateral SCC—expression (12)—is the fact that the global planner internalizes the global externality of pollution and accounts for the whole population's welfare. As a result, the global planner internalizes the potential benefits of migration flows to more-developed regions. Since the only possibility to migrate is through environmental degradation, this could lead to the unnatural prescription of inducing climate change in order to reallocate population. To rule this out and capture the true effect of climate refugees on the global SCC, migration costs are incorporated.

5.2 Unilateral (non-cooperative) policies in all regions: Nash equilibrium

Standard climate-economy models feature a global planner that implements globally optimal environmental policies. However, we do not see in reality a governmental institution setting prices optimally, nor a global agreement between all regions. The difficulty of reaching a global consensus on policies and the heterogeneity of climate damages across regions make such coordination scenario implausible. As a consequence, we expect that if all regions decide to implement carbon policies, they will do so in a non-cooperative way. Hence, the analysis of non-cooperative policies is of utmost relevance.

The following analyzes a second-best scenario in which each local planner implements its own optimal policy, assuming that other countries will implement the best response to their action. This is a suboptimal solution because local planners internalize the externality of emitting from their country's perspective, that is, they only account for the damages that one extra unit of emissions cause within their region and to their natives. It differs from the benchmark case where the origin region was environmentally inactive because instead of implementing the optimal policy taking the other countries' decision as given, in the current case each country implements the best response to other countries strategies.

The objective function of a host region local planner is

$$W_t^{NE\,host} = \sum_{t=0}^{\infty} \beta^t u_t \left(P_{r0} c_{rt} - P_{r0} \gamma_r h_r I_t \right).$$

The objective function of a local planner from an origin region is

$$W_t^{NE\,origin} = \sum_{t=0}^{\infty} \beta^t u_t \left[P_{rt} c_{rt} + \sum_{l \in H} \left((1 - \eta_{lt}) \left(\sum_{m=0}^{t\text{-}1} h_l o_r I_{t-m} \right) c_{lt} \right) \right].$$

Note that the origin social planners aggregate consumption of those currently living in their region ($P_{r,t}$) as well as those who migrated to a host country at any point in the past. The aggregate welfare of all individuals that in the initial period, $t = 0$, were living in the origin region, taking into account the migration costs borne by those who will eventually migrate to host regions. Note also that a planner from an origin region might have incentives to reallocate population to a host region if that represents higher consumption for a share of its natives. Once again, this is accounted for using migration costs.

The solution for the non-cooperative equilibrium consists of the equilibrium strategies of the different countries. Local planners design a policy path and commit to implementing it, that is, I assume full commitment of each local planner to present and future taxes. Each path of emissions is the best response to the other planners' paths. In other words, each country determines its allocations by maximizing the local objective function and considering that all other countries' strategies are unaffected by its own allocation. Then, the solution is a Nash equilibrium. I assume there is full commitment and this implies that regions define their lifetime strategies based on other regions' lifetime strategies. The numerical algorithm to obtain the quantitative solution for the non-cooperative equilibrium is detailed in Section 5.4.

Non-cooperative carbon price in host regions

Following the same procedure as in previous settings, one can find an analytical expression of the suboptimal (non-cooperative) carbon price for host and origin regions. Once again, I assume that $\kappa = 1$ to get simplified expressions.

Proposition 3: *In a Nash equilibrium setting, the host planer will increase pollution until the net marginal product of energy, $NMPE_{ht}$, equals the SCC_t from the host planner's perspective, that is, $NMPE_{ht} = SCC_t^{NEh}$ where*

$$SCC_t^{NEh} \equiv \frac{1}{\lambda_t^{NEh}} \Bigg(\overbrace{\sum_{j=0}^{\infty} -\omega_{t+j}^{NEh} \frac{\partial f_{t+j}()}{\partial E_{ht}}}^{Standard\,climate\,damages} + \overbrace{\beta^{t+1} u'_{t+1} P_{h0} \gamma_r h_r \frac{\partial i(\Delta z_t)}{\partial E_{ht}}}^{Social\,Cost\,of\,Immigration} + \overbrace{\mu_{t+1}^{NEh}(-1) \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Labor\,effect} \Bigg). \tag{15}$$

Hence, the unilaterally optimal use of energy in a host regions when all the other regions are environmentally active can be achieved by implementing a carbon price equal to $\tau_t^{NEh} = SCC_t^{NEh}$, where SCC_t^{NEh} is given by (15).

See Appendix C.5 for a detailed derivation of (15).[51] It summarizes the public costs and benefits of energy use that affect the objective of a host planner and it corresponds to the host's non-cooperative SCC, under the Nash equilibrium. The private costs and benefits in this setting are captured by the $NMPE_{ht}$. Once again, λ_t^{NEh}, ω_{t+j}^{NEh}, and μ_{t+1}^{NEh} are the shadow values of final output, (3), carbon concentrations, (8), and population evolution in the host region, (6), respectively. In equilibrium, the shadow values are equal to: $\lambda_t^{NEh} = \beta^t u'_t \frac{P_{h0}}{P_{ht}}$, $\omega_t^{NEh} = \lambda_t^{NEh} \frac{\partial Y_{ht}}{\partial z_t}$ and $\mu_t^{NEh} = \sum_{j=0}^{\infty} \left(\beta^{t+j} u'_{t+j} \frac{P_{h0}}{P_{ht+j}} \left[\frac{\partial Y_{ht+j}}{\partial P_{ht+j}} - \frac{Y_{ht+j} - K_{ht+1+j}}{P_{ht+j}} \right] \right)$.

The non-cooperative host SCC in the Nash equilibrium resembles the unilateral SCC in the host region presented in Section 4. However, the two are not equal. In particular, the Nash equilibrium SCC does not contain the *Emissions Reallocation* element. That is because the other regions also implement their own optimal strategy. In the end, each country's strategy is the best response to other countries strategies. Hence, the local planner cannot take the other countries change in emissions as given.

Non-cooperative carbon price in origin regions

Following the same simplifications as before, let λ_{ot}^{NEo}, ω_{t+j}^{NEo}, μ_{t+1}^{NEoh}, and μ_{t+1}^{NEo} be the Lagrange multipliers for final output, carbon concentrations, and population evolution for host and origin countries, respectively. Then, the unilateral carbon price in an origin region can be characterized as follows.

Proposition 4: *In a Nash equilibrium setting, the origin planer will increase pollution until the*

[51] It shows that the first-order condition of the host planner problem with respect to energy summarizes all the costs and benefits of energy use from the host country's perspective.

net marginal product of energy, $NMPE_{ot}$, equals the SCC_t from the origin planner's perspective, that is, $NMPE_{ot} = SCC_t^{NEo}$ where

$$SCC_t^{NEo} = \frac{1}{\lambda_{ot}^{NEo}} \Bigg(\overbrace{\sum_{j=0}^{\infty} -\omega_{t+j}^{NEo} \frac{\partial f_{t+j}()}{\partial E_{ot}}}^{Standard\,Climate\,Damages} + \overbrace{\mu_{t+1}^{NEoh}(-1)\frac{\partial i(\Delta z_t)}{\partial E_{ot}}}^{Labor\,Effect\,Affecting\,Immigrants}$$
$$- \overbrace{\sum_{j=1}^{\infty} \beta^t u_t' \left(\sum_{l \in H} \left(c_{lt} \left(1 - \eta_{rt}\right) h_l o_r \frac{\partial i(\Delta z_t)}{\partial E_{ot}} \right) \right)}^{New\,Immigrants\,Consume\,in\,Host}$$
$$+ \overbrace{\mu_{t+1}^{NEo} \frac{\partial i(\Delta z_t)}{\partial E_{ot}}}^{Reduction\,Local\,Production} \Bigg). \tag{16}$$

Hence, the unilaterally optimal use of energy in an origin region when all the other regions are environmentally active can be achieved by implementing a carbon price equal to $\tau_t^{NEo} = SCC_t^{NEo}$, where SCC_t^{NEo} is given by (16).

See Appendix C.6 for a detailed derivation of (16). It summarizes the public costs and benefits of emissions that affect an origin planner's objective; hence, it corresponds to the non-cooperative origin SCC, in the Nash equilibrium.

From (16) one can see that the non-cooperative origin carbon price in the Nash equilibrium consists of the sum of four components. Each one is multiplied by $\frac{1}{\lambda_{ot}^{NEo}}$, which in equilibrium is given by$\beta^t u_t'$, to express them in terms of the final good. The first component of (16) summarizes the standard climate damages. In equilibrium, $\omega_t^{NEo} = \lambda_{ot}^{NEo} \frac{\partial Y_{ot}}{\partial z_t} + \sum_{r \in H} \lambda_{rt}^{NEo} \frac{\partial Y_{rt}}{\partial z_t}$, from what one can see that the origin local planner internalizes the climate damages suffered in both host and origin regions. This is because some origin natives are living in host regions as climate refugees. The second component of (16), denoted *Labor Effect Affecting Immigrants*", also captures the fact that the local origin planner cares about emigrants' welfare forever. More specifically, it represents the *Labor Effect* that climate refugees suffer in their new country of residence as a consequence of future climate refugees. In equilibrium, $\mu_t^{NEoh} = \sum_{j=0}^{\infty} \left(\beta^{t+j} u_{t+j}' \sum_{l \in H} \left[\frac{\partial Y_{ht+j}}{\partial L_{ht+j}} - \frac{Y_{lt+j} - K_{lt+1+j}}{P_{lt+j}^2} \left(1 - \eta_{rt+j}\right) \sum_{m=0}^{t\text{-}1+\text{j}} h_l o_r I_{t-m} \right] \right)$.

The third component of the non-cooperative origin SCC is denoted *New Immigrants Consume in Host* and reflects that those who migrate to more-developed regions (host) will enjoy higher consumption. Hence, it is a benefit. Finally, the fourth component refers to the decrease in local production in the host region as a result of emigration, with $\mu_t^{NEo} = \sum_{j=0}^{\infty} \beta^{t+j} u_{t+j}' \frac{\partial Y_{rt+j}}{\partial P_{rt+j}}$.

Taking stock, the previous analysis provides analytical expressions for the unilateral carbon prices in a Nash equilibrium context. Given that local planners internalize the externality only partially, carbon prices differ substantially across regions depending on whether they are host or

origin regions. In particular, host regions' planners take into account the potential consumption dilution associated with immigration. Moreover, origin regions may benefit from reallocation of population to more-developed regions.

5.3 Additional calibration

The calibration detailed in Section 4 applies for the globally optimal and the Nash Equilibrium settings. Again, I present the simulation results for two regions, one host and one origin. Below I discuss the new parameters specific to these settings.

5.3.1 Migration costs

Migration costs are used as a tool to rule out the strategic use of emissions to reallocate population to more-developed regions. To accomplish that, I calibrate them in the following way. First, the economy is simulated under a hypothetical scenario of climate change absence. Second, I calculate the level of η_t that equalizes consumption per capita across regions in each period

$$c_{ht}(1 - \eta_t) = c_{ot}.$$

Finally, the path of η_t is stored and used for the subsequent simulations with climate damages. This ensures that absent climate damages the planners would not benefit from reallocating people to less-vulnerable and more productive regions.

5.4 Calibration results

5.4.1 The global social cost of carbon: first-best solution

Table 5 presents globally optimal carbon prices—global SCC—in the near term. The carbon price without climate displacement is larger than the unilateral host price presented before because the global planner takes the world population's welfare into account and therefore accounts for global damages. From columns (1) and (2) we see that, although the globally optimal carbon price is higher with refugees, the difference is very small. In fact, this is not necessarily the case throughout the simulation period. Figure 6 displays the evolution of carbon prices for the next 100 years. After 40 years there is a reversal and the carbon price with refugees becomes slightly lower than without refugees for the no disutility case. This is mostly driven by the fact that, with displacement, a larger population lives where emissions are less harmful. Stated differently, population flows imply that overall climate damages are reduced, since a larger share of the economic activity takes place in the least vulnerable region. Once again, the extent of the willingness to pay to avoid immigration makes the social cost of carbon either slightly or substantially larger. As such, in the case of Brexit disutility, the carbon price with refugees is persistently higher.

