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# When nature rebels: international migration, climate change, and inequality

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**Abstract** We study climate change and international migration in a two-country overlapping generations model with endogenous climate change. Our main findings are that climate change increases migration; small impacts of climate change have significant impacts on the number of migrants; a laxer immigration policy increases long-run migration, aggravates climate change, and increases north–south inequality if climate change impacts are not too small; and a greener technology reduces emissions, long-run migration, and inequality if the migrants' impact to overall climate change is large. The preference over the policies depends on whether the policy maker targets inequality, wealth, the environment, or the number of migrants.

**Keywords** Climate change · Migration · North–South model

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## 1 Introduction

Without doubt, there is a growing concern over how and whether climate change will affect international migration. Although the economic literature has dealt with many aspects of migration, the treatment of the relationship between climate change and migration has not yet been satisfactory. Our focus in this article is to shed some light on the interaction between endogenous climate change, international migration, optimal migratory policies, and inequality.

The recently published Stern review on climate change advances an unambiguous message: “An overwhelming body of scientific evidence now clearly indicates that climate change is a serious and urgent issue. The Earth’s climate is rapidly changing, mainly as a result of increases in greenhouse gases caused by human activities” (Stern 2007, p.3). This claim is without a doubt now a widely accepted fact in the scientific community. Another commonly anticipated point is that the “poorest countries will be especially hard hit by climate change, with millions potentially pushed deeper into poverty” (Stern 2007, p.487). Possible and predicted effects of climate change include land loss due to sea level rise, loss of biodiversity, productivity declines, warmer and drier climates or wetter regions, and more extreme weather events, see IPCC (2007).

As some regions are more prone to being affected by several of these adverse effects than others, it seems logical that inhabitants of these regions will try to avoid those effects. However, many poor regions either lack finances to abate or they do not emit enough to have any significant impacts from abatement activity. Usually, mitigation or adaptation are then proposed as the only possible ways of dealing with these problems. It ought to be clear, however, that those regions that are already extremely poor and vulnerable even before climate change impacts them will be unable to mitigate or adapt in the usual sense. Therefore, very often, the only hope left for people is to move away from the inhabitable area to one that might give them better living conditions.

It is this particular setting which shall be investigated in this article. We shall focus on the link from human activity over climate change to international migration. The main questions that we wish to explore are the following: What are the environmental reasons for people to migrate? What are the welfare effects? What could potentially be welfare-improving? Which are the effects of different policies?

It is well-known that the effects of climate change are difficult to measure. The evident lack of strong data thus requires a more thorough theoretical analysis of a kind that we intend to pursue here. The first section shall give an overview of the data that exist on international migration and climate change. We then build upon a model similar to Galor (1986) and investigate the key issues driving migration in a two-country, overlapping-generations world with climate change and migration. As climate change is a long-term phenomenon, we shall mainly focus on the steady-state perspective, but nevertheless allow for the effects of short-run interactions.

Migration between two countries or regions has traditionally been analyzed within the Harris–Todaro model (Harris and Todaro 1970); see also Ghatak et al. (1996) for a survey. The model of Harris and Todaro explains rural–urban migration in a general equilibrium model. However, the static framework of the Harris and Todaro model may miss endogenous feedbacks or can only assume these exogenously. Models that are able to analyze these feedbacks are two-country models like that of Galor (1986). He analyzes the welfare effect of migration in a two-country overlapping-generations model where he allows for bilateral migration where migration decisions are mainly driven by differences in preferences. Crettez et al. (1996) extend Galor's model to include land as a third production factor.[1] Here, we shall focus on climate change as a possible driver behind migration decisions.

Our main findings are as follows: (1) climate change will most likely increase overall migration; (2) even small impacts of climate change can have significant impacts on the number of migrants; (3) taking responsibility for its externality, a laxer northern immigration policy will increase world migration and worsen climate change; (4) north–south inequality may increase or decrease via appropriate green or immigration policy. Finally, the type of policy is crucial for the preference of one over the other, especially if the north tries to pursue several targets simultaneously. The targets we look at are welfare, the policy's implication for climate change on the effect on north–south inequality.

## 2 Climate change and migration: facts and future

This section is designated to provide an overview of important facts on climate change and migration, as well as to present reasons for the particular assumptions that we use later throughout the article. In the first part, we summarize key facts on climate change, and in the second part, we focus on the environment as a leading cause of migration.

### 2.1 Climate change

The IPCC Third Assessment Report (TAR) concludes that the emission of greenhouse gases from human production activity led to an increase in $CO_2$ equivalent concentrations from 290 to 440 ppm during the course of the past 150 years. The more greenhouse gases accumulate in the atmosphere, the more they will prevent the infrared radiation emitted by the sun from escaping the atmosphere of the Earth. This then leads to a warming that is expected to lie anywhere between 2°C and 6°C for the next 100 years, depending on the path we humans choose for economic development (see IPCC 2001). Most of these

[1] The literature has also focused on the impact of migration on the economy of the destination and origin countries. Migration can affect labor market outcomes such as wages (Borjas 2003) or unemployment (Bencivenga and Smith 1997), pension systems (Razin and Sadka 1999), or human capital formation (Vidal 1998) and growth (Beine et al. 2001).

increases in greenhouse gases must be attributed to the rich countries. For example, the estimates provided by Enerdata in its Energy Statistics Yearbook suggest that the European Union, North America, and Japan together account for close to 60% of annual world emissions, even though they host only 16% of the world population.

The main reason for this disparity is the way in which primary energy resources are used in production, which account for most of the $CO_2$ emitted into the atmosphere. According to the International Energy Agency, in 2004, approx. 80% of world total primary energy supply came from oil, coal, and gas. The use of these inputs differs drastically between the developed world and the less-developed world. Estimates from the International Energy Annual 2004 suggest that Northern America, Europe, Japan, and China together account for roughly 65% of the total world primary energy use. In comparison to this, the least-developed countries use roughly 5% of total world primary energy (IEA 2004). Therefore, the developed world is the main emitter of $CO_2$ and, thus, is responsible for most of the human-induced climate change.

The costs of climate change can vary drastically, depending on the size of the change in temperature. Whereas the IPCC in various publications suggests that an increase of 2°C from pre-industrial levels may lead to economic costs in the range of 2% to 5% of GWP per year, increases above that level may lead to potentially catastrophic costs.

In addition, the distribution of the damages is extremely particular to regions. It is expected that the less-developed countries will have to face close to 80% of the world damages from climate change. This is particularly troublesome for several reasons. Most of the developing countries already face the problem of binding income constraints. It is estimated that, in 2004, around 800 million people were at risk of hunger (FAO 2004), and malnutrition accounts for approximately four million deaths annually. It is believed that half of those deaths from malnutrition arise in Africa alone. The current estimates suggest that a temperature increase of 2–3°C will potentially raise the number of people at risk of hunger by 30–200 million. If the temperature increases by more than 3°C, which is a likely scenario of the IPCC, then the number of people facing hunger could increase by an additional 250–500 million. It is also believed that most of these will be observed in Africa and Western Asia (Warren et al. 2006). The World Health Organization even estimates that an additional one to three million people will then die from malnutrition, diarrhea or malaria. For example, Swart et al. (1998) estimate that temperate cereals might be faced by yield decreases of up to 22%, thereby substantially increasing food shortages.

Another problem of the effects of climate change concerns the productive capacity of countries. For example, the value added to GDP from agriculture is around 33% for less-developed countries, whereas for upper-middle-income countries, it is only 6.2% (WDI 2007). In addition, around 54% of the developing world's population works in the agricultural sector, but only 7% of developed countries' populations do so. These numbers can be up to 90% for some of the sub-Saharan countries (FAO 2004). The temperature in those countries increased on average by 3°C during the past decade, whereas the total amount of rainfall decreased by roughly 4% between 1960 and 2000. Some countries even face decreases up to 20%, like Burundi or Rwanda. This suggests that, overall, these countries have become drier. However, if they face binding income constraints, if they have a high share of agriculture in GDP, and, in addition, if most of the population is rural and works in the agricultural sectors, then these countries will face more severe consequences from climate change than can initially be grasped.

*Remark 1* Two preliminary conclusions can be drawn from the analysis above:

1. Developed countries are the main emitters and, therefore, the predominant source of human-induced climate change.
2. Developing countries are likely to face the strongest impact of climate change.

## 2.2 Migration

Here, we wish to give a list of examples where migration occurred due to environmental factors. We shall then proceed to investigate what several researchers suggest will be the future of migration from climate change in particular.

Examples are, contrary to what some critics might suggest, in fact, abundant. A quick reading of the existing literature provides many cases. For example, droughts in the USA displaced more than 30,000 people in the 1930s (Rosenzweig and Hillel 1993); a tsunami in Indonesia in 2004 displaced 500,000 people (FIG 2006); droughts in Burkina Faso and Sudan from 1968–1973 displaced around 1,000,000 people (Afolayan and Adelekan 1999; Hugo 1996). For more examples, see, e.g., McLeman (2006), Ezra (2001), Morris et al. (2002), and Kaye (1994). For a critical opinion, see Black (2001).

Several of these cases deserve an additional remark. In Sudan, it seems that only a part of the household migrates (the male usually) and then returns after the drought stops. Similar observations hold for Ethiopia, where the young generations seem to migrate when droughts occur (Afolayan and Adelekan 1999). This suggests two possibilities: either the costs to migrate are too high for everyone to bear, such that only a part of the household is able to leave, or people are particularly attached to their homes and expect better times to come again. However, these droughts usually last a short period of time and are, therefore, only transitory. One would expect that areas where irreversible changes in the climate lead to a permanently higher level of aridity would not see return migration. This is supported twofold by Henry et al. (2004). Firstly, for the case of Burkina Faso, they show that people from arid regions are more likely to migrate (temporarily and permanently) than those from wetter regions. Secondly, they suggest that long-run "migrations are likely to be more influenced by a slow-acting process such as land degradation than by episodic events such as droughts." A similar conclusion is drawn by Chen et al.

(2007), who suggest that the population distribution in China depends mainly on the proportion of arable land. Therefore, if that proportion changes due to environmental deterioration, one must also expect a change in the population distribution.