Figure 6: Evolution of carbon prices under first-best setting

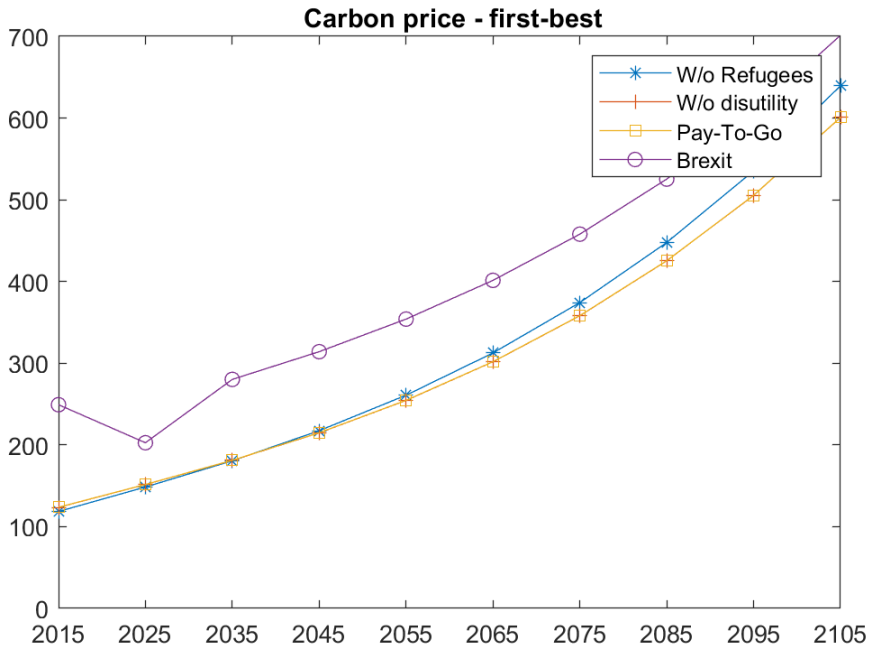


Table 5: First-best, Globally Optimal Carbon Price, SCC^{GSP}

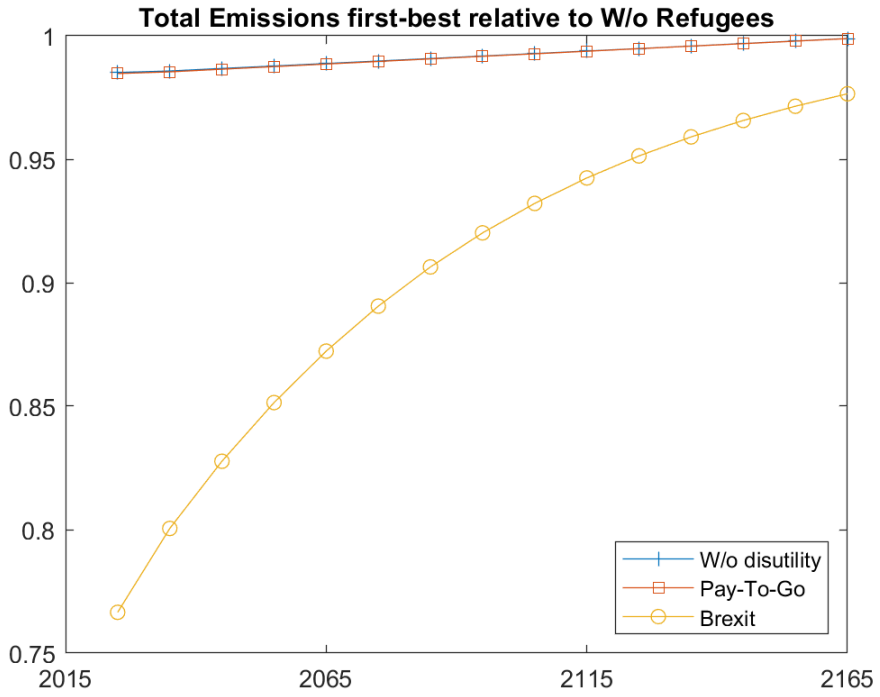
	W/o Climate Refugees	W Climate Refugees		
		W/o Disutility	W Disutility	
			Pay to Go	Brexit
$ per ton of carbon	(1)	(2)	(3)	(4)
C&H disasters	118.58	123.66	123.81	249.22
C&H&M disasters		121.25	1121.33	179.10

Notes: This table presents short-term globally optimal carbon prices under the different scenarios and calibrations of the migration response to different types of natural disasters ("C&H disasters" includes only climatological and hydrological disasters. "C&H disasters" includes also meteoroglogical disasters).

A high (low) carbon tax is associated with lower (higher) emissions. Consistent with this, Figure 7 shows that global emissions are lower under displacement in the first 100 years. Figure E.2 in the Appendix shows the evolution of global emissions in relation with the unilateral host setting presented before.

It is particularly relevant to highlight the role of migration costs, η_t. Given that migration is not micro-founded in this model but, rather forced I use migration costs as a reduced-form solution to rule out the planner's strategic use of emissions to induce displacement to the most productive region. Under a scenario in which both regions have the same climate damages, this is exactly the case and immigrants' consumption per capita after migration costs is equal to that in the origin region.

Figure 7: Evolution of total emissions under first-best setting, relative to the no displacement case



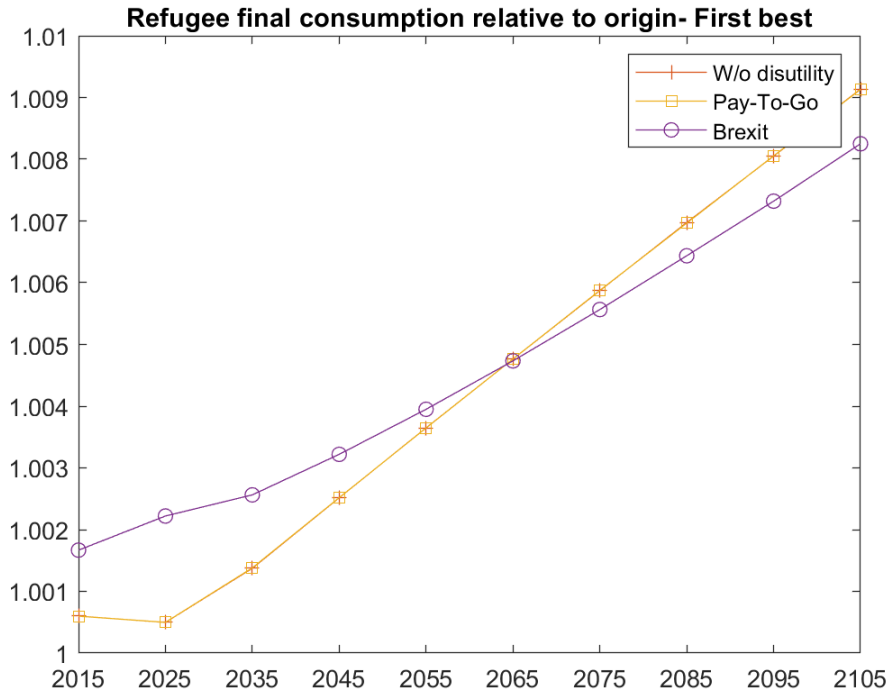
However, when the two regions have a different evolution of climate damages, that is, are differently affected by the same amount of carbon concentrations, then some differences in consumption per capita after migration costs persist. This can be seen in Figure 8, which shows that an immigrant experiences some—albeit minimal—consumption gain from migrating.

Taking stock, this setting illustrates that the first-best policy under climate displacement is quantitatively and qualitatively different from the unilateral host optimal policy. Not only there is no substantial increase in the carbon tax when climate refugees are taken into account, but there is even a slight reduction after some periods. This is partially because the *Labor Effect* is now global and takes into account the consequences of population flows in both regions. In addition, as population flows from the origin to the host region, there is a lower percentage of the population exposed to severe climate damages, that is, global climate damage is lower. Finally, migration costs play a key role in ruling out the strategic use of emissions, thus in providing a comprehensive interpretation of the results. Given that climate damages evolve differently in each region, some adaptation strategy persists.

5.4.2 Non-cooperative policies in all regions: Nash equilibrium setting

The following presents the simulation results under non-cooperative policies in all regions. Local planners care only about their initial natives, regardless of their current residence. The numerical algorithm to obtain the quantitative solution for the non-cooperative equilibrium is as follows. I

Figure 8: Refugees vs. origin natives' consumption comparison under first-best setting



assume that each country sets an allocation (emissions and savings path) to maximize the local objective function, taking the other regions allocations as given. I optimize iteratively for each region holding allocations from other regions in the previous iteration fixed, and I continue this sequence until the control variables are unchanged. Given that the outcome of the quantitative analysis is invariant to initial conditions, this enhances the confidence that the Nash equilibrium is unique.

Table 6 summarizes the short-term carbon prices for the host and the origin region and under each scenario, namely: without refugees, without disutility, etc. First, we see that without displacement, carbon prices are higher in the origin country (column 1). This is because climate damages are higher in the origin country. However, once climate refugees are accounted for, the gap is reduced (column 2) because the host carbon price increases substantially, while the origin carbon price decreases slightly. The Nash equilibrium carbon price for the host region increases further under higher values of the social cost of immigration (columns 3 and 4). With regards to the origin region, we can see that the overall climate damages faced by the origin planner are lower with displacement (lower carbon price) because a share of its population is located in a less affected area. However, the reduction is minimal.

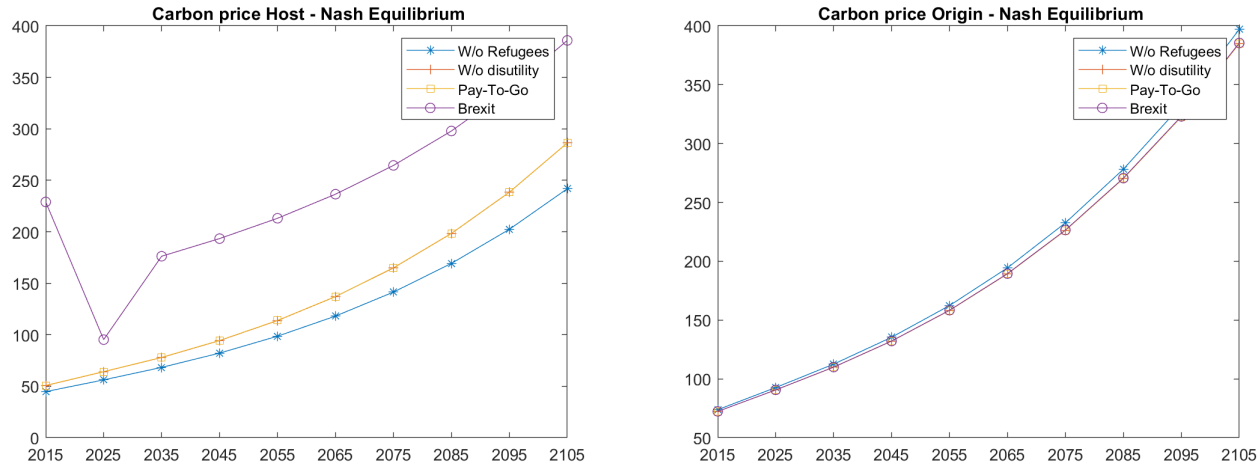
Figure 9 displays the evolution of carbon prices in the host and in the origin country for the next 100 years and shows that the pattern from the near term persists in time. Figure E.2 in the Appendix shows the evolution of global emissions in relation with the unilateral host and the first-best settings presented before.

Table 6: Carbon Price Under Nash Equilibrium, SCC^{NEh} and SCC^{NEo}

		W/o Climate Refugees	W Climate Refugees		
			W/o Disutility	W Disutility	
$ per ton of carbon	Region	(1)	(2)	Pay to Go (3)	Brexit (4)
C&H disasters	Host	44.72	50.62	50.77	228.97
	Origin	73.81	72.30	72.31	72.32
C&H&M disasters	Host	44.72	47.82	47.90	114.59
	Origin	73.81	73.09	73.09	73.01

Notes: This table presents short-term non-cooperative carbon prices for the host and the origin region under the different scenarios and calibrations of the migration response to different types of natural disasters ("C&H disasters" includes only climatological and hydrological disasters. "C&H disasters" includes also Meteoroglogical disasters).

Figure 9: Evolution of carbon prices under Nash equilibrium



Taking stock, the Nash equilibrium setting shows that polluting strategies are different—even opposing—for host and origin regions. Similar to the first setting presented, where the host region acts unilaterally and the origin region is inactive, unilateral carbon prices increase in the host region after accounting for climate refugees. This stands in contrast to the origin region's strategy, which slightly lowers its carbon price under displacement. Although origin regions suffer higher damages, they could potentially benefit from a reallocation of population to less-vulnerable areas. Comparing these results to the first-best setting we can conclude that, even though the globally optimal carbon price remains almost unchanged after accounting for the presence of climate refugees, the unilateral incentives to tackle climate change are affected. This is particularly the case for host regions.

6 Extensions

6.1 Border Control

I next investigate the interaction between a carbon policy and a border control policy. The baseline model presented above assumes there are no border barriers to climate refugees.[52] I now assume that host regions are able to block the inflow of immigrants.

In each period the planner decides the share of refugees that can effectively enter the country, ψ_t. Hence, a share $1-\psi_t$ of immigrants is deported to their origin region. The deportation cost per immigrant is denoted by χ_t and is measured in terms of final consumption. χ_t is borne by the host region and can potentially vary over time.

The following presents the case of a host region acting unilaterally, while the origin is in laissez-faire. The lifetime objective function of the social planner is given by

$$W_t^{UhBC} = \sum_{t=0}^{\infty} \beta^t \left[u \left(P_{h0} c_{ht} - P_{h0} \gamma \psi_t i(\Delta z_{t-1}) \right) \right],$$

subject to the regional budget constraint, $c_{ht} = \frac{Y_{ht} - K_{ht+1}}{P_{ht}} - \chi_t (1-\psi_t) i(\Delta z_{t-1})$, where $0 \leq \psi_t \leq 1 \ \forall t$, $P_{ht} = P_{ht-1} + \psi_t i(\Delta z_{t-1})$ and $P_{ot} = P_{ot-1} - \psi_t i(\Delta z_{t-1})$. Note that the budget constraint includes the costs of border control.

Assuming that $\kappa = 1$, hence $L_{ht} = P_{ht}$, the host unilateral SCC with border control is given by:

$$SCC_t^{UhBC} = \frac{1}{\lambda_t^{BC}} \Bigg(\overbrace{\sum_{j=0}^{\infty} -\omega_{t+j}^{BC} \frac{\partial f_{t+j}(.)}{\partial E_{ht}}}^{Standard\,Output\,Damages} - \overbrace{\mu_{t+1}^{BCo} (-1) \psi_t \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Emissions\,Reallocation}$$
$$+ \overbrace{\beta^{t+1} u'_{t+1} P_{h0} \gamma \psi_t \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Social\,Cost\,of\,Immigration} + \overbrace{\mu_{t+1}^{BCh} (-1) \psi_t \frac{\partial i(\Delta z_t)}{\partial E_t}}^{Labor\,effect} \Bigg), \tag{17}$$

where λ_t^{BC} denotes the Lagrange multiplier on the final production function (3), ω_t^{BC} is the concentration's multiplier (8), and μ_t^{BCh} and μ_t^{BCo} are the multipliers associated with the evolution of population in the host and the origin region, respectively. The characterization of the shadow values in the optimum is equivalent to the benchmark case.