Apart from droughts, one can observe that extreme weather events also lead to permanent migration. For example, according to Morris et al. (2002), after a strong hurricane in Honduras and Nicaragua in 1998, the amount of migrants to the USA and adjacent countries rose sharply. Clearly, economic deprivation thus induces people to migrate, but it can also simply be in order to avoid the same event happening in the future. For example, even 1 year after Hurricane Katrina had passed, Louisiana had a 4.87% lower population due to emigration (Christie 2006).

In Indonesia, a tsunami in 2004 displaced around 500,000 people (International Federation of Surveyors (FIG 2006) internally, meaning they did not leave the country. However, one can expect that they increased the economic and social pressures in the areas they moved into and will therefore affect the migration decisions in those places. Thus, people who were before on the brink of migrating might now finally decide to move.

*Remark 2* Permanent migration seems to occur because of irreversible or long-lasting problems like desertification or continuous environmental degradation that removes the subsistence possibility of people, or simply because people expect further extreme events in the future and try to avoid these.

In the light of the review above, we can expect significant future migration. For example, it is estimated that the amount of people affected by natural disasters has tripled to a staggering number of two billion people over the course of only one decade. Approximately 211 million people are believed to be affected each year. Scientific evidence suggests that this amount is likely to increase the larger the change in temperature from climate change, as this leads to more floods, extreme weather events, and desertification (IPCC, Stern review).

As approximately two billion people are living in arid, semi-arid, and sub-humid regions, one can expect that even small climatic changes will induce particularly large damages there. For example, it is suggested that the resilience of many arid regions is already weakened. Estimates conclude that up to 20% of drylands are degraded, droughts seem to become more frequent (Millenium Ecosystem Assessment 2005), groundwater depletion intensifies, and groundwater quality deteriorates due to increased fertilizer use (Brown 2000; Brown et al. 1988). It is thus clear that, if the temperature and the weather variability increase as is expected, then the resilience of the ecosystems will have difficulties in supporting further stresses.

Many people will then only have the option to leave their homes in order to find a place that is able to support them. For example, the number of migrants increases annually by approximately three million people, half of which come from Africa. It is believed that most of these come from rural areas with severe land degradation. Estimates suggest that more than 135 million people could be at risk of needing to migrate due to desertification alone (INCCCD 1994), and roughly 200 million due to sea-level rise (Myers 1996). If desertification and land degradation thus continue as expected, then the number of migrants will shoot up, too.

Another reason for migration can be the effect of climate change on health and, thus, working ability. Flavin and Tunali (1998) inform that illnesses like cholera, malaria, and others are very likely to spread vastly due to increased temperatures and higher humidity. They inform that an increase of around 3°C can potentially increase mosquito-transmitted diseases by up to two times in tropical regions and by up to 10 times in areas like Europe. Higher water temperatures can increase the production of algae, which again can increase the probability of cholera outbreaks. It is estimated that around three million people die from malaria each year, with up to 500 million suffering near fatal consequences. Additionally, around 17.3 million deaths worldwide (around 33% of total) are believed to be caused by infectious diseases. These deaths are thought to be caused due to shortages of water, which result in more use of contaminated water and lower cleanliness (see WHO 1996). The dark figures for lost working hours due to illness from infectious diseases should by far exceed the deaths. If we use the same ratio as near fatal consequences to fatalities for malaria (ratio of 170), this leads to a (certainly too large) figure of three billion people losing some working hours. This, however, can provide some estimate for lost working hours or reduction in productivity. If this extrapolation is only marginally correct, then this presumes a strong effect of climate change on productivity.

Faced with these figures, one cannot easily reject the need to further investigate the impact of climate change on migration and its feedbacks. We shall therefore develop a theoretical model that incorporates these feedbacks. Through this, we expect to add to the understanding of the relationship between the economy, migration, and climate change.

## 3 The model

Here, we construct a two-country, general equilibrium, overlapping-generations model. As we wish to concentrate on analyzing international migration, we shall simply assume that firms are profit maximizers in a perfectly competitive world with international capital mobility. Generations, however, first analyze how much welfare they are likely to obtain at home and then compare this to the welfare they might get from migrating to another region. In case migration is expected to leave them better off, then they shall migrate. Our approach is designed to understand, step-by-step, the welfare implications from migration when climate change plays a significant role for welfare. Most of the article will concern itself with the steady-state perspective of our dynamic model. In terms of notation, we shall denote per capita with small letters and total population with large letters. The first subscript refers to the country and the second to the point in time. We write subscript $i$ to denote a solution that applies to both north and south, such that $i = N, S$. Constant returns to scale will be abbreviated by CRTS, decreasing returns to scale by DRTS, and total factor productivity by TFP.

### 3.1 The firm's problem

We assume that in each region there exists a representative firm which produces in a perfectly competitive market using capital and labor as inputs. The production function in each country is of a Cobb-Douglas type where we allow for decreasing returns to scale, such that $Y_{it} = A_{it}K_{it}^{\alpha}L_{it}^{\beta}$, and $\alpha + \beta < 1$.

The discussion on whether production is subject to DRTS or CRTS has been ongoing for quite some while. DRTS have also been used in theoretical models by, e.g., Facchini and Willmann (2005), and are empirically supported by the estimations of the Global Trade Analysis Project (GTAP), see Narayanan and Walmsley (2008), as well as by other empirical studies (Basu and Fernald 1997). On the one hand, DRTS makes one vulnerable to the replication argument, which is solely a theoretical argument suggesting that a firm producing under DRTS can split in two and thereby increase overall output. On the other hand, DRTS seems to be a realistic assumption given the empirical evidence that has accumulated during the recent years (see GTAP dataset). We decided to give up a slight amount of theoretical rigor in favor of what is apparently the more realistic assumption. A partial reconciliation between the use of DRTS and the replication argument is that allowing for DRTS can also imply that one views other unpriced and roughly constant factors (like land or other externalities) as another factor of production. We would then have, for example, land, $Q$, such that $Y_{it} = B_{it}K_{it}^{\alpha}L_{it}^{\beta}Q_{i}^{1-\alpha-\beta}$, and via simplification arrive at $Y_{it} = A_{it}K_{it}^{\alpha}L_{it}^{\beta}$ with $A_{it} = B_{it}Q_{i}^{1-\alpha-\beta}$ (see also Cigno 1981, for a model with a three-factor CRTS production function and endogenous population).

TFP in the north is constant, $A_{Nt} = A_N$, whereas the one in the south is $A_{St} = A_S(T_t)$, where $T_t$ is the change in temperature at time $t$ from human-induced climate change. We view this as a proxy for the effect that climate change bears on production. The assumption of climate change affecting TFP can be rationalized by taking TFP as accounting for any residual factor of production that is unpriced. Firstly, assume TFP accounts for the amount of land used in production, then, increases in the sea-level or desertification reduce the amount and productivity of land. Secondly, assume TFP captures health effects, then one can argue that climate change is expected to increase the amount of malaria cases, which has significant impacts on the health and, thus, productivity of workers. The assumption that climate change only impacts the south derives from the observations presented in the previous section.

**Assumption 1** We assume $A_S(\underline{T}) \geq A_S(T), \forall T > \underline{T}$.

$\underline{T}$ denotes the level of temperate without human-induced climate change. This assumption allows us to compare the different scenarios with and without climate change.

Firms then maximize profits according to $\max_{\{L_{it}\}} \Pi_{it} = A_{it}K_{it}^{\alpha}L_{it}^{\beta} - w_{it}L_{it}$, for $i = N, S$, where equilibrium wages are given by

$$w_{it} = \beta A_{it}K_{it}^{\alpha}L_{it}^{\beta-1}. \tag{1}$$

Following Hahn and Solow (1995), we assume that, in the case of DRTS, the excess profits are distributed to the investors, which is the young generation of the previous period, such that $\Pi_{it} = (1-\beta)A_{it}K_{it}^{\alpha}L_{it}^{\beta}$, which gives a return to a unit of capital of

$$R_{it+1} = (1-\beta)A_{it+1}K_{it+1}^{\alpha-1}L_{it+1}^{\beta}. \tag{2}$$

In the case of CRTS, we would have $1-\beta = \alpha$, and there would not be excess profits.

## 3.2 The generation's problem

Here, we shall only analyze migration from the south to the north, in line with empirical observations. The generations in the south choose according to a two-step procedure. In the first step, they calculate their maximum utility at home (this step is equivalently done by the north). In the second step, they calculate whether it is more profitable for them to migrate or to stay in their home country.

In the first step, we thus have

$$\max_{s_{it}} \log(c_{it}) + \rho\log(d_{it+1}) \qquad \text{subject to} \tag{3}$$

$$w_{it} = s_{it} + c_{it}, \tag{4}$$

$$R_{it+1}s_{it} = d_{it+1}, \tag{5}$$

for $i = N, S$, where $w_{it}$ refers to wages in region $i$ at time $t$, $\log(c_{it}) + \rho\log(d_{it+1})$ is the utility of consuming $c_{it}$ when young and $d_{it+1}$ when old, $\rho \in (0, 1)$ is the discount factor, $s_{it}$ are the savings, and $R_{it+1}$ is the return on the savings.