The planner can implement border control to reduce the inflow of refugees and, consequently, the social cost of immigration and the net cost of the labor effect. At the same time, the restriction of refugees reduces the benefit of emissions reallocation. In equilibrium, $\chi_t - \gamma = \frac{\mu_t^{BCo} - \mu_t^{BCh}}{\beta^t u'_t P_{h0}}$, that is, the level of immigration restriction will be such that it balances the costs and benefits of population

[52] Although this is reasonable from a lon-run equilibrium perspective, in the short run countries can implement border control measures to restrict population inflows.

inflows.

Figure 10 shows the evolution of carbon prices under border control, assuming there is no social cost of immigration ($\gamma = 0$). It presents two different scenarios with border control and compares them to the benchmark cases with and without forced migration. In the first scenario, I assume that border control is costless, namely $\chi = 0$. In the second scenario, I assume that the cost of border control is positive, $\chi > 0$, and I calibrate it using data from the US department of Homeland Security. More specifically, I use the annual number of detentions of illegal population and the expenditure in border control for 2019, which yields an estimate of the cost of border control equal to $\chi = 4.6 \times 10^5$. The simulation results in Figure 10 illustrate that under a US-calibrated cost of border control, the carbon tax is equal to the setting without border control. This indicates that the cost of controlling the entrance of refugees is larger than the net cost of receiving them. Hence, the deportation policy is suboptimal. As a result, the inflow of population is equal to the benchmark case (see Figure 11, bottom panel). However, under the extreme situation in which border control is costless ($\chi = 0$), the unilaterally optimal carbon price is substantially lower—its level resembles the one without climate refugees—and the amount of immigration is strongly restricted (Figure 11, top panel). These results indicate that the optimal carbon and immigration policy depend strongly on the cost of implementing border control measures.

6.2 The welfare costs of ignoring forced migration

Climate refugees have been ignored by the economic literature on optimal carbon policies and by policy makers. Table 7 shows host country's welfare costs of this omission under the unilateral host country setting. It compares natives' welfare without climate refugees to that with climate refugees but under the wrong policy. Welfare costs are measured as the percentage consumption increase that would be necessary in every period to make individuals as well off as in the case without forced migration. The required compensation is positive and higher under high values of anti-immigration sentiment.

Table 7: Welfare Costs of Ignoring Climate Refugees

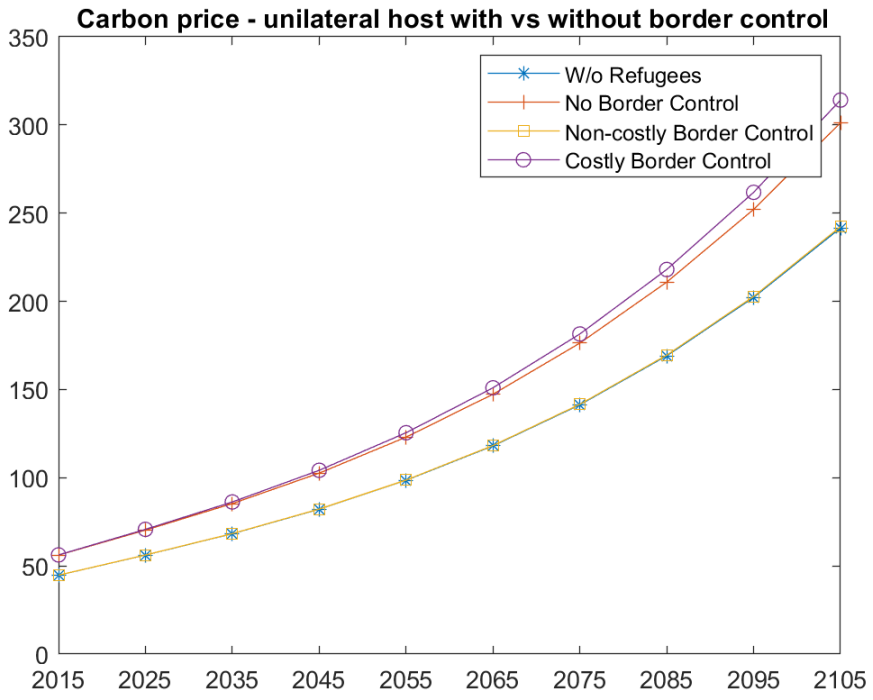
	W/o Disutility (1)	Pay to Go (2)	Brexit (3)
% change	0.23	0.23	0.24

Notes: Percentage increase in consumption required to achieve the same level of welfare as in the no climate refugees setting.

6.3 Alternative discounting, higher climate damages, and Negishi weights

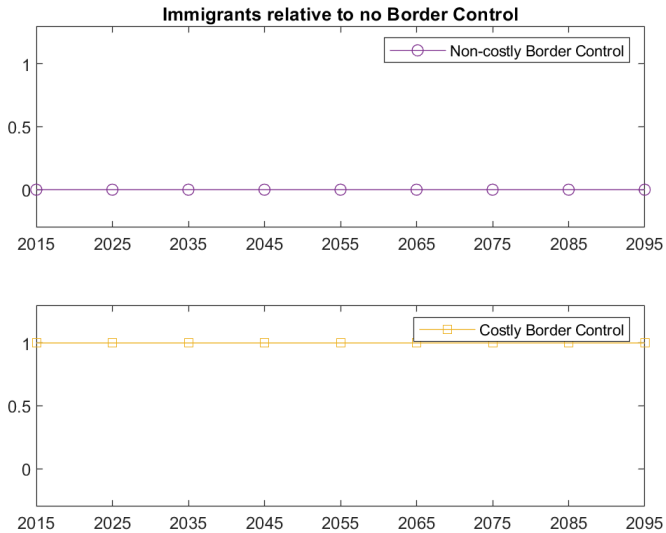
The quantitative exercises presented above assume an annual discount factor β of 0.958, that is, a 1.5% discount per year. This follows Nordhau's calibration of the discount rate. While economists

Figure 10: Evolution of carbon prices with border control (no social cost of immigration)



Notes: This figure presents the evolution of carbon taxes under four different settings: i. "W/o Refugees," where forced migration is not considered; ii. "No Border Control," where forced migration is considered, the social cost of immigration is assumed to be zero and there is no border control; iii. "Non-costly Border Control," same as in ii. but including costless border control; and iv. "Costly Border Control," which is the same as ii. but including costly border control.

Figure 11: Evolution of climate refugees under border control, relative to no border control



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

have long recognized the discount factor as one of the central parameters to quantify the effects of climate change, there is huge disagreement on its value. Some argue that future losses are as worrying as losses today, so there should be almost no discounting. This point is supported, among others, by Stern (2007), who advocates for a 0.1% discount rate. Panel B of Table 8 shows the unilateral host carbon prices under Stern discounting. For comparison, Panel A repeats the results under the benchmark calibration. One can see that unilateral host carbon prices under Stern discounting increase by more than three-fold. This confirms the relevance of β in quantitative models. However, the conclusions of the main part of the paper remain unchanged under Stern discounting, namely that climate refugees increase host countries' unilateral SCC.

IAMs use the damage function, Ω, as the link between an economic growth model and the climate. Hence, Ω is the tool that quantifies climate damages. However, the damage function is subject to high levels of uncertainty because the true economic impacts of climate change are still unknown. In this paper, I take the functional form and calibration of Ω from GHKO, which uses an exponential approximation of the seminal damage function in Nordhaus' DICE model.[53] Some scientists and economists have argued that this function leads to implausibly low damages. For that reason, I re-run the quantitative analysis under a more severe consideration of climate damages. Panel C in Table 8 shows the level of carbon prices when the likelihood of "catastrophic" damages is three times higher than Nordhaus' consideration.[54] One can see that carbon prices increase twofold.

[53]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.

[54]I use Nordhau's calibration for "catastrophic" damages.

Once again, the conclusions of the main part of this paper remain unchanged.

Table 8: Unilateral Climate Action in Host Region

	W/o Climate Refugees	W Climate Refugees		
		W/o Disutility	W Disutility	
			Pay to Go	Brexit
$ per ton of carbon	(1)	(2)	(3)	(4)
Panel A: Benchmark				
	44.72	56.14	56.45	247.43
Panel B: Stern discounting				
	147.48	161.49	161.81	370.26
Panel C: Higher climate damages				
	87.93	99.54	99.83	291.31

Notes: This table presents some sensitivity analysis of the short-term unilateral carbon prices for the host region. Throughout, the forced 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.

In the first-best setting presented above, the global planner's objective function depends on world consumption, regardless of the origin of each individual. Hence, the planner does not consider the distribution of consumption across individuals' countries of origin. I now present the optimal global policy when the planner is concerned about consumption distribution. More 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 equal to the inverse of each region's marginal utility of consumption in the initial period.[55] 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 will be preserved and results respond to a will of addressing climate-related issues.[56] Table 9 presents the first-best carbon prices using regional weights. Although the estimates are

[55]Regional weights are calculated as

$$\Upsilon_r = \frac{\frac{1}{U'_r}}{\sum_r \frac{1}{U'_r}}.$$

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

slightly larger than in the benchmark simulations, the picture relative to the no displacement scenario remains unchanged.

Table 9: First-best Carbon Prices with Regional Weights

	W/o Climate Refugees	W Climate Refugees		
		W/o Disutility	W Disutility	
			Pay to Go	Brexit
$ per ton of carbon	(1)	(2)	(3)	(4)
	131.63	137.60	137.81	324.84

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. Throughout, the refugee response to climate change is calibrated using climatological and hydrological disasters.

6.4 Alternative climate refugee function

The benchmark model takes a very conservative approach on the international displacement response to climate change. It assumes that only contemporaneous changes in concentrations lead to forced migration. Hence, it abstracts from any delayed effect of concentrations on natural disasters and its consequent migration response.

In what follows, I relax this rigidity by implementing a migration response to the accumulated amount of carbon. More specifically, climate refugees are a function of the change in concentrations with respect to the initial period. This implies that emissions today contribute to future-periods refugees as long as they have not fully depreciated. 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 cause new refugees in each of the following j years.

Table 10 shows the unilateral carbon prices in the host region, with an inactive origin region. In line with what has just been mentioned, carbon prices with climate refugees are larger under this alternative climate refugee function compared to the benchmark—and more conservative—specification.

Table 10: Unilateral Climate Action in Host Region, Alternative Refugee Function

	W/o Climate Refugees	W Climate Refugees		
		W/o Disutility	W Disutility	
			Pay to Go	Brexit
$ per ton of carbon	(1)	(2)	(3)	(4)
	44.72	58.37	58.82	249.06

Notes: This table presents the unilateral carbon prices in the host region, with an inactive origin region, using a less conservative climate refugee function. Emissions today cause refugees in the future as long as they are not fully depreciated. Throughout, the refugee response to climate change is calibrated using climatological and hydrological disasters.

7 Conclusions

During recent decades, the economic analysis of climate change has made progress in providing more accurate estimates of the social cost of carbon (Nordhaus and Boyer 2000; GHKT). This paper contributes to this endeavor by focusing on an unaccounted for consequence of climate change: climate refugees. The existing literature on optimal carbon policy either abstracts from climate refugees or considers general migration and omits the analysis of optimal carbon policies.[57]

In this paper, I analyze how climate-forced migration shapes global and unilateral optimal carbon prices, both theoretically and quantitatively. I start by documenting empirically the phenomenon of climate displacement from developing to developed regions. While the existing empirical literature typically estimates the migration response to slow and progressive changes in climate, in this paper I focus specifically on forced migration due to natural disasters caused by climate change. I then develop an integrated assessment model with climate refugees to analyze carbon policies. I find that the theoretical characterization of optimal policies changes substantially in the presence of climate refugees. Hence, the interaction between climate and displacement is a crucial dimension of climate change. This theoretical framework is rich enough to estimate the costs of carbon quantitatively.

Although the term climate refugee is not recognized by international law, I define it as an individual who is forced to move internationally because of a natural disaster. Exploiting the randomness of natural disasters and using time and country fixed effects, I find that natural disasters cause population flows from developing countries to high-income and less-vulnerable countries. This result is robust to multiple specifications and data sources. Contrary to what existing empirical studies on general climate migration have found, the migration response to natural disasters is stronger in low-income countries than in middle-income countries.

To understand the relationship between climate refugees and carbon policies, a general equilibrium framework is required. Pollution is the source of two externalities. First, it damages the

[57]For instance, Beneviste, Oppenheimer, and Fleurbaey 2020, Cruz Alvarez and Rossi-Hansberg 2021 or Bretschger and Xepapadeas 2021 incorporate migration into IAMs but do not account for the consequences of climate-induced migration to calculate optimal policies.

environment and reduces economic output. Second, it induces population flows, which affect regions' labor input. The theoretical model developed in this paper provides a novel framework for analyzing the SCC and unilateral environmental policies more realistically. The inclusion of climate refugees provides new economic insights on the global and unilateral SCC. I simulate the model and find that estimations match with consolidated literature when the new features are switched off. Hence, the model output is of comparable order of magnitude with previous research. Moreover, while the magnitude of the globally optimal carbon price does not change substantially after accounting for climate refugees, host regions' prices increase considerably. Hence, regions that are developed and less-vulnerable to climate effects should be willing to fight climate change more strongly. This is especially the case for host societies with a high anti-immigrant sentiment.

Finding the causal relationship between climate change and migration is challenging because there are multiple reasons behind the decision to migrate. This paper focuses on climate refugees and abstracts from general climate migration and economic migration with the aim of providing properly identified estimates. One interesting extension would be to include economic and climate migration. Such an analysis would yield updated estimates of the social cost of carbon that would account for population flows as a result of slow and progressive changes in climate.

It would also be interesting to examine how internal refugees, that is, forced migrants within regions, would affect unilateral carbon prices in origin regions. There might be some benefits to reallocating population to less-vulnerable areas within a country, unless these areas are less economically developed or already overpopulated.

Another interesting feature to be explored further is the social cost of immigration. There is still little empirical knowledge about natives' attitudes toward immigration, most likely because these attitudes vary substantially across individuals and time. Given the impossibility of achieving a global agreement to tackle climate change, we can expect environmental policies to remain unilateral and to reflect individual countries' preferences for environmental degradation and migration. As shown in the quantitative results, natives' attitudes toward immigrants can affect the magnitude of carbon prices considerably. Hence, a better understanding of this feature would be necessary.

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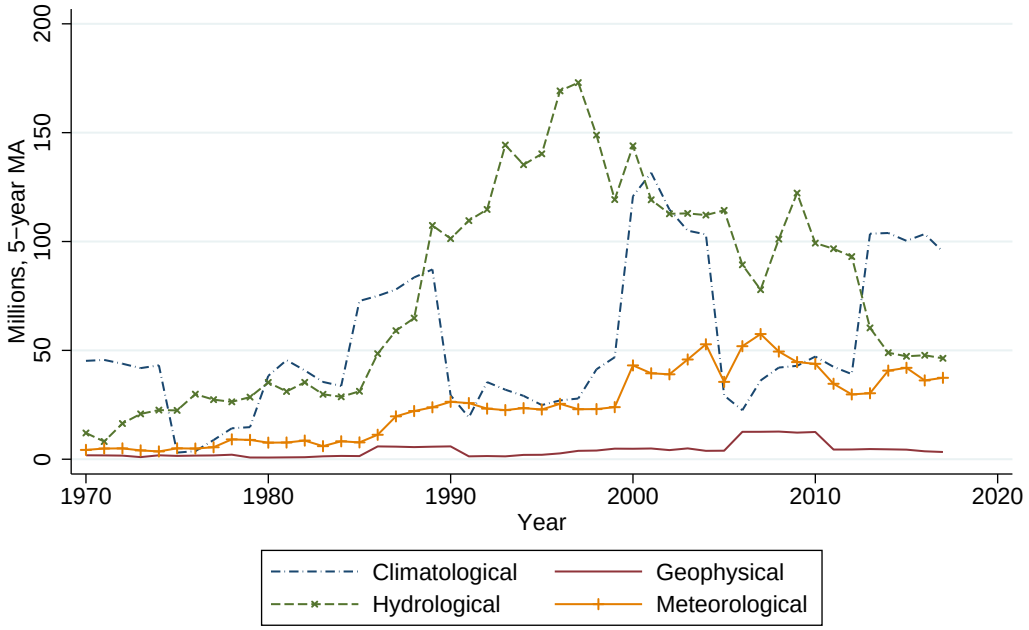
Appendices

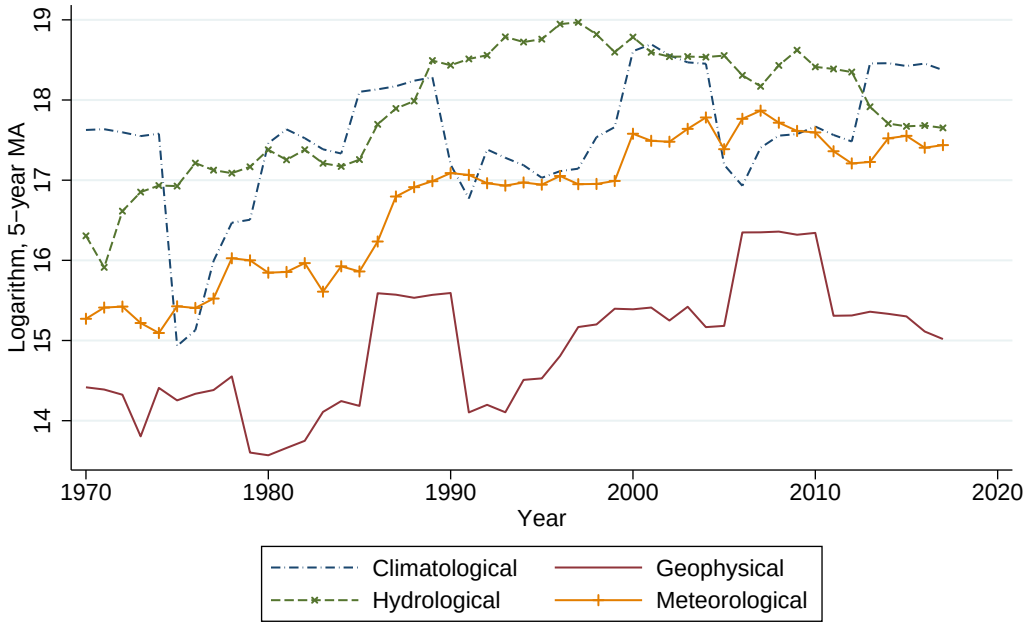
A Empirical Analysis: Figures

Figure A.1: Total number of people affected by disaster group (1970–2017)



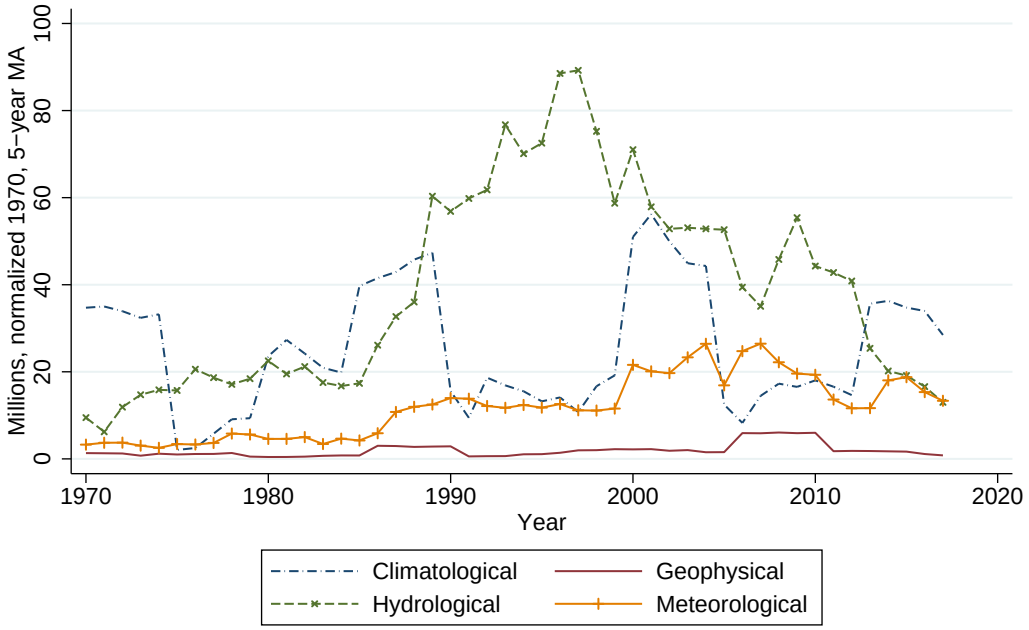
Note: This graph shows the evolution of people affected by natural disasters worldwide. Units are in millions and data points are five-year moving averages. *Source:* Author, based on EM-DAT database.

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



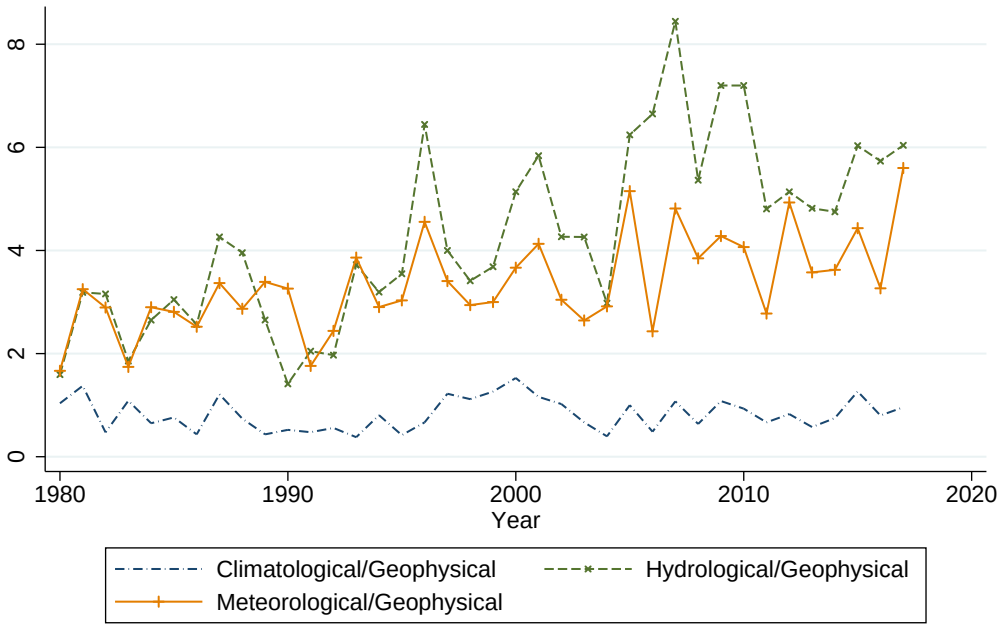
Note: This graph shows the evolution of people affected by natural disasters worldwide. Units are in logs and data points are five-year moving averages. *Source:* Author, based on EM-DAT database.

Figure A.3: Total number of people affected by disaster group, normalized by 1970 population (1970–2017)



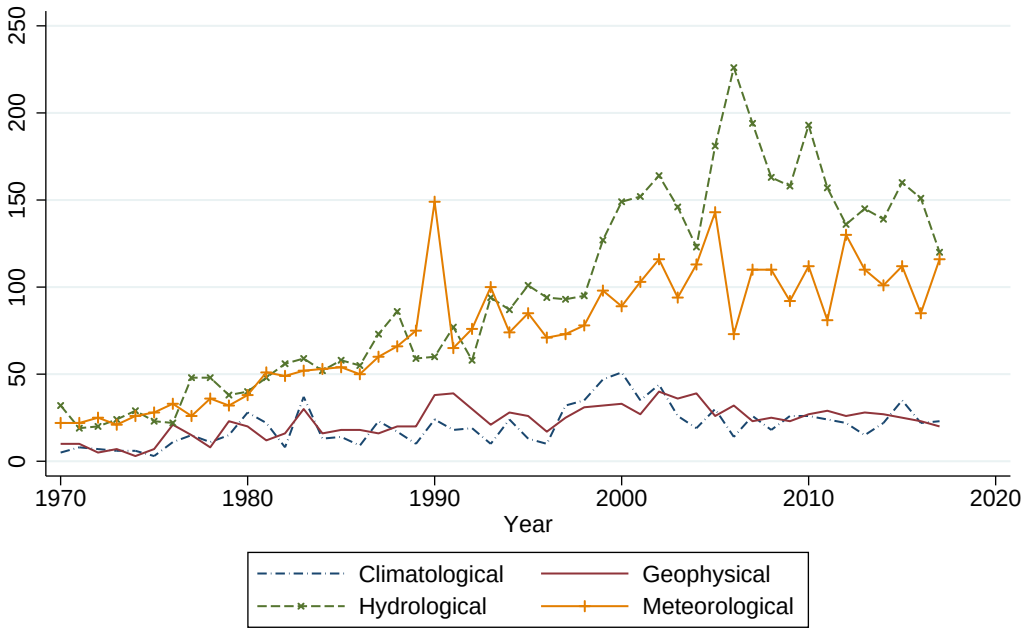
Note: This graphs shows the evolution of people affected by natural disasters worldwide. Units are in millions and data points are five-year moving averages. The number of people affected is normalized by the country population in 1970 following: $\#affected_{i,t}^{Normalized} = \#affected_{i,t} \frac{Pop_{i,t}}{Pop_{i,1970}}$, where i and t stand for country and year, respectively. *Source:* Author, based on EM-DAT database.

Figure A.4: Frequency of natural disasters relative to geophysical events (1970–2017)



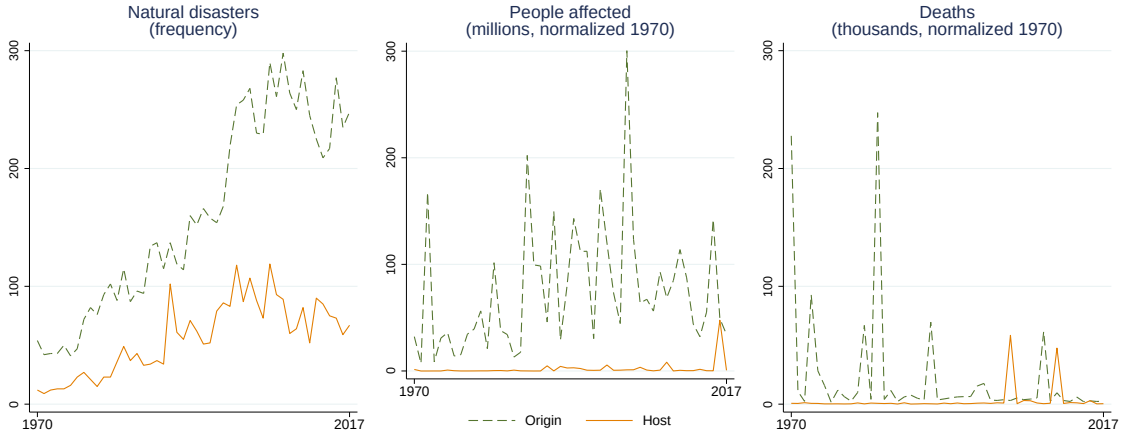
Note: This graph checks for reporting bias (unreported events) in early periods. I assume that i) reporting bias is orthogonal to disaster type; and ii) geophysical events are unrelated to climate change. Given i) and ii), the ratio between each disaster type and geophysical events should cancel any potential bias. The graph shows the evolution of each disaster group without bias, that is, as a ratio of geophysical events. One can see the same trends as in Figure 1, which indicates that the increasing pattern of disasters is not attributable to reporting bias. *Source:* Author, based on EM-DAT database.