This gives optimal $s_{it} = \rho w_{it}/(1+\rho)$, consumption $c_{it} = w_{it}/(1+\rho)$, and $d_{it+1} = \rho w_{it}R_{it+1}/(1+\rho)$. We write indirect utility in the steady state as

$$\tilde{u}_i = \log\left(\frac{w_i}{1+\rho}\right) + \rho\log\left(\frac{\rho R_i w_i}{1+\rho}\right). \tag{6}$$

In the second step, the agents from the south compare whether their lifetime utility will be higher when migrating, and if this is the case then they migrate north. If an agent wants to migrate, this will cost him/her an amount $c_N x$ and $d_N x$, where $x \in (0, 1)$ reflects adaptation costs in various forms. This gives a lifetime utility of $u_{Nm} = \log(xw_{Nt}) + \rho\log(xd_{Nt+1})$ for agents that migrate north. We wish to keep these migration costs as general as possible, allowing for both subjective and financial costs. Our preferred interpretation is subjective costs, which are reflected in the ex ante probability of finding a job or in the welfare loss (expressed in consumption units) of having to adopt to different cultures and circumstances. In this sense, we avoid putting an explicit structure behind the level of migration costs. Government policies obviously also affect migratory costs. Whereas some countries are rather liberal towards the amount of migrants they take, other countries restrict the inflow of migrants and regions like the EU build migratory camps in Africa to catch potential migrants even before they can attempt to cross the boarder. When agents thus compare indirect utilities, they then calculate

$$\begin{aligned}\Delta &= \tilde{u}_{Nm} - \tilde{u}_S, \qquad \text{if} \qquad \tilde{u}_{Nm} > \tilde{u}_S,\\ &= 0 \qquad\qquad\qquad \text{if} \qquad \tilde{u}_{Nm} \leq \tilde{u}_S.\end{aligned}$$

If this difference is positive, then a proportion of the generation in the south will migrate to the north.[2]

From this, we obtain that an agent born in the south is in equilibrium indifferent between living in the south and migrating to the north if

$$\log\left(x\frac{w_N}{w_S}\right) = -\frac{\rho}{1+\rho}\log\left(\frac{R_N}{R_S}\right). \tag{7}$$

The population accumulates according to $L_{Nt+1} = L_{Nt} + m_{St+1}L_{St}$ and $L_{St+1} = L_{St} - m_{St+1}L_{St}$, where $m_{St} \geq 0$ refers to the percent of people migrating in that point of time. We denote the total population that has migrated as $\sum_{\tau=1}^{t} m_\tau L_{\tau-1} = M_t$. In the steady state, we then have $L_N = \bar{L}_N + M$ and $L_S = \bar{L}_S - M$, where $M \geq 0$.

### 3.3 International capital market

In the framework presented here, we can solve for both the case of no trade in capital and for the case of free trade. We assume that capital depreciates fully during the course of one generation. This assumption, for example, finds support in de la Croix and Michel (2002). No international capital mobility implies that savings $s_{it}$ in one region become the capital $k_{it+1} = K_{it+1}/L_{it+1}$ of that region in the next period, $s_{it} = k_{it+1}$. Free capital mobility requires that total world capital stock is equal to total world savings, such that $L_{Nt+1}k_{Nt+1} + L_{St+1}k_{St+1} = L_{Nt}s_{Nt} + L_{St}s_{St}$, and perfect competition on the international capital market implies $R_N = R_S, \forall t$.

Henceforth, we shall denote frictionless international capital markets as integrated, and the case of no international capital mobility shall be called

[2]Modelling migration decisions in this way is common in the literature and implies that a decline in southern income stimulates migration pressure. However, it is important to have in mind that a decreasing income in low-income countries may also lead to a reduction in the number of emigrants if liquidity constraints become more binding. We thank an anonymous referee for pointing out this fact.

autarky. We already start with a first important result, which we provide in the subsequent proposition.

**Proposition 1** *Given the optimization problem of the firm and the problem of the generations, the long-run results of the integrated case are equivalent to those of the autarky case.*

*Proof* In the autarky case, the interest rate is given by $R_i = \frac{(1-\beta)(1+\rho)}{\beta\rho}$. As both $\beta$ and $\rho$ are the same for north and south, this implies that both interest rates are the same. As $R_N = R_S$ by assumption in the integrated case, we can solve for $K_S = \left[\frac{A_N}{A_S}\left(\frac{L_N}{L_S}\right)^{\beta}\right]^{\frac{1}{\alpha-1}} K_N$, which, together with the clearing of the world capital market, implies that the long-run capital stock is the same in both the integrated and autarky cases. □

This proposition therefore allows us to derive the results without having to subsequently compare both the integrated and the autarky cases.[3] We remind the reader that this result only holds in the long run at the steady state. Whether one allows for autarky or integrated markets will nevertheless have a significant impact on the transition period, with the main impact being on the speed of convergence. In the following sections, we therefore focus on the long-run steady state and assume integrated markets.

### 3.4 The climate sector

The climate sector is as follows: The total stock of the north's capital drives the amount of emissions of $CO_2$ equivalent gases, denoted $E_t$. $CO_2$ equivalent concentrations $Z_t$ are increased by emissions and reduced by a natural decay. The resulting temperature is non-linearly increased by $CO_2$ equivalent concentrations.

$$\begin{aligned} E_t &= \mu K_{Nt} \\ Z_t &= (1-\delta) Z_{t-1} + \gamma E_t, \\ \Delta T_t &= g(Z_t), \end{aligned} \tag{8}$$

with $g'(Z) > 0$ and $g''(Z) < 0$ and initial condition $T_0 = \underline{T}$. Then, the temperature change from human production activities affects the productivity in the south, such that $A_{St} = A_S(T_t)$. Our interpretation of the temperature change is that it measures the deviation from the pre-industrial climate level caused by productive activity.

As observed in the previous section, we assume that emissions from the south are negligible. This assumption is even strengthened if we were to

[3] It should be clear that this result only holds if preference and production parameters are the same and in the absence of any taxation or subsidy.

consider the south as being composed of small developing countries only. We know that large emerging economies like China or India represent 18.4% and 4.9% of the world's $CO_2$ emissions in 2004, while Western Europe, the USA, Canada, and Japan together contribute 46% of total emissions. African countries and other developing countries like Bangladesh or small Pacific Islands represent negligible amounts of the world's $CO_2$ emissions.

## 4 Solving the model

To summarize, we have the following equations at steady state:

$$w_i = \beta A_i K_i^{\alpha} L_i^{\beta-1}, \quad \text{where} \quad A_S = A_S(K_N) \tag{9}$$

$$R_i = (1-\beta) A_i K_i^{\alpha-1} L_i^{\beta}, \tag{10}$$

$$K_S = \left[ \frac{A_N}{A_S} \left( \frac{L_N}{L_S} \right)^{\beta} \right]^{\frac{1}{\alpha-1}} K_N, \tag{11}$$

$$K_N + K_S = L_N s_N + L_S s_S, \tag{12}$$

$$s_i = \frac{\rho w_i}{1+\rho}, \tag{13}$$

$$\log\left( x \frac{w_j}{w_i} \right) = -\frac{\rho}{1+\rho} \log\left( \frac{R_j}{R_i} \right), \tag{14}$$

$$\Delta T = g\left( \frac{\gamma \mu}{\delta} K_N \right). \tag{15}$$

$$L_N + L_S = \bar{L}_N + \bar{L}_S. \tag{16}$$

To remind, we have $A_S = A_S(T)$ with $A'_S(T) < 0$. At steady state, we know that temperature is a function of the capital stock in the north, and with some abuse of notation, we shall denote $A_S(T)$ simply as $A_S(K_N)$. Equation 9 gives wages in each country, Eq. 10 is the interest obtained on investing a unit of capital, Eq. 11 is equality of interest rates on the international market, Eq. 12 is the market clearing condition for capital due to international capital mobility, Eq. 13 gives optimal savings in each country, Eq. 14 holds if no one from country $i$ wants to migrate to country $j$, and Eq. 15 is the steady state temperature, a proxy for climate change. For the moment, we shall not introduce any policy considerations.

The following assumption is based on empirical evidence and helps us to focus our analysis.

**Assumption 2** Throughout the article, we assume that $A_{N0} > A_{S0}$, meaning that TFP in the north is higher at $t = 0$ than in the south. Furthermore, in accordance with the data, we have $\bar{L}_N < \bar{L}_S$.

If one were to allow for two-way migration, then the conditions given in Assumption 2, which are easily verified through data, would still imply that, in the long run, only one-way migration occurs.

Proposition 2 summarizes the results in Section 4.

**Proposition 2** *Given the problem as described in Eqs. 9 to 16, we find that endogenous climate change is a significant propagator of world migration and reduces per capita welfare in both the north and the south.*

Due to the various feedbacks involved, we shall derive these results step-by-step, where we firstly allow for no feedbacks and then switch them on one after the other.

### 4.1 Benchmark case

Firstly, we assume no climate change effect on total factor productivity and no labor mobility but international capital mobility. The steady state capital stock will then be given by $K_i = \left[\frac{\rho}{1+\rho}\beta A_i L_i^{\beta}\right]^{\frac{1}{1-\alpha}}$. This leads to $w_i = \left[\beta A_i \left(\frac{\rho}{1+\rho}\right)^{\alpha} L_i^{\alpha+\beta-1}\right]^{\frac{1}{1-\alpha}}$ and $R_i = \frac{(1-\beta)(1+\rho)}{\beta\rho}$. Per capita wages are therefore higher the higher TFP is in that region, but per capita wages are lower the higher the population is. Total capital stock is increased by TFP and by the population size. We denote indirect utility in the benchmark case by $\tilde{u}^a$, and it will be given by

$$\tilde{u}_i^a = \Phi + \frac{1+\rho}{1-\alpha} \log\left(\beta A_i L_i^{\alpha+\beta-1}\right), \tag{17}$$

where $\Phi = \frac{\alpha(1+\rho)}{1-\alpha} \log\left(\frac{\rho}{1+\rho}\right) + \log\left(\frac{1}{1+\rho}\right) + \rho \log\left(\frac{1-\beta}{\beta}\right)$. By Assumption 2, we thus know that $\tilde{u}_N^a > \tilde{u}_S^a$. Under DRTS, a larger $L_i$ implies a smaller $\tilde{u}_i^a$. The only variables affecting indirect utilities are thus TFP and L. Those are also precisely the ones which are affected by climate change and the focus of our study.

In this benchmark case, we obtain a temperature of

$$T^a = g\left(\frac{\gamma\mu}{\delta}\left[\frac{\rho}{1+\rho}\beta A_N L_N^{\beta}\right]^{\frac{1}{1-\alpha}}\right).$$

The steady state change in temperature is increased by the productivity in the north, i.e., a more productive north implies more capital, thus more emissions and, therefore, a stronger climate change. Similarly, the less patient agents are (a lower $\rho$), the more they will consume when young and, therefore, the lower the polluting capital stock will be, which reduces long-run climate change. The more people live in the north the more they will produce overall and, therefore, the stronger climate change will be. This also suggests that a larger migration to the north should increase climate change, an intuition that we confirm later. The dirtier the production technology (higher $\mu$) and the stronger emissions impact $CO_2$ concentrations (e.g., emissions made higher up, for example, from airplanes, impact $CO_2$ stocks longer and worse than emissions on the ground), the higher the long-run temperature will be.