Figure A.5: Frequency of large disasters by group (1970–2017) (Large disaster: $\geq$ 1,000 people affected or $\geq$ 100 deaths)



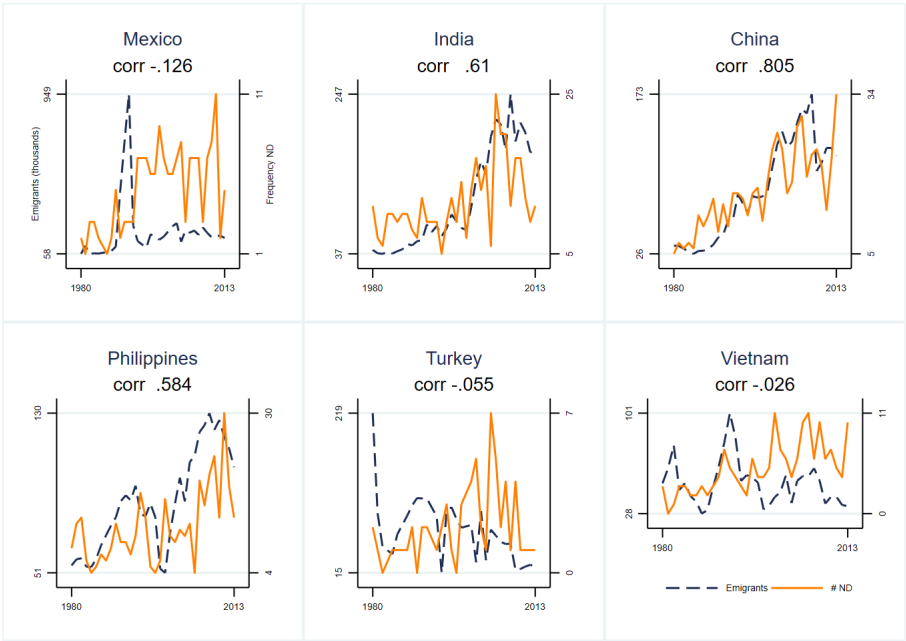
Note: This graph shows the evolution of large natural disasters, namely those events that have caused at least 100 deaths or directly affected at least 1,000 people. Compared to the full sample (Figure 1), the pattern is almost unchanged, which suggests that the increase is not driven by small disasters that are potentially more likely to suffer from reporting bias. *Source:* Author, based on EM-DAT database.

Figure A.6: Host–origin comparisson, yearly data (1970–2017)



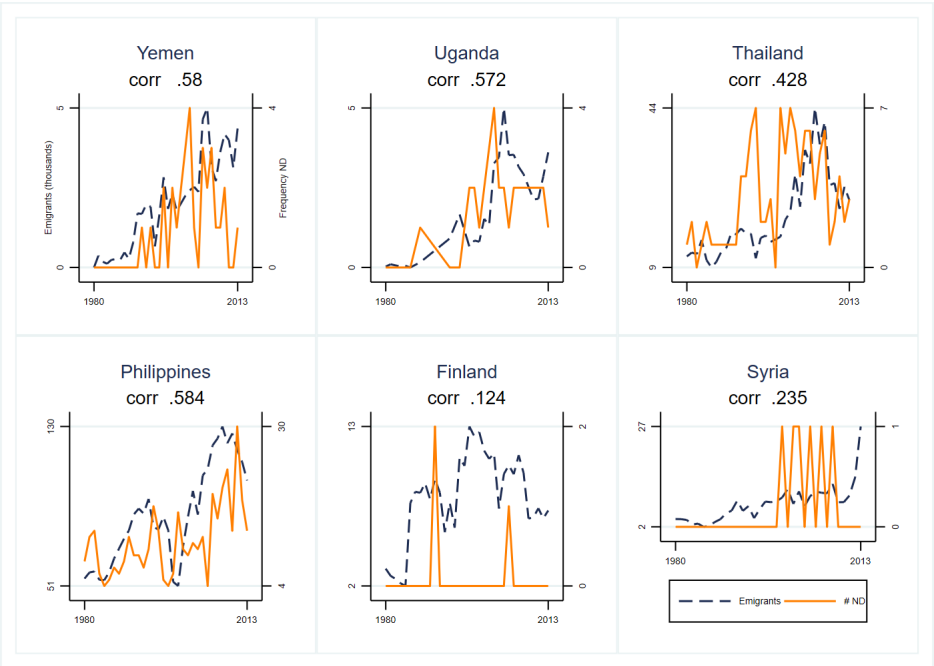
Note: This graphs shows the evolution of natural disasters, the number of people affected by them, and the number of deaths by country group (host and origin). The number of people affected and the number of deaths are normalized by 1970 population. Yearly data. *Source:* Author, based on EM-DAT database.

Figure A.7: Migration flows to host countries vs. occurrence of natural disasters (largest out-migration)



Note: This graph shows the evolution of migration flows and natural disasters by country. It includes the top six countries with a higher average annual out-migration. *Source:* Author, based on EM-DAT database and UN data.

Figure A.8: Migration flows to host countries vs. occurrence of natural disasters



Note: This graph shows the evolution of migration flows and natural disasters by country for six additional countries. Unsurprisingly, Finland and Syria present very low correlation. While the result for the former could be attributable to adaptation, the latter could be a result of the prevalence of conflict. *Source:* Author, based on EM-DAT Database and UN DATA.

B Empirical Analysis: Robustness Checks

In this section, I present robustness checks to the empirical analysis. 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 check for that, Table **??** 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 mean. The estimated coefficients increase more than twofold.

Table B.1: Regressions with 3-year periods

Dep var: log(# migrants)	(1)	(2)	(3)	(4)
log(Nat. Disasters (#))	0.342***	0.305***		
	(0.06)	(0.07)		
log(Affected (#))			0.031***	0.032***
			(0.01)	(0.01)
FE (C, T)	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	N	Y	N	Y
Observations	1,882	1,389	1,882	1,398
Adj. R^2	0.883	0.872	0.882	0.871
Dep. var. mean	8.066	8.773	8.498	8.773
Countries	180	156	180	156

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 1980–2013. This table reproduces columns (2) and (3) from Table 1, both for natural disasters and people affected by them, but it uses three-year observations instead of yearly observations. The sample size is smaller with controls because of missing information for some countries.

Table **??** 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 migration per capita as the dependent variable. Column (2) weighs the occurrence of natural disasters by the share of affected population.[1] Column (3) 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 (4) 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, it may be reasonable to assume that they respond differently than

[1] Defined as: $\frac{Occurrence * TotalAffected}{Population}$

other origin countries due to their socioeconomic characteristics. Excluding them from the sample does not change the results (column 5), which ensures that these countries are not driving the results.

Table B.2: Robustness checks I

Dep var: log(# migrants)	Per capita (1)	(2)	IHSin (3)	w/o C, I (4)	w/o S, SK (5)
log(Nat. Disasters (#))	0.105**		0.151**	0.098*	0.107**
	(0.05)		(0.07)	(0.05)	(0.05)
log(ND (#)-affected w)		0.221**			
		(0.11)			
FE (C, T)	Y	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	Y	Y	Y	Y	Y
Observations	4,183	4,225	4,228	4,118	4,121
Adj. R^2	0.833		0.817	0.869	0.872
Dep. var. mean	-7.491	12918	8.295	7.630	7.654
Countries	156	156	156	154	154

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 1980–2013. This table presents some robustness checks. Column (1) presents results for the log-log specification and migration per capita. Columns (2) weights the number of natural disasters by share of affected population. Column (3) uses the inverse hyperbolic sin transformation of the dependent variable. Column (4) reproduces the main log log regression excluding China and India. Column (5) excludes Singapore and South Korea.

Table **??** 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. As a proxy for conflicts, I use the number of battle-related deaths from the World Bank database. Column (2) controls for the climate vulnerability index by **?**. Column (3) controls for the second lag of the independent variable, and the estimate remains almost unchanged. 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 significant migration response. This shows that this paper takes a conservative approach when measuring climate refugees, since it 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 insignificant concavity. Finally, column (5) uses a Poisson model. Results are robust to all these alternative specifications.

The countries included in the host group differ substantially in their relationship and proximity to origin countries. To gain an idea of the heterogeneity of host countries in terms of their immigration patterns, Table **??** presents results after splitting the host region into three subregions: Europe, North America, and Oceania. While the effect

Table B.3: Robustness checks II

Dep var: log(# migrants)	(1)	(2)	Contr 2lag (3)	Polinomial (4)	Poisson (5))
log(Nat. Disasters (#))	0.118**	0.101**	0.102*	0.198**	0.008**
	(0.06)	(0.05)	(0.05)	(0.09)	(0.00)
Conflict $_{t-1}$	0.042***				
	(0.02)				
Climate Vulnerability		0.108***			
		(0.01)			
log(Nat. Disasters (#))^2				-0.062	
				(0.05)	
log(Nat. Disasters (#))$_{t-2}$			0.129***		
			(0.04)		
FE (C, T)	Y	Y	Y	Y	Y
Population$_{t-1}$, pcGDP$_{t-1}$	Y	Y	Y	Y	Y
Observations	3,222	3,914	3,783	4,184	4,184
Adj. R^2	0.888	0.871	0.877	0.874	
Dep. var. mean	7.914	7.801	7.725	7.688	7.688
Countries	156	144	156	156	

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 1980–2013. This table presents some 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 by Closset et al (2017). 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.

of natural disasters is positive in all destination regions, North America presents the highest values.

The focus of this paper is on international forced migration. However, Table **??** presents a brief insight on internal migration. The Internal Migration Monitor Center provides annual estimates of the population internally displaced for climate and conflict reasons, by country and from year 2008 to 2017. Table **??** includes countries that in previous tables are considered origin as well as those that are considered host.[2] It shows there is a strong contemporaneous relationship between climate internal migration and the occurrence of climate disasters, and a negative but insignificant relation with conflict displacement. This suggests differentiated underlying mechanisms of conflict versus climate-triggered migration. First, conflict migrants are not contemporaneously related to the occurrence of a natural disaster event. Second, there is a significant and negative relation between past natural disasters and conflict migration.[3] This suggests that there

[2]Results are almost identical when the sample is restricted to origin countries.

[3]It is not shown in the table, but significance disappears after the second lag.

Table B.4: Regressions by Destination Region

	Europe		North America		Oceania	
Dep var: log(# migrants)	(1)	(2)	(3)	(4)	(5)	(6)
log(Nat. Disasters (#))	0.102	0.084	0.227***	0.191***	0.094**	0.060
	(0.08)	(0.08)	(0.06)	(0.06)	(0.05)	(0.04)
log(Gdp per capita)$_{t-1}$		-0.164		-0.633**		-0.188
		(0.24)		(0.28)		(0.19)
FE (C, T), Population	Y	Y	Y	Y	Y	Y
Observations	4224	3654	4290	3668	3941	3308
Adj. R^2	0.848	0.854	0.914	0.917	0.894	0.907
Dep. var. mean	5.927	6.106	6.307	6.573	4.387	4.545
Countries	165	156	162	151	165	155

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 1980–2013. The table reproduces columns (1) and (2) from Table 1, disaggregating by destination region.

is an exhaustion of conflict migrants in the periods following a natural disaster. Exploring the underlying reasons behind these findings is outside the scope of this analysis.

Table **??** shows the results under the main log-log specification for each type of disaster separately. Every type presents positive estimates, and hydrological and climatological disasters have higher and significant magnitudes.

This analysis focuses on migration from origin countries to host countries only, leaving aside the origin–origin international migration because data on migration flows across origin countries is non-existent. Some argue that origin-origin disaster-induced migration is minor because contiguous countries are typically similarly affected by natural disasters. That is, after a shock in a country, population might flow to contiguous countries temporarily, until the new home country is hit by a shock. Overall, the movements are likely to balance in the medium-long run (**?**). Figures B.1 and B.2 attempt to provide some evidence along this line, without pretending to be conclusive. Figure B.1 looks at the three groups of origin countries (African, Asian, South-Central America) separately and shows that the annual cross-country mean and standard deviation of natural disasters is quite constant across years (with a slight upward (increasing) trend for mean (standard deviation)). Figure B.2 shows that there is not a clear set of countries that persistently dominate in the frequency of natural disasters, suggesting there is no reason to believe there is a clear flow of climate migration only to certain countries. In line with this theory, **?** do not find any evidence for an influence of natural disasters on migration within African countries. In addition, **?** provide several stylized facts on the distribution of refugees in general and find that in contrast to past decades, refugees tend to travel longer distances, are less likely to stay in neighboring countries, and are

Table B.5: Internal Migration (2008–2017)

Dep var: log(# migrants)	Climate Migration (1)	Conflict Migration (2)
log(Nat. Disasters (#))	1.977***	-0.359
	(0.33)	(0.26)
log(Nat. Disasters (#))$_{t-1}$	0.370	-0.708***
	(0.35)	(0.26)
FE (C, T)	Y	Y
Observations	856	856
Adj. R^2	0.533	0.696
Dep. var. mean	6.943	2.935
Countries	130	130

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 2008–2017. The table shows the relationship between natural disasters and internal migration, that is, migration within the borders of a country. The explanatory variable is the incidence of disasters (occurrence), which corresponds to the number of disasters. Zeros in the dependent and independent variable are treated as follows: the variable is transformed using ln(x+1).

more likely to reside in high-income OECD-countries.