## 4.2 Benchmark and migration

We now move to the case of benchmark with migration. The equilibrium condition for migration from the south to the north then implies $xw_N = w_S$. Rewritten, we obtain the condition that no one moves from the south to the north if

$$x^{1-\alpha} A_N L_N^{\alpha+\beta-1} = A_S L_S^{\alpha+\beta-1}. \tag{18}$$

A steady state in migration from the south to the north then exists[4], where we denote the steady state level of $M$ as $M^{am}$, if $x^{1-\alpha} A_N \bar{L}_N^{\alpha+\beta-1} > A_S \bar{L}_S^{\alpha+\beta-1}$. Intuitively, this condition requires that, at the initial point in time, agents from the south have an incentive to migrate north. This condition holds due to our assumption 2 and is furthermore verified in the data. We can solve for the total amount of migrants in the steady state,[5] given by

$$M^{am} = \frac{(A_S)^{\frac{1}{\alpha+\beta-1}} \bar{L}_S - \left(x^{1-\alpha} A_N\right)^{\frac{1}{\alpha+\beta-1}} \bar{L}_N}{(A_S)^{\frac{1}{\alpha+\beta-1}} + \left(x^{1-\alpha} A_N\right)^{\frac{1}{\alpha+\beta-1}}}. \tag{19}$$

A larger stock of population in the north reduces the incentives to migrate due to the DRTS. On the other hand, the larger the population in the south, the more migrants would we expect since per capita welfare in the south is lower the larger the population in the south is.

Moreover, we find that

$$\frac{dM^{am}}{dA_N} = \frac{1}{1-\alpha-\beta} \frac{1}{A_N} \frac{\left(A_S A_N x^{1-\alpha}\right)^{\frac{1}{\alpha+\beta-1}} \left(\bar{L}_N + \bar{L}_S\right)}{\left[A_S^{\frac{1}{\alpha+\beta-1}} + \left(x^{1-\alpha} A_N\right)^{\frac{1}{\alpha+\beta-1}}\right]^2} > 0. \tag{20}$$

Thus, if productivity in the north is enhanced (increase in $A_N$), then the north will become more attractive due to higher wages, leading to more migration. Furthermore, if globalization is associated with lower transportation costs,

[4] Proof: We check whether the equilibrium condition can exist by varying $M$ along its domain $[0, \bar{L}_S]$. We get $\lim_{M\to 0} x^{1-\alpha} A_N L_N^{\alpha+\beta-1} > \lim_{M\to 0} A_S L_S^{\alpha+\beta-1} > 0$, and $\lim_{M\to \bar{L}_S} x^{1-\alpha} A_N L_N^{\alpha+\beta-1} < \lim_{M\to \bar{L}_S} A_S L_S^{\alpha+\beta-1}$. Since $x^{1-\alpha} A_N L_N^{\alpha+\beta-1}$ is a monotonically decreasing function of $M$ and since $A_S L_S^{\alpha+\beta-1}$ is a monotonically increasing function of $M$ from a positive number to infinity, we conclude that a unique steady state exists if $x^{1-\alpha} A_N \bar{L}_N^{\alpha+\beta-1} > A_S \bar{L}_S^{\alpha+\beta-1}$.

[5] Under CRTS, no non-trivial steady state exists since $x^{1-\alpha} A_N = A_S$ is a knife-edge condition. Thus, we have either no migration or complete migration.

then migration costs would also be lower (i.e., a higher $x$) and more people will find it profitable to migrate. This can be seen from the following:

$$\frac{dM^{am}}{dx} = \frac{1-\alpha}{1-\alpha-\beta}\,\frac{1}{x}\,\frac{\left(A_S A_N x^{1-\alpha}\right)^{\frac{1}{\alpha+\beta-1}}\left(\bar{L}_N+\bar{L}_S\right)}{\left[A_S^{\frac{1}{\alpha+\beta-1}}+\left(x^{1-\alpha}A_N\right)^{\frac{1}{\alpha+\beta-1}}\right]^2} > 0 \tag{21}$$

We denote indirect utility in the benchmark case with migration by $\tilde{u}_i^{am}$, and it is given by

$$\tilde{u}_S^{am} = \Phi + \frac{1+\rho}{1-\alpha}\log\left(\beta A_S\left(\bar{L}_S - M^{am}\right)^{\alpha+\beta-1}\right), \tag{22}$$

$$\tilde{u}_N^{am} = \Phi + \frac{1+\rho}{1-\alpha}\log\left(\beta A_N\left(\bar{L}_N + M^{am}\right)^{\alpha+\beta-1}\right) \tag{23}$$

Thus, we obtain that, if one allows for migration, then $\tilde{u}_S^{am} > \tilde{u}_S^a$, whereas $\tilde{u}_N^{am} < \tilde{u}_N^a$. Therefore, the south benefits from international migration, whereas the north loses. This result is attributable to the decreasing returns in production. If the north is initially better off, then people from the south migrate north until the per capita utility in the north decreases to such a level that migration does not pay any longer. Since fewer people in the south now share the same (or more) capital, this raises the average wage in the south, and therefore, utility increases.

Steady state temperature is then

$$T^{am} = g\left(\frac{\gamma\mu}{\delta}\left[\frac{\rho}{1+\rho}\beta A_N\left(\bar{L}_N + M^{am}\right)^{\beta}\right]^{\frac{1}{1-\alpha}}\right).$$

Since there are now more people living in the north, which all pollute according to the northern living standards, this will unambiguously lead to an increase in emissions and, therefore, long-run temperature. A current estimate by the UN of the amount of migrants in the north is around 10%. Assuming that they lead the same lifestyle as the northern population, this may work as a significant propagator of climate change. By reducing migration costs and raising the number of migrants, increased globalization would raise temperature. A rise in northern productivity would directly exacerbate climate change by increasing the productive capacity of the north, but also indirectly affect temperature by making the north more attractive and leading to more migration.

### 4.3 Benchmark with climate

Here, we shall assume that there is a climate change effect on total factor productivity in the south but no migration possibilities. We denote indirect utility by $\tilde{u}_i^{ac}$. In this case, the north will grow to the same long-run level of capital as in the benchmark case and end up with the same indirect utility, such that $\tilde{u}_N^{ac} = \tilde{u}_N^a$.

The steady state capital stock of the south is, however, depending on the amount of climate change induced by the production of the north. The productivity in the south can then be written $A_S = A_S\big(K_N\big)$, with $K_N = \big[\frac{\rho}{1+\rho}\beta A_N L_N^{\beta}\big]^{\frac{1}{1-\alpha}}$. Therefore, the indirect utility of the south at steady state will be given by

$$\tilde{u}_S^{ac} = \Phi + \frac{1+\rho}{1-\alpha}\log\left(\beta A_S(K_N)L_S^{\alpha+\beta-1}\right), \tag{24}$$

which implies that $\tilde{u}_S^{ac} < \tilde{u}_S^{a} < \tilde{u}_N^{ac} = \tilde{u}_N^{a}$. As expected, the externality imposed by the north on the production capacity of the south reduces total welfare in the south. The indirect utility in the south is a decreasing function of emissions in the north (since $A'_S(K_N) < 0$). The stronger the effect of climate change on TFP, i.e., the larger the slope of $A_S(K_N)$ for a given $K_N$, the lower indirect utility in the south will be. Conclusively, the worse the impact of climate change, the less each person in the south will produce, which will lead to a lower average income. For example, a likely scenario for temperature increases is 3°C, which could imply at least a doubling of malaria victims in the south (Flavin and Tunali 1998). With currently three million death annually and 500 million near fatalities (and consequently many lost working hours), the productivity decreases in the regions that see a doubling of malaria victims can be enormous. Since there are no migrants in this scenario and since the integrated case is equivalent to the autarky case, we observe no change in production in the north and, therefore, no divergence from the total emissions in the benchmark case.

### 4.4 Benchmark with climate and migration

We now extend the previous case by allowing for migration. A steady state in migration from the south to the north then exists,[6] where we denote the steady state level of $M$ as $M^{acm}$, given that $x^{1-\alpha}A_N\bar{L}_N^{\alpha+\beta-1} > A_S(K_N)\bar{L}_S^{\alpha+\beta-1}$. This requires that, at some point in time, be it at $t = 0$ or when climate change has sufficiently reduced TFP in the south, there exists an incentive to migrate north. The total amount of migrants in the steady state is then given by

$$M^{acm} = \frac{(A_S(K_N))^{\frac{1}{\alpha+\beta-1}}\bar{L}_S - \left(x^{1-\alpha}A_N\right)^{\frac{1}{\alpha+\beta-1}}\bar{L}_N}{(A_S(K_N))^{\frac{1}{\alpha+\beta-1}} + \left(x^{1-\alpha}A_N\right)^{\frac{1}{\alpha+\beta-1}}}. \tag{25}$$

We know that $\frac{\partial K_N}{\partial M} > 0$. This implies more climate change, and therefore, TFP in the south with migration is lower than if one does not allow for migration. In terms of indirect utility, we can then conclude that $\tilde{u}_S^{acm} < \tilde{u}_S^{am}$ iff $M^{acm} \geq M^{am}$. The denominator of Eq. 25 is increasing when $\Delta A_S < 0$ and the nominator is increasing when $\Delta A_S < 0$. This comes about because migration implies two things: Firstly, more migration means more climate change, which reduces income in the south; secondly, more migration implies a higher per capita

[6] Proof: $\lim_{M\to 0} LHS > \lim_{M\to 0} RHS > 0$, and $\lim_{M\to \bar{L}_S} LHS < \lim_{M\to \bar{L}_S} RHS$.

steady state income in the south. It is this cumulative effect, where more migration implies further climate change, which leads to $M^{acm} > M^{am}$. We can therefore conclude that $\tilde{u}_S^{acm} < \tilde{u}_S^{am}$. Let us observe that increased globalization translated by an increase in $x$ would now have the following effect:

$$\frac{dM^{acm}}{dx} = \frac{\frac{\partial M^{am}}{\partial x}}{1 - \frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial L_N}}. \tag{26}$$

The nominator is positive and the sign of the denominator is ambiguous because $\frac{\partial M^{acm}}{\partial A_S} < 0$.[7] A necessary condition for an interior solution to $M^{acm}$ requires $\frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial L_N} < 1$. This condition holds only if changes in $A_S$ have small impacts on the number of migrants or if climate change has minimal impacts on TFP in the south. Put differently, if the migration costs change, then the impacts unfold subsequently as follows: Initially, more people wish to migrate since the costs are lower, and thus, the perceived benefit of moving to the north is higher. The secondary effect of this is, however, that more migrants pollute more and therefore induce a further decrease in the productivity of the south. If migrants have only a small impact on climate change, then $M^{acm}$ will be insignificantly higher than $M^{am}$. However, if the impact of migrants on total climate change is large enough and climate change impacts the migration decisions strongly, then this could potentially lead to a corner solution: All inhabitants from the south wish to migrate to the north. In any case, we can conclude that $dM^{acm}/(dx) > dM^{am}/(dx)$.