Finally, I check whether the results are specific to the EM-DAT database. To do so, I use the GEOMET database from **?** instead, which gathers from different sources data on earthquakes, volcanic eruptions, storms, floods, and droughts including their intensity.[4] This allows me not only to effectively check that results are not driven by the database employed but also to extend the analysis and weight by the disasters' intensity.

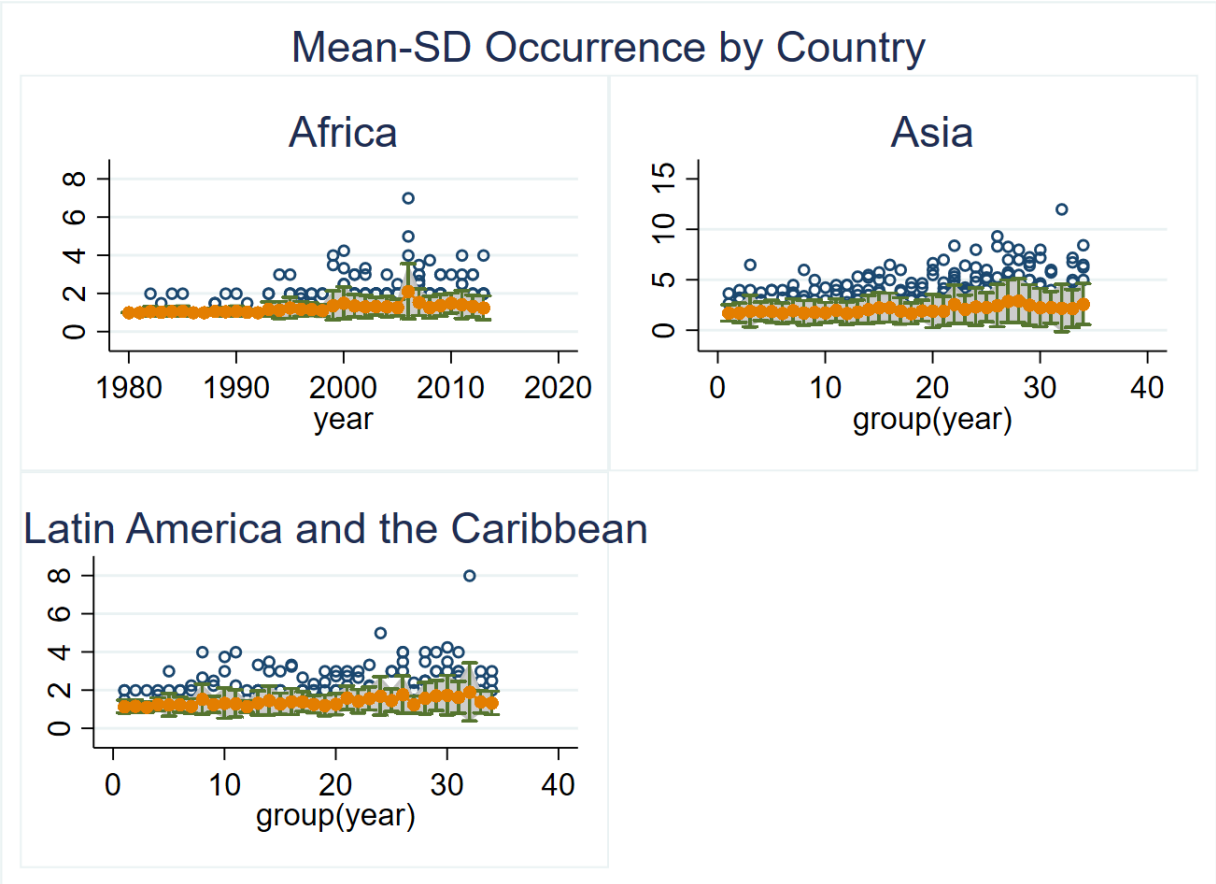
[4]GeoMet is a valuable data set since it provides information on the physical intensity of natural disasters. On the contrary, EMDAT provides only the human affectation and monetary damages mostly based on insurance data, which are correlated with the GDP of the country of occurrence.

Table B.6: Regressions by Disaster Group

Dep var: log(# migrants)	Climatological (1)	Hydrological (2)	Meteorological (3)
log(Nat. Disasters (#))	0.179*	0.233***	0.116
	(0.10)	(0.06)	(0.07)
FE (C, T)	Y	Y	Y
Observations	3,208	4,327	3,643
Adj. R^2	0.840	0.860	0.862
ymean	6.776	7.371	7.067
Countries	165	165	165

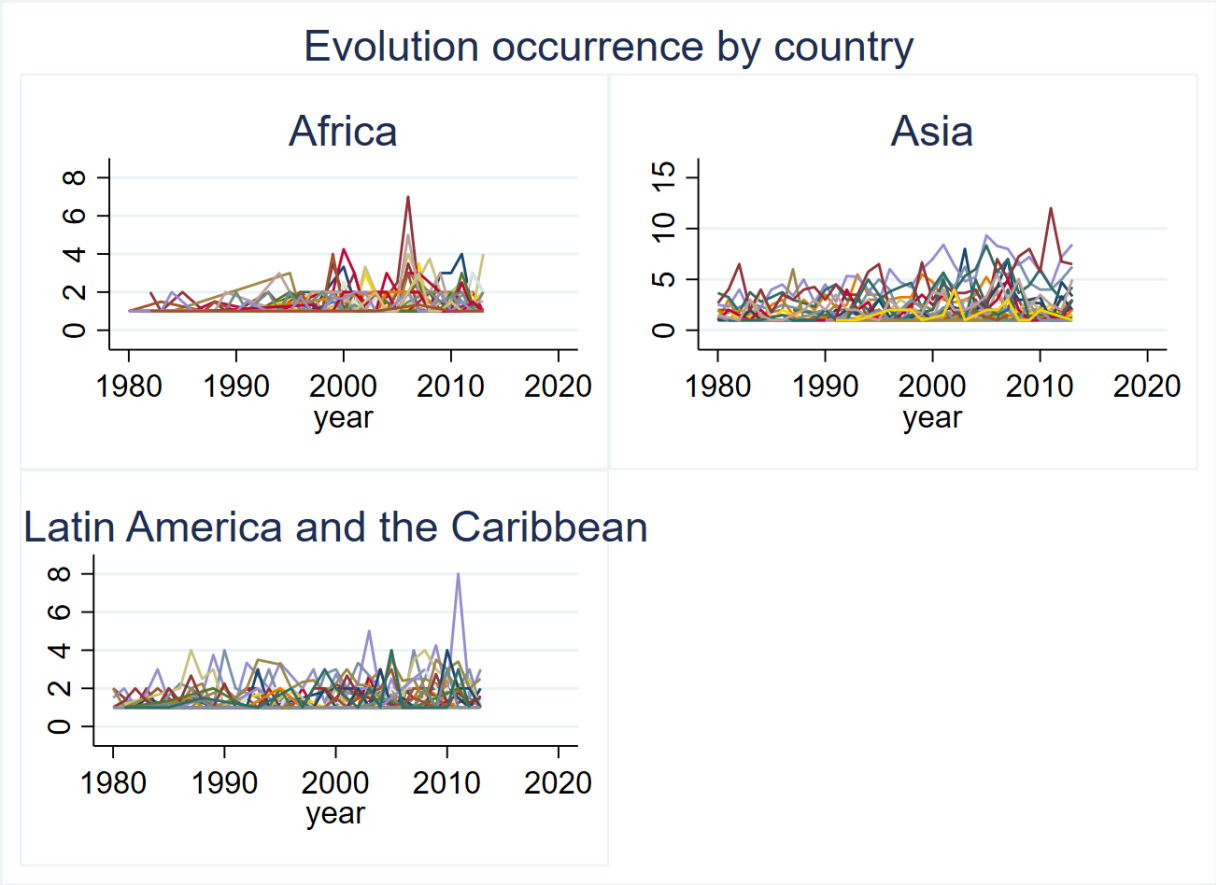
Notes: *** p < 0.01, ** p < 0.05, * p < 0.1. Standard errors, in parentheses, are clustered at the country level. UN immigration data, EMDAT disaster data. Sample period: 1980–2013. The table presents the relationship between natural disasters and migration to host regions by disaster subgroup.

Figure B.1: Annual mean and standard deviation of the occurrence of natural disasters



Source: Author, based on EM-DAT database. *Note:* Annual means and standard deviations of the occurrence of countries belonging to each area: Africa, Asia, and Latin America and Caribbean. Bin scatter.

Figure B.2: Evolution of the frequency of natural disasters by country



Source: Author, based on EM-DAT database. *Note:* Evolution of the occurrence of countries belonging to each area: Africa, Asia, and Latin America and the Caribbean. Bin scatter.

C Mathematical Derivations

C.1. Derivation of origin region emissions under laissez-faire

The following details the derivation of equation (11). The origin region is in laissez-faire, which implies that energy—emissions—use is determined in the decentralized equilibrium. The origin region is subject to the same functional forms as the host region. Final good producers are assumed competitive; hence, a representative firm will use energy up until the marginal product equalizes the marginal cost. In this setting, the representative firm controls both the production of the final good and the energy input. This implies that final gross output can be expressed as

$$\bar{Y_{ot}} = A_{ot}K_{ot}^{\alpha}\left(L_{ot} - \frac{E_{ot}}{A_{ot}^{e}}\right)^{\upsilon} E_{ot}^{1-\alpha-\upsilon},$$

where one has substituted in for the labor clearing constraint, $L_{ot} = L_{ot}^{Y} + L_{ot}^{e}$, and the energy production function, $E_{ot} = A_{ot}^{e}L_{ot}^{e}$. Equating the first derivative of gross output with respect to E_{ot} to zero one obtains that the optimal level of energy use in the decentralized economy is given by

$$E_{ot} = \frac{1-\alpha-\upsilon}{1-\alpha}A_{ot}^{e}L_{ot}.$$

Since $L_{ot} \equiv P_{ot}$ in the origin region, this is equivalent to equation (11).

C.2. Solution to the Host planner problem and Proof of Proposition 1

The following details the solution to the host planner problem in the unilateral host setting and the proof of Proposition 1. In this setting there are only two regions -host and origin-. The host country implements carbon policy unilaterally while the origin region is environmentally inactive.

The host planner problem is given by

$$\max_{K_{ht+1},E_{ht}} W_{ht} = \sum_{t=0}^{\infty} \beta^{t} u_{ht}\left(P_{h0}v(c_{ht}, I_{ht})\right) = \sum_{t=0}^{\infty} \beta^{t} log\left[P_{h0}\left(c_{ht} - \gamma i(\Delta z_{t-1})\right)\right]$$

subject to the constraints

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

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

$z_t = f(E_{h1}, E_{o1}, E_{h2}, E_{o2}, ..., E_{ht}, E_{ot})$

$L_{ht} = L_{ht-1} + i(\Delta z_{t-1})$

$P_{ot} = P_{ot-1} - i(\Delta z_{t-1})$

$E_{ot} = \xi_t P_{ot}$

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

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

Let λ_t be the shadow value of final output (Y_{ht}), ω_t of carbon concentrations (z_t) and μ_t^h, μ_t^o of labor in the host (L_{ht}) and in the origin region (P_{ot}), respectively. Substitute the resource constraint into the objective function and substitute E_{ot} into z_t . The labor inequality is fulfilled in equality. In order to simplify notation, remove L_{ht}^d by solving E_{ht} for L_{ht}^d and plugging it into the production function. Do the same for the labor clearing constraint. I take a conservative approach and assume that immigration is only a function of the first period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$.

The Lagrangian is

$$\begin{aligned}
\mathcal{L} =& \sum_{t=0}^{\infty} \beta^t u \left(P_{h0} \frac{Y_{ht} - K_{ht+1}}{L_{ht}} - P_{h0} \gamma i(\Delta z_{t-1}) \right) \\
&- \sum_{t=0}^{\infty} \lambda_t \left(Y_{ht} - \Omega(z_t) A_{ht} K_{ht}^{\alpha} \left(L_{ht} - \frac{E_{ht}}{A_{ht}^e} \right)^{\upsilon} E_{ht}^{1-\alpha-\upsilon} \right) \\
&- \sum_{t=0}^{\infty} \omega_t \left(z_t - f\left(..., E_{ht}, \xi_t P_{ot} \right) \right) \\
&- \sum_{t=0}^{\infty} \mu_t^h \left(L_{ht} - L_{ht-1} - i(\Delta z_{t-1}) \right) \\
&- \sum_{t=0}^{\infty} \mu_t^o \left(P_{ot} - P_{ot-1} + i(\Delta z_{t-1}) \right)
\end{aligned}$$

The first order conditions are

$[Y_{ht}]$

$$\beta^t u_t' \frac{P_{h0}}{L_{ht}} - \lambda_t = 0$$

That is, the shadow value of one unit of final good production (λ_t) is equal to the marginal utility of consumption.

$[K_{ht+1}]$

$$-\beta^t u_t' \frac{P_{h0}}{L_{ht}} + \lambda_{t+1} \alpha \frac{Y_{ht+1}}{K_{ht+1}} = 0$$

Combining the first order conditions for Y_{ht} and K_{ht+1} one obtains the Euler equation

$$\frac{u_t'}{u_{t+1}'} \frac{L_{ht+1}}{L_{ht}} = \beta \alpha \frac{Y_{ht+1}}{K_{ht+1}}$$

$[z_t]$

$$\lambda_t \overbrace{\frac{\partial Y_{ht}}{\partial z_t}}^{=\frac{\partial \Omega_t}{\partial z_t}\overline{Y_{ht}}} - \omega_t = 0$$

Using the first order condition with respect to Y_{ht}, one can rewrite it as

$$\omega_t = \beta^t u_t' \frac{P_{h0}}{L_{ht}} \frac{\partial Y_{ht}}{\partial z_t}$$

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.

$[L_{ht}]$

$$-\beta^t u_t' \frac{P_{h0}\left(Y_{ht} - K_{ht+1}\right)}{L_{ht}^2} + \lambda_t \overbrace{\frac{\partial Y_{ht}}{\partial L_{ht}}}^{=\upsilon \frac{Y_{ht}}{L_{ht} - \frac{E_{ht}}{A_{ht}^e}}} - \mu_t^h + \mu_{t+1}^h = 0$$

Solve for μ_t and solve recursively. Then, plug in for λ_{t+j}

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

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

$[P_{ot}]$

$$\sum_{j=0}^{\infty} \omega_{t+j} \frac{\partial f_{t+j}()}{\partial P_{ot}} \xi_{t+j} - \mu_t^o + \mu_{t+1}^o = 0$$

Solving for μ_t^o, solving recursively and plugging for ω_t yields

$$\mu_t^o = \sum_{j=0}^{\infty} (j+1) \beta^{t+j} u_{t+j}' \frac{P_{h0}}{L_{ht+j}} \frac{\partial Y_{ht+j}}{\partial z_t} \frac{\partial f_{t+j}(.)}{\partial P_{ot}} \xi_{t+j}$$

So, the shadow value of population in the origin at the optimum equals the output damage associated to the pollution caused by the origin population, in utils.

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

$[E_{ht}]$

Taking into account the assumption on the immigration function: $i(\Delta z_{t-1}) = i^*(E_t)$

$$\begin{aligned}&- \beta^{t+1}u'_{t+1}P_{h0}\gamma\frac{\partial i(\Delta z_t)}{\partial E_t} + \lambda_t \qquad \overbrace{\frac{\partial Y_{ht}}{\partial E_{ht}}}^{=-\upsilon\frac{Y_t}{L_t-\frac{E_t}{A^e_{ht}}}\frac{1}{A^e_{ht}}+(1-\alpha-\upsilon)\frac{Y_{ht}}{E_{ht}}\equiv NMPE_{ht}} \\ &+ \sum_{j=0}^{\infty}\omega_{t+j}\frac{\partial f_{t+j}()}{\partial E_{ht}} + \mu^h_{t+1}\frac{\partial i(\Delta z_t)}{\partial E_t} - \mu^o_{t+1}\frac{\partial i(\Delta z_t)}{\partial E_t} \\ &= 0\end{aligned}$$

Solving the last expression for the private consequences of energy use, namely $\frac{\partial Y_{ht}}{\partial E_{ht}} \equiv NMPE_{ht}$, one obtains equation (12).

C.3. The labor effect. Proof of Result 1

The following details the derivation of Proposition 2. In order to identify the net impact of the "Labor effect", let's recover the expression for μ^h_t in the optimum

$$\mu^h_t = \sum_{j=0}^{\infty}\left(\beta^{t+j}u'_{t+j}\frac{P_{h0}}{L_{ht+j}}\left[\underbrace{\frac{\partial Y_{ht+j}}{\partial L_{ht+j}} - \frac{Y_{ht+j} - K_{ht+1+j}}{L_{ht+j}}}_{\equiv\sigma}\right]\right)$$

where the sign of μ^h_t is determined by the sign of σ. Let's first assume that: i) the economy is in the Laissez-fair; ii) there are no climate damages to final output; and iii) there is no capital. That is, the production function is $Y_{ht} = A_{ht}(L_{ht} - \frac{E_{ht}}{A^e_{ht}})^{\upsilon}E_{ht}^{1-\nu}$. Under these assumptions, σ becomes $\sigma = \frac{\partial Y_{ht+j}}{\partial L_{ht+j}} - \frac{Y_{ht}}{L_{ht}}$. The level of emissions in the Laissez-fair is proportional to total population and given by

$$E_{ht} = (1-\nu)A^e_{ht}L_{ht}$$

Then, σ becomes

$$\begin{aligned}\sigma &= \nu\frac{Y_{ht+j}}{L_{ht} - \frac{E_{ht}}{A^e_{ht}}} - \frac{Y_{ht+j}}{L_{ht+j}} \\ &= Y_{ht+j}\left[\nu\frac{1}{L_{ht} - (1-\nu)L_{ht}} - \frac{1}{L_{ht}}\right] \\ &= 0\end{aligned}$$

Hence, under the Laissez-fair, without climate damages and without capital, the Labor effect of climate refugees is zero. In other words, the increase in population caused by previous pollution has no effect on future consumption per capita, thus, it doesn't affect natives welfare. Note this is a direct consequence of the Cobb-Douglas production

function and the energy production, which uses labor. Essentially, these imply that that labor is the "unique" input and the production function exhibits constant returns to scale.

Let's now incorporate climate damages to final output and move away from the Laissez-fair by assuming that there is some level of climate action. It is reasonable to assume that with climate damages, the carbon tax is positive. Thus, E_{ht} will be lower than in the Laissez-fair scenario, namely $E_{ht} = (1-\nu-\varepsilon)A^e_{ht}L_{ht}$ with $\epsilon > 0$. Back to the latest expression for σ, one can easily see that

$$\begin{aligned}\sigma &= Y_{ht+j}\left[\nu\frac{1}{L_{ht+j}-(1-\nu-\varepsilon)L_{ht+j}} - \frac{1}{L_{ht+j}}\right]\\ &< 0\end{aligned}$$

Hence, once we account for climate damages the net "Labor effect" is a negative externality that adds up to the carbon tax. The intuition behind this finding is that the use of emissions now damages final production, through Ω, hence its use will be lower. In this context, an additional unit of labor doesn't have a neutral impact on per capita output (i.e., consumption). Instead, it dilutes it.

Finally, incorporating capital into the model implies that a marginal increase in labor dilutes per capita consumption even further. This is because the production function with capital exhibits decreasing returns to the labor input. Hence, the "Labor effect" is a negative externality.

C.4. Solution to the Global Planner (Proof of Proposition 2)

The following solves the global planner problem and proves Proposition 3. The global planning problem is given by

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

st

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

$Y_{rt} = \Omega_r(z_t)A_{rt}K^{\alpha}_{rt}\left(L^Y_{rt}\right)^{\upsilon}E^{1-\alpha-\upsilon}_{rt}$

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

$E_t = \sum_r E_{rt}$

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

$P_{rt} = P_{rt-1} - o_r i(\Delta z_{t-1})\, if\, r \in O$

$L^d_{rt} + L^Y_{rt} \leq L_{rt}$

$E_{rt} = A^e_{rt}L^d_{rt}$

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

Let λ_{rt}^{GSP} be the shadow value of final outputs (Y_{rt}), ω_t^{GSP} of carbon concentrations (z_t) and μ_{rt}^{GSPh}, μ_{rt}^{GSPo} of population evolution in the host and in the origin regions, respectively. Substitute the resource constraint into the objective function and substitute E_t into z_t . The labor inequality is fulfilled in equality for every region. In order to simplify notation, remove L_{rt}^d by solving E_{rt} for L_{rt}^d and plug it into the production functions. Do the same for the labor clearing constraints and assume $\kappa = 1$. Once again, I take a conservative approach and assume that immigration is only a function of the first 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 of the Lagrangian are

$[Y_{rt}]$

$$\beta^t u_t' \frac{\Theta_{rt}}{P_{rt}} - \lambda_{rt}^{GSP} = 0 \, if \, r \in H$$

$$\beta^t u_t' - \lambda_{rt}^{GSP} = 0 \, if \, r \in O$$

$[K_{ht+1}]$

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

$$-\beta^t u_t' + \lambda_{rt+1}^{GSP} \alpha \frac{Y_{rt+1}}{K_{rt+1}} = 0 \, if \, r \in O$$

$[z_t]$

$$\sum_r \lambda_{rt}^{GSP} \overbrace{\frac{\partial Y_{rt}}{\partial z_t}}^{=\frac{\partial \Omega_{rt}}{\partial z_t} \overline{Y_{rt}}} - \omega_t^{GSP} = 0$$

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 $r \in H$

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

Solve for μ_t and solve recursively. Then, plug 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}, solving for μ_{rt}^o 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 $i(\Delta z_{t-1}) = i^*(E_t)$

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

This corresponds to equation (14), after solving for $\frac{\partial Y_{rt}}{\partial E_{rt}} \equiv NMPE_{rt}$.

C.5. Solution to the Nash Equilibrium Setting - Unilateral host (Proof of Proposition 3) The following details the solution of the host planners problems under a Nash equilibrium setting. A host region local planning problem is

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

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

$Y_{ht} = \Omega(z_t) A K_{ht}^{\alpha} \left(L_{ht}^{Y}\right)^{\upsilon} E_{ht}^{1-\alpha-\upsilon}$
$z_t = f(E_1, E_2, ..., E_t)$
$E_t = \sum_r E_{rt}$
$P_{rt} = P_{rt-1} + h_r i(\Delta z_{t-1})\, if\, r \in H$
$L_{ht}^{d} + L_{ht}^{Y} \leq L_{ht}$
$E_{ht} = A_{ht}^{e} L_{ht}^{d}$
$P_{ht} = L_{ht}$, since I assume $\kappa = 1$

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}) and in the origin region (P_{ot}), respectively. Substitute the resource constraint into the objective function and substitute E_t into z_t . The labor inequality is fulfilled in equality. In order to simplify notation, remove L_{ht}^{d} by solving E_{ht} for L_{ht}^{d} and plugging it into the production function. Do the same for the labor clearing constraint. I take a conservative approach and assume that immigration is only a function of the first period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$.

The first order conditions of the lagrangian are

$[Y_{ht}]$

$$\beta^t u_t' \frac{P_{h0}}{P_{ht}} - \lambda_t^{NEh} = 0$$

$[K_{ht+1}]$

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

$[z_t]$

$$\lambda_t^{NEh} \overbrace{\frac{\partial Y_{ht}}{\partial z_t}}^{=\frac{\partial \Omega_{ht}}{\partial z_t} \overline{Y_{ht}}} - \omega_t^{NEh} = 0$$

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.

$[P_{ht}]$

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

Solve for μ_t^{NEh} and solve recursively. Then, plug 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.

$[E_{ht}]$

Taking into account the assumption mentioned earlier: $i(\Delta z_{t-1})=i^*(E_t)$

$$-\beta^{t+1}u_{t+1}'P_{h0}\gamma_r h_r\frac{\partial i(\Delta z_t)}{\partial E_{ht}}+\beta^t u_t'\frac{P_{h0}}{P_{ht}}\overbrace{\frac{\partial Y_{ht}}{\partial E_{ht}}}^{=-\upsilon\frac{Y_t}{L_t-\frac{E_t}{A_{ht}^e}}\frac{1}{A_{ht}^e}+(1-\alpha-\upsilon)\frac{Y_{ht}}{E_{ht}}\equiv NMPE_{ht}}$$

$$\sum_{j=0}^{\infty}\omega_{t+j}^{NEh}\frac{\partial f_{t+j}()}{\partial E_{ht}}+\mu_{t+1}^{NEh}\frac{\partial i(\Delta z_t)}{\partial E_t}$$

$$=0$$

Similarly to the previous settings, this corresponds to equation (15).

C.6. Solution to the Nash Equilibrium Setting - Unilateral origin (Proof of Proposition 4)

The following details the solution of the origin planners problems under a Nash equilibrium setting. An origin region local planning problem is

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

st

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

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

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

$E_t=\sum_r E_{rt}$

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

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

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

$E_{ot} = A^e_{ot} L^d_{ot}$

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. Substitute the resource constraint into the objective function and substitute E_t into z_t. The labor inequality is fulfilled in equality. In order to simplify notation, remove L^d_{rt} by solving E_{rt} for L^d_{rt} and plugging it into the production function. Do the same for the labor clearing constraint. I take a conservative approach and assume that immigration is only a function of the first period change in concentrations, hence essentially $i(\Delta z_{t-1}) = i^*(E_t)$.

The first order conditions of the Lagrangian are

$[Y_{ot}]$
for $r = 0$

$$\beta^t u'_t - \lambda_{ot}^{NEo} = 0$$

for $r \in H$

$$\beta^t u'_t \frac{1}{P_{rt}} (1 - \eta_{rt}) \sum_{m=0}^{t\text{-}1} h_l o_r I_{t-m} - \lambda_{rt}^{NEo} = 0$$

$[K_{ot+1}]$

$$-\beta^t u'_t + \lambda_{ot+1}^{NEo} \alpha \frac{Y_{ht+1}}{K_{ht+1}} = 0$$

$[z_t]$

$$\lambda_{ot}^{NEo} \overbrace{\frac{\partial Y_{ot}}{\partial z_t}}^{=\frac{\partial \Omega_{ot}}{\partial z_t} \overline{Y_{ot}}} + \sum_{r \in H} \lambda_{rt}^{NEo} \overbrace{\frac{\partial Y_{rt}}{\partial z_t}}^{=\frac{\partial \Omega_{rt}}{\partial z_t} \overline{Y_{rt}}} - \omega_t^{NEo} = 0$$

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.