Similarly, higher productivity in the north would now not only make the north more attractive but also impact southern productivity via

$$\frac{dM^{acm}}{dA_N} = \frac{\frac{\partial M^{am}}{\partial A_N} + \frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial A_N}}{1 - \frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial L_N}}. \tag{27}$$

The nominator is positive while the a necessary condition for an interior solution to $M^{acm}$ requires again $\frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial L_N} < 1$. This condition is satisfied when changes in southern productivity have sufficiently small effects on migration or when climate change does not impact southern productivity too much. As in the benchmark case with migration, an increase in northern productivity will raise northern income per capita and make the north more attractive to migration (first term of the nominator). Moreover, a higher TFP in the north will raise its productive capacity and induce a decrease in southern productivity via climate change (second term of the nominator). Increased migration will have an indirect impact on climate change and further reduce southern productivity (second term of the denominator).

[7] In fact, we have $\frac{\partial M^{acm}}{\partial A_S} = -\frac{1}{1-\alpha-\beta} A_S^{\frac{2-\alpha-\beta}{\alpha+\beta-1}} \frac{(x^{1-\alpha}A_N)^{\frac{1}{\alpha+\beta-1}}(\bar{L}_S+\bar{L}_N)}{\left(A_S^{\frac{1}{\alpha+\beta-1}} + (x^{1-\alpha}A_N)^{\frac{1}{\alpha+\beta-1}}\right)^2} < 0.$

The strength of climate change will be given by

$$T^{acm} = g\left(\frac{\gamma\mu}{\delta}\left[\frac{\rho}{1+\rho}\beta A_N\left(\bar{L}_N + M^{acm}\right)^{\beta}\right]^{\frac{1}{1-\alpha}}\right).$$

Clearly, $T^{acm} > T^{am}$. In this scenario, therefore, not only the direct migration incentives play a vital role, but the cumulative effects of more migrants do as well. If more migrants also increase emissions in the north and, therefore, further reduce income in the south, this can imply a strengthening of the migration incentive and will increase climate change further. Since approximately 10% of all the northern population is made up of migrants, this snowball effect may be substantial and should not be neglected in policy decisions. An intensification of globalization or higher northern productivity may, in fact, reinforce climate change through an increased migration.

### 4.5 A data experiment

Our objective is to give some numbers to these otherwise analytical results. This should be viewed as a rough exercise that allows us to extrapolate some numerical implications of the model. We take data from today, extrapolate into the future (year 2050), and then use these estimates as an approximation for the steady state values.

GTAP data suggest that world GDP in the year 2000 was 31.278 billion US$, of which the USA, Western Europe, and Japan held 70%. We assume those will be the migrants' destination countries (north). The south is then composed of most of the remaining countries of the world (we do not consider Australia and New Zealand in our calculations). Assuming a growth rate of 1% for the north and 2% for the south, we calculate GDP in 2050 to be 36 billion for the north and 25 billion for the south. Total world population is 6.6 billion, of which USA, Western Europe, and Japan currently hold 17%. In the year 2050, the estimates of the World Population Prospects of the United Nations (2008) are 1.1 billion for Europe plus Northern America, and 8 billion for the rest of the world. In the year 2000, 52.5 million migrants born in the south live in the north (UN data and Docquier and Marfouk, 2006). We take this as the baseline case with migration but without climate change. The average sources of GDP worldwide are skilled plus unskilled labor, giving $\beta = 0.44$, and capital, giving $\alpha = 0.37$, which suggests significant decreasing returns in production.

Knowing $Y$, $\alpha$, $L$, and $\beta$, we can use our Cobb–Douglas functional form $Y = AK^{\alpha}L^{\beta}$ to calculate $K_i$ as follows: take the interest rate $r_i = \alpha A_i K_i^{\alpha-1}L^{\beta}$, then divide by $Y$, which gives $r/Y = \alpha/K$. Solve for $K$, which gives $K = \alpha Y/r$. We know $\alpha$ and $Y$, assume $r = 1.02$, then we can calculate $K_N$ and $K_S$. We then calculate $A_i$ from solving the income equation for $A$, giving $A = Y/(K^{\alpha}L^{\beta})$. Independent of the scaling, the ratio $\sigma \equiv A_S/A_N$ is always the same. Rewriting Eq. 25 as $x = \sigma^{1/(1-\alpha)}(L_N/L_S)^{(1-\alpha-\beta)/(1-\alpha)}$, we obtain the $x$ that matches the value of migrants in 2000, namely $x = 0.27$.

**Table 1** Effect of climate change on migration

| Decrease in $\sigma$ | 0 | −1% | −2% | −3% | −4% | −5% |
|---|---|---|---|---|---|---|
| Migrants in 2050, (in millions) | 98.8 | 150.9 | 205.8 | 263.5 | 324.0 | 387.6 |
| Change in migrants' stock | 0.0% | 52.8% | 108.4% | 166.7% | 228.1% | 292.5% |
| Share of migrants (north) | 9.0% | 13.7% | 18.7% | 24.0% | 29.5% | 35.2% |
| Share of migrants (south) | 1.2% | 1.9% | 2.6% | 3.3% | 4.1% | 4.9% |
| Share of migrants (world) | 1.5% | 2.3% | 3.1% | 4.0% | 4.9% | 5.9% |

Source: GTAP, United Nations (2008) and own computations

Having now constructed the variables that we need, we proceed to calculate the effects of climate change on steady state migration. Since barely any data or knowledge exists on the consequences of climate change on productive capacity, we take a shortcut and assume that climate change visualizes as a percentage decline in $\sigma$. Table 1 shows that the proportion of migrants in the north, $M/(\bar{L}_N + M)$, will change from 9% to up to 35% if the ratio of productivity $\sigma$ $(= A_S/A_N)$ drops by up to 5%. This suggests that even small impacts of climate change can lead to significant changes in the number of migrants.

The results in this section immediately raise questions of various concerns: Empirically, how can we differ between incentives for migration, namely, purely utilitarian incentives and forced migration? Ethically, what value do we give to space and place (or origin) and is someone responsible for taking the migrants? Politically, how are we to deal with possible migration of up to 35% of a northern country's population? Economically, what is the effect of various policies on the number of migrants, on the inequality between north and south, as well as on the amount of climate change?

Though each of the above questions poses challenging problems, we are only going to deal with the economic ones here. In Section 5, we deal with policies of the north.

## 5 Northern policies

We now investigate the effects of two possible policies that the north could undertake, one which affects the migration costs and one which changes emissions efficiency. For simplicity, we dub policies that affect the migration costs simply *immigration policy* or *border controls*, and those that change emissions efficiency *greener technology*. A less restrictive immigration policy would then lead to lower migration costs (increases in $x$). It is certainly true that many northern governments undertake immigration policies in order to regulate the amount of migrants. In our specific case, one can imagine that the north takes responsibility for the climate change that it imposes upon the south and, therefore, relaxes its immigration policy. This is could be understood as an aftercare policy. Regarding the policy directed towards emissions efficiency, many researchers believe that technological improvements are the key means of relieving production from the climate change constraints, especially given that preferences are not expected to change sufficiently. If such a policy is undertaken by the north, then one could interpret it as a preventive policy, since one would expect that a greener technology leads to lower emissions, which should reduce overall migration. We also calibrate our model with real-world data to study whether the USA or Europe would, in the long run, invest more in green technology or immigration policy. In the subsequent propositions, whenever we refer to "abstracting from climate change," we mean $A_S(T_t) = A_S(\underline{T}), \forall T$.

The following analysis considers that policies are costly in the long run. Let $\tau$ be a production tax paid by firms in the north per unit of output produced and let $\tau_x$ and $\tau_\mu$ be amounts per unit of output produced invested by the government in, respectively, border controls and green technology. Since the government taxes production, it adheres to the polluter-pays principle. The government's budget constraint is then given by

$$\tau Y_N = (\tau_x + \tau_\mu) Y_N \tag{28}$$

The following analysis would not lead to qualitative changes in migration, climate change, and inequality in case of long run costliness of these policies (given that taxes are not too large). The results would only be simplified by the fact that there is no taxation and, thus, an absence of the impact of taxes on production.[8] The only effect that we see is a level effect, but not a qualitative change in the results. We now assume that the immigration costs ($x$) and the impact of the northern production on emissions ($\mu$) are both a function of government expenditure. We therefore have that $x(\tau_x Y_N)$ and $\mu(\tau_\mu Y_N)$, where both functions are decreasing in their respective arguments. In the previous analysis, higher production had a negative effect on climate change via the generated pollution and attracted more migrants because of a higher north–south indirect utility gap. Through the mechanisms in $x(\tau_x Y_N)$ and $\mu(\tau_\mu Y_N)$, higher production will also generate higher tax revenues, which strengthen immigration controls and amplify the amounts invested in green technologies. As a consequence, increased migration will have not only a negative feedback effect on climate change but also a positive feedback effect via an increase in tax revenues.

[8]While policies may certainly bear costs at the time they are implemented, it could be argued that these costs will be zero in the long run. This could be the case if one considers, for example, R&D expenditure in emission reductions: If a greener technology is developed once, then it is clear that further R&D expenditure is not necessary in the long run. Similarly, immigration policy that leads to a higher probability of obtaining a job for the migrants only requires a discussion in the parliament. The long-run costliness of policies will, however, not change the results. A formal demonstration is available on request from the authors.