$[P_{ot}]$

$$+\lambda_{ot}^{NEo} \overbrace{\frac{\partial Y_{ot}}{\partial P_{ot}}}^{=\upsilon \frac{Y_{ot}}{P_{ot} - \frac{E_{ot}}{A^e_{ot}}}} - \mu_t^{NEo} + \mu_{t+1}^{NEo} = 0$$

Solve for μ_t and solve recursively. Then, plug in for λ_{t+j}

$$\mu_t^{NEo} = \sum_{j=0}^{\infty} \beta^{t+j} u'_{t+j} \frac{\partial Y_{rt+j}}{\partial P_{rt+j}}$$

$[P_{ht}]$

$$\beta^t u'_t \left[\sum_{l \in H} \left(-\frac{Y_{lt} - K_{lt+1}}{P_{lt}^2} (1 - \eta_{rt}) \sum_{m=0}^{t\text{-}1} h_l o_r I_{t-m} \right) \right] + \sum_{l \in H} \lambda_{l \in Ht}^{NEo} \frac{\partial Y_{lt}}{\partial P_{lt}} - \mu_t^{NEoh} + \mu_{t+1}^{NEoh} = 0$$

Plugging in for ω_t, solving for μ_t^o and solving recursively yields

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

$[E_{ht}]$

Taking into account the usual assumption: $i(\Delta z_{t-1}) = i^*(E_t)$

$$\lambda_{r=ot}^{NEo} \overbrace{\frac{\partial Y_{ot}}{\partial E_{ot}}}^{=-\upsilon \frac{Y_{ot}}{P_{ot} - \frac{E_{ot}}{A_{ot}^e}} \frac{1}{A_{ot}^e} + (1-\alpha-\upsilon) \frac{Y_{ot}}{E_{ot}} \equiv NMPE_{ot}} + \sum_{j=0}^{\infty} \omega_{t+j}^{NEo} \frac{\partial f_{t+j}()}{\partial E_{ot}} + \mu_{t+1}^{NEoh} \frac{\partial i(\Delta z_t)}{\partial E_{ot}}$$
$$- \mu_{t+1}^{NEo} \frac{\partial i(\Delta z_t)}{\partial E_{ot}} + \sum_{j=1}^{\infty} \beta^t u'_t \left(\sum_{l \in H} \left(c_{lt} (1 - \eta_{rt}) h_l o_r \frac{\partial i(\Delta z_t)}{\partial E_{ot}} \right) \right)$$
$$= 0$$

Similarly to the previous settings, this corresponds to equation (16).

D Calibration

This section provides additional details on the model calibration.

D.1 Social cost of immigration

I calibrate the social cost of immigration using data on different programs and policies, detailed below. I complement these with World Bank data on consumption and population, as well as United Nations data on the stock of immigrants per country. To find natives' 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—or disutility—parameter γ solving the following expression:

Table D.1: Pay to Go Programs, Detailed Information. Year 2015. 38,700 Immigrants Returned under the Assisted Voluntary Return Program (used for calibration)

Type of program	Total amount (Eur)	Financing institution	Countries
Assisted Voluntary Return Program	111.8 million (Variation across countries: 100e. (BG, HU, LV), 3.750e. (NO), 3.300e. (SE)	75% EU, 25% countries. Some countries contributed more than 50% (ES, SE 100%)	AT, BE, BG, CY, DE, EE, ES, FI, FR, HU, IE, IT, LT, LV, MT, NL, PL, SE, SI, SK, UK, & NO
Reintegration programs	40 million	21% EU, 79% Countries. Some countries contributed more than 50% (SE, UK 100%)	AT, BE, DE, FR, HU, NL, SE, SI, UK & NO

Notes: This table summarizes the expenditures under the Pay to Go programs. Some imply the return of immigrants to their country of others, while others include reintegration programs. The latter are not included in the calibration of the disutility parameter. *Sources:* 1. https://qz.com/1179970/european-refugee-crisis-countries-that-pay-migrants-the-most-to-go-home/ 2. European Migration Network report. "Overview: Incentives to return to a third country and support provided to migrants for their reintegration." 3. https://www.migrationpolicy.org/article/pay-go-countries-offer-cash-immigrants-willing-pack-their-bags

$$ln((1-\rho)c) = ln(c - \gamma * immigrants)$$

where ρ denotes the share of per capita consumption that natives are willing to forgo according to each program/policy.

a) 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. Table **??** provides a summary of these programs. For the calibration of the disutility parameter I only use the expenditures for the "Assisted Voluntary Return Programs".

b) Details on Brexit:

In August 2016, Eric Kaufmann (University of London) conducted a survey to investigate the migration motives behind Brexit.[6] I use this survey to calibrate the social cost of immigration. I focus on the following survey question: "Roughly 185,000 more people entered Britain last year from the EU than went the other way. Imagine there was a cost to reduce the inflow. How much would you be willing to pay to reduce the number of Europeans entering Britain?" Table **??** displays the survey answers to that question,

[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.

[6]The survey's sample size is 1,500. More details can be found at: https://blogs.lse.ac.uk/politicsandpolicy/hard-brexit-only-if-its-free/

Table D.2: Brexit Survey Results, 2016

	Total	Remain	Leave	Did not vote
Pay nothing. Numbers remain at 185,000.	38	60	18	38
Pay 1% of my income to reduce numbers to 150,000	5	5	5	5
Pay 2% of my income to reduce numbers to 150,000	3	4	4	1
Pay 3% of my income to reduce numbers to 80,000	4	2	6	4
Pay 4% of my income to reduce numbers to 45,000	3	1	5	3
Pay 5% of my income to reduce numbers to zero	11	3	20	8
Don't know	36	26	42	41

Notes: This table displays the answers to the question "How much would you be willing to pay to reduce the number of Europeans entering Britain?" from the Brexit survey. In the calibration exercise, I exclude individuals answering "I don't know". Three groups of voters are considered: those who wanted to remain in the EU, those who wanted to leave, and those who did not vote in the referendum.

in percentage points, disaggregating by individuals' choice in the Brexit referendum.

E Additional Results

This section presents additional results.

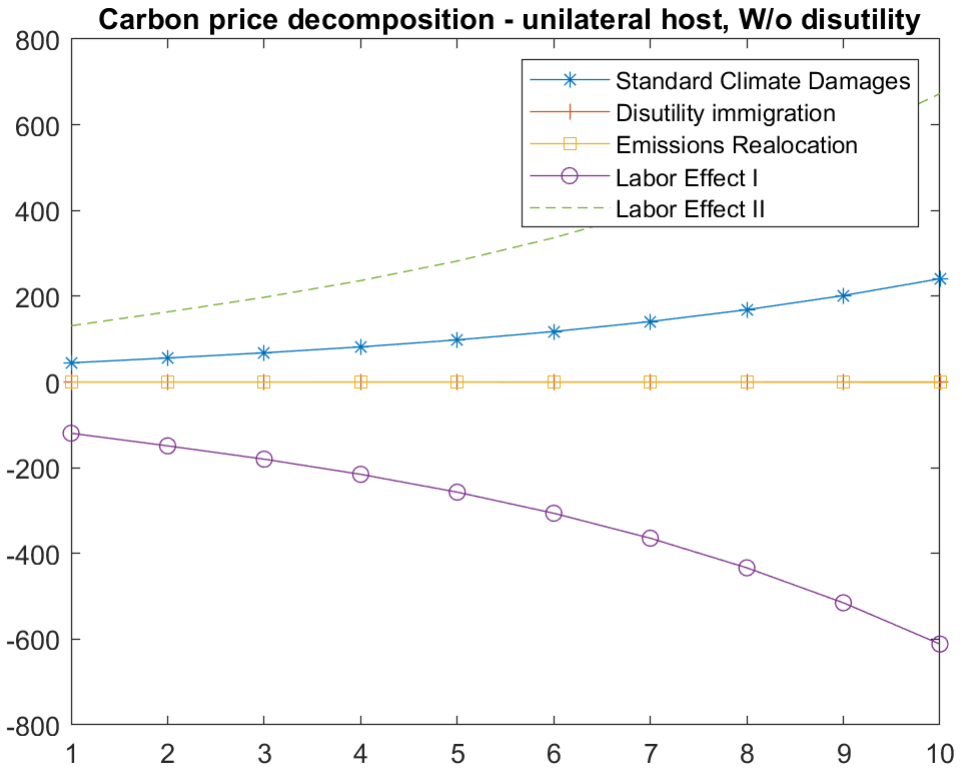
Unilateral SCC decomposition:

Figure **??** shows the decomposition of the unilateral host carbon price into the four components 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.

Global emissions comparison across scenarios:

Figure **??** displays the evolution of total emissions in the next 50 years for the unilateral

Figure E.1: Carbon price decomposition.



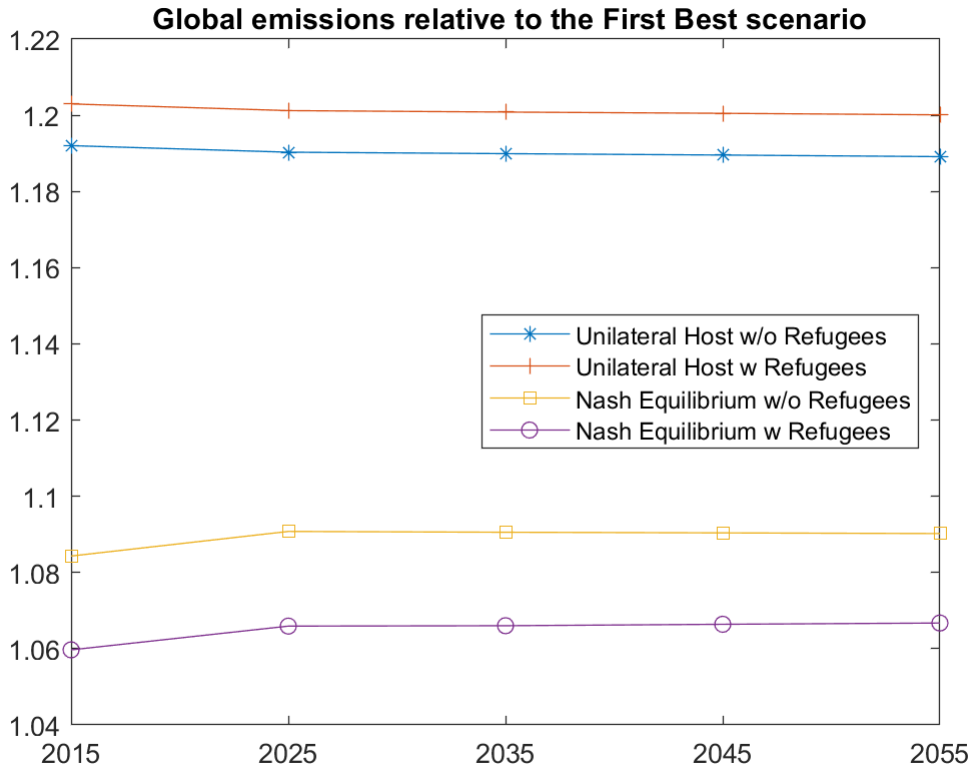
Notes: This figure shows the evolution of each component of the carbon price under the setting in which only the host country implements the carbon policy unilaterally. The disutility of immigration is zero.

host and the Nash equilibrium setting, relative to the first-best. For each setting, I show the cases with and without refugees. One can see that relative global emissions are larger under the unilateral host setting, that is, when only host countries undertake climate action. The difference between each setting and the first best is larger in the presence of climate refugees, which indicates that when climate refugees are considered, the distance to the first-best allocation of pollution is larger.

F Displacement as an Adaptation Strategy

In this appendix, I provide a different comparison for the first-best scenario with climate refugees. The first-best quantitative results presented in the main text display the estimated global carbon price with refugees and compare it to the carbon price without refugees. This responds to my aim of comparing this paper's new findings to the existing estimates of the global SCC, which do not consider such displacement. This approach implies that my findings are the result of adding two elements into the analysis, namely natural disasters and its corresponding displacement. Here I present a slightly different analysis in which I compare the new estimates to a situation without displacement but

Figure E.2: Relative global emissions



Notes: This figure shows global emissions under each setting—unilateral host and Nash equilibrium—relative to the first-best setting. For each setting, it show the cases with and without refugees.

where people in the origin region suffer the economic damages of natural disasters.[7] I model it as a direct utility cost and I calibrate it using EM-DAT data on the economic impact of natural disasters in origin regions.

Table **??** shows the globally optimal carbon prices with disasters damages (column 2). For comparison, columns (1) and (3) display the benchmark results without refugees and with refugees—and without disutility, respectively. One can see that the conclusions are practically unaltered because the carbon price with disasters' damages and no refugees (column 2) is only marginally larger than the benchmark without refugees (column 1).

[7]Note that, when the damage function already takes the effects of natural disasters into account, that exercise suffers from double counting. The DICE damage function used in this model only takes into account some natural disasters, which could imply some degree of double counting. However, this is simply used as an illustrative example that does not affect the conclusions of this paper.

Table F.1: Global Carbon Prices, First-best with Disasters Damages

	No Climate Refugees		Climate Refugees
	(1)	(2)	(3)
	No Disasters Damages	Disasters Damages	Without Disutility
$ per ton of carbon	118.58	118.62	123.66

Notes: This table displays the globally optimal carbon price incorporating the damages associated with natural disasters as a direct utility cost (column 2). For comparison, columns (1) and (3) display the benchmark results without climate refugees and with refugees but without disutility, respectively.