In the presence of such a tax scheme, firms must solve the problem $\max_{\{L_{it}\}} \Pi_{it} = (1-\tau)A_{it}K_{it}^{\alpha}L_{it}^{\beta} - w_{it}L_{it}$, for $i = N, S$, where optimal wages are given by

$$w_{it} = \beta(1-\tau)A_{it}K_{it}^{\alpha}L_{it}^{\beta-1}. \tag{29}$$

Again, excess profits are distributed to the investors (the young generation of the previous period) such that $\Pi_{it} = (1-\beta)(1-\tau)A_{it}K_{it}^{\alpha}L_{it}^{\beta}$, which gives a return to a unit of capital of

$$R_{it+1} = (1-\beta)(1-\tau)A_{it+1}K_{it+1}^{\alpha-1}L_{it+1}^{\beta}. \tag{30}$$

Following the analysis in Section 3, the capital stock in the steady state will be $K_i = \left[\frac{\rho}{1+\rho}\beta(1-\tau)A_iL_i^{\beta}\right]^{\frac{1}{1-\alpha}}$.

The steady state utility in the north is

$$\tilde{u}_N = \Phi + \frac{1+\rho}{1-\alpha}\log\left(\beta(1-\tau)A_NL_N^{\alpha+\beta-1}\right). \tag{31}$$

while steady state migration changes to

$$M = \frac{A_S^{\frac{1}{\alpha+\beta-1}}\bar{L}_S - \left(x^{1-\alpha}(1-\tau)A_N\right)^{\frac{1}{\alpha+\beta-1}}\bar{L}_N}{A_S^{\frac{1}{\alpha+\beta-1}} + \left(x^{1-\alpha}(1-\tau)A_N\right)^{\frac{1}{\alpha+\beta-1}}}. \tag{32}$$

We now derive the direct impact of taxes on the stock of steady-state migrants. It is straightforward to calculate that $dM^{am}/d\tau < 0$. Since taxes reduce the total capital stock in the north, they provide less incentive for part of the southern population to migrate north. Allowing for climate change to affect migration leads to $dM^{acm}/d\tau < 0$ if $A_S > -(1-\tau)A_S'(K_N)(\partial K_N/\partial\tau + \partial K_N/\partial M^{acm}\partial M^{acm}/\partial\tau)$. If the number of migrants is very responsive to increases in taxes and if climate change bears a significant impact on the productivity in the south, then a small increase in taxes has the potential to reduce the stock of migrants.

In the next two sections, we analyze how the north should optimally allocate its tax revenues between border controls and clean technologies.[9] The government maximizes Eq. 31 subject to $\tau = \tau_j$, where $j = x, \mu$. From Eq. 31, we know that the northern government will raise taxes iff

$$L_N < -(1-\alpha-\beta)(1-\tau_j)\frac{dM^i}{d\tau_j} \quad j = x, \mu, \quad i = am, acm. \tag{33}$$

A necessary condition is that $\frac{dM^i}{d\tau_j} < 0$. The intuition is that an increase in taxes, which reduces per capita income in the north, has to lead to a sufficiently strong reduction in migration to increase northern utility. The following assumption insures that the north sets positive taxes.

[9]We neglect the fact that the government may wish to raise taxes but not invest everything in border controls, respectively, green technologies, an assumption equivalent to the no-Ponzi scheme assumption.

**Assumption 3** In the subsequent analysis, we assume that condition 33 is always satisfied.

5.1 Investment in border controls

We assume here that all the government's tax revenues are invested in border controls only. The following proposition summarizes the results of this section.

**Proposition 3** *Abstracting from climate change, a higher investment in border controls leads to a reduction in the southern utility and an increase in the northern one; to a reduction in steady state temperature and to an increase in north–south inequality. In the presence of climate change, investments in border controls will further decrease the long-run number of migrants, improve the environment, and decrease or increase north–south inequality.*

Abstracting from climate change, taxes affect migration as follows:

$$\frac{dM^{am}}{d\tau_x} = \frac{\frac{\partial M^{am}}{\partial \tau_x} + \frac{\partial M^{am}}{\partial x}\left(\frac{\partial x}{\partial \tau_x} + \frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial K_N}\frac{\partial K_N}{\partial \tau_x}\right)}{1 - \frac{\partial M^{am}}{\partial x}\frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial K_N}\frac{\partial K_N}{\partial L_N}} \tag{34}$$

For an interior solution in migration, we require that the denominator of Eq. 34 is positive. As $\frac{\partial M^{am}}{\partial \tau_x} < 0$ and $\frac{\partial M^{am}}{\partial x} > 0$, the sign of $\frac{dM^{am}}{d\tau_x}$ depends on the terms inside the parentheses. An increase in taxes reduces migration if

$$\frac{\partial x}{\partial \tau_x} < -\frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial K_N}\frac{\partial K_N}{\partial \tau_x} \tag{35}$$

Since immigration costs depend on the tax rate and on production, a higher tax rate may either increase or decrease the amounts spent on border controls. An increase in the tax rate implies a per unit (of production) increase allocated to border controls (term on LHS), but also a reduction in steady state production leading to a reduction in tax revenues.[10] We can show that the former effect will dominate the latter if taxes are not too high such that production is not reduced too much.[11] If the level of the tax rate is initially low, then an increase will lead to higher tax revenues. On the contrary, if tax levels are already high at the beginning, a further increase in the tax rate will decrease tax revenues. In effect, this result points towards a Laffer curve. If, however, we assume that increases in the tax rate always lead to more taxes, then $\frac{dM^{am}}{d\tau_x}$ is always negative.

[10] It is straightforward to see that the direct impact of taxes on steady-state production is negative, since $Y_N = \left[\left(\frac{\rho}{1+\rho}\beta\right)^{\alpha}(1-\tau)^{\alpha} A_N L_N^{\beta}\right]^{\frac{1}{1-\alpha}}$.

[11] Imagine the following functional form for the immigration costs $x(\tau_x Y_N)$: $x = \frac{\bar{x}}{1+a\tau_x Y_N}$, where $a > 0$ is a parameter and $\bar{x}$ are immigration costs without government intervention. Then, condition 35 drops down to $\tau_x < 1 - \alpha$. Thus, the northern government can improve the welfare of its citizens if taxes on production are not larger than the share of non-capital revenues in production.

What happens in the south? If condition 35 holds, we know that the utility in the south will decrease, because $\frac{d\tilde{u}_S^{am}}{d\tau_x} = \frac{1+\rho}{1-\alpha}(1-\alpha-\beta)\frac{1}{L_S}\frac{\partial M}{\partial \tau_x} < 0$. If we assume that the government increases taxes only if it leads to an increase in the northern utility, i.e., the increase in taxes leads to a sufficiently high decrease in migrants to induce $\frac{d\tilde{u}_N^{am}}{d\tau_x} > 0$, then north–south inequality will increase.

Allowing for climate change, we obtain the following result:

$$\frac{dM^{acm}}{d\tau_x} = \frac{\frac{\partial M^{acm}}{\partial \tau_x} + \frac{\partial M^{acm}}{\partial x}\left(\frac{\partial x}{\partial \tau_x} + \frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial K_N}\frac{\partial K_N}{\partial \tau_x}\right) + \frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial \tau_x}}{1 - \frac{\partial K_N}{\partial L_N}\left(\frac{\partial M^{acm}}{\partial x}\frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial K_N} + \frac{\partial M^{acm}}{\partial A_S}\frac{\partial A_S}{\partial K_N}\right)} \tag{36}$$

The numerator is negative if condition 35 holds. The denominator is positive for an interior $M^{acm}$, which implies $|\frac{dM^{acm}}{d\tau_x}| > |\frac{dM^{am}}{d\tau_x}|$.[12] Similar to Section 4.4, the denominator is positive if changes in $A_S$ have small impacts on the number of migrants or if climate change has small impacts on TFP in the south. If the deterioration of the climate impacts the migration decisions strongly, then this could lead to a corner solution where no inhabitants of the south wish to migrate to the north.

Condition 35 is also sufficient for taxes to improve the environment. Temperature in the steady state is a function $T = g(\frac{\gamma\mu}{\delta}K_N)$,

$$\frac{dT^{acm}}{d\tau_x} = \frac{\partial T^{acm}}{\partial K_N}\left(\frac{\partial K_N}{\partial \tau_x} + \frac{\partial K_N}{\partial L_N}\frac{dM^{acm}}{d\tau_x}\right)$$

Because $\frac{\partial K_N}{\partial \tau_x} < 0$ and $\frac{\partial K_N}{\partial L_N} > 0$, the effect of taxes on temperature will depend on $\frac{dM^{acm}}{d\tau_x}$, which one would expect to be negative given the previous analysis. Taxes will improve TFP in the south not only by diminishing the productive capacity in the north but also by reducing the number of migrants and, thus, their effect on climate change (the second term inside the parentheses). In such a case, the indirect utility in the south might increase if DRTS are dominated by the positive effect of taxes on southern TFP

$$\frac{d\tilde{u}_S^{acm}}{d\tau_x} = \frac{1+\rho}{1-\alpha}\left[\frac{1-\alpha-\beta}{L_S}\frac{dM^{acm}}{d\tau_x} + \frac{1}{A_S}A'_S(K_N)\left(\frac{\partial K_N}{\partial \tau_x} + \frac{\partial K_N}{\partial M^{acm}}\frac{dM^{acm}}{d\tau_x}\right)\right] \tag{37}$$

The first term in Eq. 37 captures the effect of DRTS: a reduction in the number of migrants implies that more people have to share the same pie. The second term acts in the opposite direction: fewer migrants leads to less climate change, then this allows for a higher per capita production in the south.

[12] If we take the same functional form as in endnote 11 for the immigration costs, then it is easy to show that a *sufficient* condition for $\frac{dM^{acm}}{d\tau_x} < 0$ is $\tau_x < 1-\alpha$.

The effect on inequality is as follows: A reduction in inequality from the immigration policy requires $d(\tilde{u}_N/\tilde{u}_S)/(d\tau_x) < 0$. This is equivalent to the condition

$$\frac{1+\rho}{1-\alpha}\left[-(1-\alpha-\beta)\left(\frac{\tilde{u}_S}{L_N}+\frac{\tilde{u}_N}{L_S}\right)\frac{dM^{acm}}{d\tau_x}-\frac{\tilde{u}_S}{1-\tau_x}\right.$$
$$\left.-\,\tilde{u}_N\frac{A'_S(K_N)}{A_S}\left(\frac{\partial K_N}{\partial \tau_x}+\frac{\partial K_N}{\partial L_N}\frac{dM^{acm}}{d\tau_x}\right)\right]<0$$

The first term inside the square brackets is positive and represents DRTS. A decline in migration lowers southern utility because more people have to share less wealth due to the DRTS. The indirect effect of less migration on inequality is given by the two other terms, which are negative. The second term inside the square brackets shows that higher taxation has a (direct) negative impact on northern utility ($\tilde{u}_N \downarrow$ if $\tau_x \uparrow$). The third term indicates that higher taxation also acts upon the southern productivity via a direct decrease on the northern productive capacity $\left(\frac{\partial K_N}{\partial \tau_x} < 0\right)$ and via an indirect decrease in $K_N$ through a reduction in the feedback effect of migrants on climate change $\left(\frac{\partial K_N}{\partial L_N}\frac{\partial M}{\partial \tau_x} < 0\right)$. In short, without DRTS, higher taxation will reduce inequality provided condition 35 holds, while the two other effects work in favor of equality. We can therefore conclude that north–south inequality will increase or diminish depending on which of the terms is stronger.

Finally, it is certainly true that many northern governments undertake immigration policies in order to regulate the amount of migrants. One could very well imagine that the north is concerned with aftercare measures. For example, by taking responsibility for inducing climate change on the south and therefore taking care of the forced migrants, the north might adopt a more relaxed immigration policy. Such an aftercare policy implies that the government reduces the tax rate, which increases the number of migrants (provided that a lower tax rate leads to lower total taxes, see Eq. 35), worsens climate change, and results in an a priori ambiguous effect on north–south inequality.

### 5.2 Investment in greener technologies

Alternatively to the aftercare border control policy, investing in greener technology may be understood as a precautionary or preventive policy. When the government decides to invest all its tax revenues in green technologies, then we obtain results that are summarized in the following proposition.

**Proposition 4** *More taxes directed towards a greener technology will reduce the number of migrants, improve the environment, and either increase or decrease north–south inequality.*

We can calculate the effect of $\tau_\mu$ on $M^{acm}$ as

$$\frac{dM^{acm}}{d\tau_\mu} = \frac{\frac{dM^{am}}{d\tau_\mu} + \frac{\partial M^{acm}}{\partial A_S}\left[\frac{\partial A_S}{\partial \mu}\left(\frac{\partial \mu}{\partial \tau_\mu} + \frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial \tau_\mu}\right) + \frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial \tau_\mu}\right]}{1 - \left(\frac{\partial A_S}{\partial \mu}\frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial L_N} + \frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial L_N}\right)\frac{\partial M^{acm}}{\partial A_S}} \tag{38}$$

The first term in the numerator is the direct effect of taxes: less income in the north makes is less attractive to migrate from the south. The second part in the numerator describes the marginal impact of climate change (brought about by changes in taxes) on the motivation to migrate. These terms include the direct effect of greener technology from higher taxes; the impact of lower income due to higher taxes on climate change; the impact of a lower production level due to higher taxes. The denominator in Eq. 38 is governed by two opposite feedback effects of migrants on climate change. When higher taxation induces less migration, then the tax base will be reduced and fewer resources will be allocated to green technologies. The second term inside the brackets corresponds to the "traditional" feedback effect: more migration means more productive capacity in the north and, thus, more pollution. Provided that the denominator is positive, then a sufficient condition for $\frac{dM^{acm}}{d\tau_\mu} < 0$ is given by

$$\frac{\partial \mu}{\partial \tau_\mu} + \frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial \tau_\mu} < 0.$$

The interpretation of this condition is analogous to Eq. 35. An increase in investments in green technologies has the following effect on southern productivity

$$\frac{dA_S^{acm}}{d\tau_\mu} = \frac{\frac{\partial A_S^{acm}}{\partial \mu}\left(\frac{\partial \mu}{\partial \tau_\mu} + \frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial \tau_\mu}\right) + \frac{\partial A_S^{acm}}{\partial K_N}\frac{\partial K_N}{\partial \tau_\mu} + \left(\frac{\partial A_S^{acm}}{\partial \mu}\frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial L_N} + \frac{\partial A_S^{acm}}{\partial K_N}\frac{\partial K_N}{\partial L_N}\right)\frac{\partial M}{\partial \tau_\mu}}{1 - \left(\frac{\partial A_S^{acm}}{\partial \mu}\frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial L_N} + \frac{\partial A_S^{acm}}{\partial K_N}\frac{\partial K_N}{\partial L_N}\right)\frac{\partial M}{\partial A_S}} \tag{39}$$

The denominator is the same as the denominator in Eq. 38, and the same reasoning applies concerning its sign. If the effect of migrants on climate change is not too strong, then the denominator is positive and we have an interior solution for $A_S^{acm}$. In this case, the numerator will be positive as well and $\frac{dA_S^{acm}}{d\tau_\mu} > 0$. Lower migration decreases pollution by decreasing northern production (direct effect) but may increase pollution via a reduction in tax revenues (indirect effect). Since $\frac{\partial M}{\partial \tau_\mu} < 0$ and $\frac{\partial M}{\partial A_S} < 0$, if the direct impact of migrants on pollution is stronger than the indirect impact, then this is a sufficient condition for $\frac{dA_S^{acm}}{d\tau_\mu} > 0$.

The effect of higher investments in green technologies on southern utility will be

$$\frac{d\tilde{u}_S^{acm}}{d\tau_\mu} = \frac{1+\rho}{1-\alpha}\left[\frac{1-\alpha-\beta}{L_S}\frac{dM^{acm}}{d\tau_\mu} + \frac{1}{A_S}\frac{dA_S^{acm}}{d\tau_\mu}\right] \tag{40}$$

Higher investments in green technologies have a negative effect on utility in the south due to DRTS $\left(\frac{dM^{acm}}{d\tau_\mu} < 0\right)$ and a positive effect on $\tilde{u}_S$ via improvements in southern productivity $\left(\frac{dA_S^{acm}}{d\tau_\mu} > 0\right)$. The effect of higher investments on southern utility will depend on which of the effects dominate.

The effect on inequality is as follows. A reduction in inequality from the immigration policy requires $d(\tilde{u}_N/\tilde{u}_S)/(d\tau_x) < 0$. This is equivalent to the condition

$$\frac{1+\rho}{1-\alpha}\left[-(1-\alpha-\beta)\left(\frac{\tilde{u}_S}{L_N}+\frac{\tilde{u}_N}{L_S}\right)\frac{dM^{acm}}{d\tau_\mu}-\frac{\tilde{u}_S}{1-\tau_\mu}-\tilde{u}_N\frac{1}{A_S}\frac{dA_S^{acm}}{d\tau_\mu}\right]<0 \tag{41}$$

If DRTS are not too strong, then inequality decreases provided $\frac{dA_S^{acm}}{d\tau_\mu} > 0$.

The investment in green technology, interpretable as a precautionary/preventive policy, may have a double-dividend. By investing more in green technology, the impact of production on climate change will be reduced, leading to fewer migrants. This implies that the north will see increases in utility (provided the policy is sufficiently effective), as well as the south. Conclusively, this double dividend policy may bear a win–win strategy for both regions.

### 5.3 Investment in clean technologies or in border controls

Should a northern government, that maximizes the utility of a northern citizen, invest in greener technology or in immigration controls? Assume the government has a fixed amount of resources $\tau = \bar{\tau}$, then the budget constraint can be written as $\tau_\mu = \bar{\tau} - \tau_x$. The northern government will choose the optimal share of tax revenues by maximizing the utility of a northern citizen subject to $\tau_x$ and $\tau_\mu$. Since changes in the tax rate then only affect the amount of migrants (as total taxes are fixed), the optimal share of tax revenues allocated will be where the marginal benefit of investing in border controls equalizes the marginal benefit of investing in greener technology. Since $\bar{\tau} - \tau_x = \tau_\mu$, we can simplify, and by assuming an interior solution, we find

$$-\frac{\partial M}{\partial \tau_x}\frac{\partial x}{\partial \tau_x}=\frac{\partial M}{\partial A_S}\frac{\partial A_S}{\partial \mu}\frac{\partial \mu}{\partial \tau_\mu}\frac{\partial \tau_\mu}{\partial \tau_x} \tag{42}$$

Condition 42 states that the optimal policy mix $\{\tau_x^*, \tau_\mu^*\}$ is achieved when a change in migration due to subsidies in border controls is exactly compensated by an opposite change in migration via foregone investments in green technologies. The sign of $\frac{dM^{acm}}{d\tau_x}$ will determine if the government should spend more on border controls or more on green technologies. When $\frac{dM^{acm}}{d\tau_x} > 0$, the government will raise $\tau_x$ and reduce $\tau_\mu$ such that the tax rate remains fixed at $\bar{\tau}$.

The reverse is true for $\frac{dM^{acm}}{d\tau_x} < 0$. A change in $\tau_x$ will have the following impact on the number of migrants

$$\frac{dM^{acm}}{d\tau_x} = \frac{\frac{\partial M}{\partial \tau_x}\frac{\partial x}{\partial \tau_x} + \frac{\partial M}{\partial A_S}\frac{\partial A_S}{\partial \mu}\frac{\partial \mu}{\partial \tau_\mu}\frac{\partial \tau_\mu}{\partial \tau_x}}{1 - \frac{\partial M}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial M} - \frac{\partial M}{\partial A_S}\frac{\partial A_S}{\partial \mu}\frac{\partial \mu}{\partial Y_N}\frac{\partial Y_N}{\partial M} - \frac{\partial M}{\partial x}\frac{\partial x}{\partial Y_N}\frac{\partial Y_N}{\partial M}}, \tag{43}$$

The numerator of Eq. 43 depicts the impact of the policy mix. For a fixed tax rate, an increase in $\tau_x$ allocates more resources to border controls, which directly reduce migration (first term). At the same time, a rise in $\tau_x$ deprives the production sector of subsidies for green technologies, which induces an exacerbation of climate change and more migration (second term). The denominator shows the multiple feedback effects of migration on climate change (second term) and on the tax base (third and fourth terms). These different feedback effects have different impacts on migration. The first effect states that the migration-induced climate change will generate further migration and the two other terms suggest that migration will increase production and, thus, the tax base, which allocates more resources to the government to reduce migration indirectly via green technologies or directly via border controls. A sufficient condition to have a positive denominator then requires $\frac{\partial M}{\partial A_S}\frac{\partial A_S}{\partial K_N}\frac{\partial K_N}{\partial M} < 1$. This condition holds if changes in $A_S$ have small impacts on the number of migrants or if climate change has minimal impacts on TFP in the south.

## 5.4 A numerical illustration

In the following, we shall give a numerical illustration by comparing the situation of two developed regions. Consider the north to be either EU-15 (EU) or North America (NAM), which comprises USA and Canada. Will each of these two regions spend more on green technologies or on border controls? In order to address this issue, we do a similar extrapolation exercise as before and choose the following functional forms: $A_S(T) = \frac{A_S}{1+\omega T}$, $T = \mu K_N$, $x = \frac{\bar{x}}{1+a\tau_x Y_N}$, $\mu = \frac{\bar{\mu}}{1+b\tau_\mu Y_N}$. Condition 42 can then be rewritten as

$$\frac{\omega\mu K_N}{1+\omega\mu K_N}\frac{b}{a}\frac{1+a\tau_x Y_N}{1+b\tau_\mu Y_N} = 1-\alpha \tag{44}$$

The aim of the following illustration is to find a tax scheme $\{\tau_x; \tau_\mu\}$ satisfying condition 44. This exercise is performed twice, that is for the cases where the north is represented by either Europe-15 or by North America, and subsequently, we compare the so-obtained tax schemes of either region.

### *5.4.1 Calibration of $\bar{L}_N$, $\bar{L}_S$, and $A_N$*

As in Section 4.5, the structural parameters $\alpha$, $\beta$, and $\rho$ are respectively equal to 0.37, 0.44, and 0.9. The unknown parameters $\omega$, $a$, and $b$ are set (subject to subsequent sensitivity analysis) respectively to 0.045, 0.01, and 0.5. In condition 44, the variables $\mu$, $K_N$, and $Y_N$ are endogenous, while the following variables need to be calibrated: $\bar{L}_S$, $\bar{L}_N$, $\bar{L}_N$, $\bar{A}_S$, $\bar{\mu}$, and $\bar{x}$.

**Table 2** Calibration of exogenous variables

| | $\bar{L}_N$ | $\bar{L}_S$ | $A_N$ | $\bar{\mu}$ | $\bar{x}$ | $\bar{A}_S$ |
|---|---|---|---|---|---|---|
| North=Europe-15 | 0.39 | 5.74 | 8.69 | 0.91 | 0.2197 | 5.04 |
| North=North America | 0.31 | 5.75 | 10.60 | 1.67 | 0.1744 | 5.69 |

Table 2 summarizes the values for these variables, which take on different values whether the north is considered as being Europe-15 (EU) or North America (NAM). Knowing the total population in the south and the number of southern migrants in Europe and North America from the data of Docquier and Marfouk (2006), it is easy to compute the population originating from the south $\bar{L}_S$. According to Docquier and Marfouk (2006), the share of migrants from developing countries in EU and NAM corresponds to 10.13% and 4.9% in 2000. We can thus compute the number of migrants in Europe and North America, as well as $\bar{L}_{\mathrm{EU}}$ and $\bar{L}_{\mathrm{NAM}}$. Then, $\bar{L}_S$ equals around 5.75 billion in 2000 in both cases. The next step is to compute the technology level in the north, $A_N$. Using the data from the WDI (2007), GDP PPP equals $Y_{\mathrm{NAM}} = 10.43$ and $Y_{\mathrm{EU}} = 9.27$ thousands billion in 2000. Following the procedures described in Section 4.5, we obtain $K_{\mathrm{NAM}} = 3.78$ and $K_{\mathrm{EU}} = 3.36$, $A_{\mathrm{NAM}} = 10.6$ and $A_{\mathrm{EU}} = 8.96$, as well as the TFP in the south, which is calculated in the same way, giving $A_S = 4.429$. In the following, we explain the calibration of the last parameters for Europe and North America: $\bar{\mu}$, $\bar{x}$, and $\bar{A}_S$.

### *5.4.2 Calibration of $\bar{\mu}$, $\bar{x}$ and $\bar{A}_S$*

First, we set $\bar{\mu}_{\mathrm{NAM}}$ and $\bar{\mu}_{\mathrm{EU}}$ equal to the observed values for $\mu$. It can be observed that total emissions in North America are twice as much as in EU-15 with respectively $E_{\mathrm{NAM}} = 6.32$ compared to $E_{\mathrm{EU}} = 3.06$ thousand billion tons in 2000. Knowing from Eq. 8 that $\mu = \frac{E}{K_N}$, we obtain the emissions per productive capital ratio $\mu_{\mathrm{NAM}} = 1.67$ and $\mu_{\mathrm{EU}} = 0.91$ for 2000. The parameters $\bar{\mu}_{\mathrm{NAM}}$ and $\bar{\mu}_{\mathrm{EU}}$ are set equal to those values. We thereby assume that these observed values for $\mu$ correspond to a situation without taxes on production ($\tau = 0$). Our analysis will then consist in exploring how the introduction of a tax rate of $\tau > 0$ should be allocated between green technologies and border controls.[13] The observed values for $\mu$ indicate that the production of the EU-15 is much more emissions-saving than the one of NAM. The reason is largely due to the North American climate policy. In fact, it is well-known that the USA and Canada are ranked behind Western European countries in terms of emissions to GDP ratio to carbon dioxide ratio, which is an indicator that represents a major aspect of a composite environmental performance

[13]Alternatively, imposing $\bar{\mu}_{\mathrm{NAM}}$ and $\bar{\mu}_{\mathrm{EU}}$ to be equal to what the data suggest for $\mu$ could be interpreted to reflect a situation where existing taxes on production are implicitly taken into account in the data. Our analysis would then be to focus on how the introduction of an additional tax rate on production should be allocated between border controls and clean technologies.

index developed by the CIESIN center of Yale University; see CIESIN (2006). Second, knowing $\bar{L}_N$, $\bar{L}_S$, $A_N$, and $M$ for Europe and North America, as well as $A_S$, we can compute migration costs as in Section 4.5: $x_{\mathrm{EU}} = 0.2197$ and $x_{\mathrm{NAM}} = 0.1744$. These values indicate that migrants face higher migration costs when migrating to North America than to Europe. Again, considering that these values correspond to a situation without taxes or where existing taxes are implicitly taken into account, we apply these values to $\bar{x}_{\mathrm{EU}}$ and $\bar{x}_{\mathrm{NAM}}$. Finally, since we have $\omega$, $\bar{\mu}$, $K_N$, and $A_S$, we can calculate $\bar{A}_S$ for Europe and North America.

## 6 Results

Given the proposed functional forms for $x$, $\mu$, and $A_S$, the calibrated values for the parameters, and the equations of Section 5 for the endogenous variables $K_N$, $M$, and $Y_N$, the resulting steady state of the model with a production tax rate of 10% will give us the policy mix $\{\tau_x; \tau_\mu\}$ satisfying condition 44 for Europe-15 and North America. The so-obtained tax scheme corresponds to the decision rule of a northern government, which maximizes the utility of northern citizens and which does not internalize the feedback effects of migration on climate change and on the tax base. We obtain that Europe should invest a larger share of its tax revenue in immigration costs than North America ($\tau_x^{\mathrm{EU}} = 67.4\%$ compared to $\tau_x^{\mathrm{NAM}} = 50.16\%$), and correspondingly invest less in green technologies than North America ($\tau_\mu^{\mathrm{EU}} = 32.6\%$ compared to $\tau_\mu^{\mathrm{NAM}} = 49.84\%$). An explanation of these findings is that North America has a more emission-intensive production and higher border controls than Europe. Thus, compared to Europe, it would be optimal to invest a larger share of its revenue in green technologies and less in border controls.

The results of this exercise should obviously—like any calibration exercise with unknown parameters—be approached with care. The conclusions rest solely on a per capita utilitarian approach, neglecting any other ethical or political dimensions. We used a rather stylized model and did not account for other reasons to migrate (like wars), which could lead to different policy decisions. However, our findings are informative about how a region should choose its optimal tax revenues when needing to allocate these between green technologies and border controls (or anything else that affects subjective migration costs).

## 7 Conclusion

In this article, we investigate the relationship between climate change and international migration. We make use of a two-regions, overlapping-generations model similar to that of Galor (1986), but we allow for climate change to affect the productivity in the south.

Our main findings are that climate change will most likely increase world migration and that even small changes in its impact can imply significant changes in the amount of migrants in the long run. A simple calibration exercise suggests that the number of migrants increases by a factor of four if climate change reduces southern productivity by approximately 5%. However, from our empirical overview in the first part of this paper, it is very likely that the reduction in southern productivity will exceed 5% in the future. Thus, it goes without saying that migration is expected to re-shape world orders if it is not properly guided by international policies.

We then analyze what effect a softer immigration policy and investment in greener technology might have on the long-run number of migrants, on the environment, and on north–south inequality. Both policies could be undertaken for different reasons. Whereas we interpret the softer immigration policy as an aftercare policy that makes the north take responsibility for the effects of climate change, which it itself imposed upon the south, the investment in greener technology may be understood as a precautionary or preventive policy. We show that the immigration policy clearly increases the number of migrants but worsens climate change and has an ambiguous effect on north–south inequality. Investment in greener technology leads to fewer long-run migrants, a better environment, but, again, an ambiguous sign for the inequality measure. It is therefore clear that any policy undertaken by the north will depend on the importance that the north places upon the displacement of people, climate change, or inequality. Importantly, the qualitative results do not depend on whether the costs of the policies are sunk in the future or whether the policies incur continuous costs. With a numerical example, we show that the USA, compared with the EU, should invest more of its tax revenues in green technologies and less in border controls, a result that stems from the differences in production technologies and existing immigration policies.

There are many extensions that this model could see. Firstly, it should be interesting to analyze the short-run migration decisions and compare these to the long-run choices. Since we know that a policy that has positive effects in the long-run might have significant costs in the short-run, it can be important to compare the costs and benefits of both. Furthermore, though in the long-run this is clearly unimportant, in the short-run, we could see significant impacts of population growth. Including this in this model is, however, a challenging task.

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