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Soheil Shayegh and Greg P. Casey

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By Soheil Shayegh, Fondazione Eni Enrico Mattei (FEEM)
Greg P. Casey, Institute at Brown for Environment and Society, Brown University

Summary

We examine the effect of climate change on fertility rates and human capital accumulation in developing countries, focusing on the instrumental role of migration. In particular, we investigate how climate-induced migration in developing countries will affect those who do not migrate. Holding all else constant, climate shocks raise the return to acquiring skills, because skilled individuals compared to unskilled ones have greater opportunity to migrate after the shock. In response to this change in incentives, parents choose to invest more in education and have less children, a process known as the 'quantity-quality' trade-off. These effects partially offset the damages of climate change, even for those who do not migrate.

Keywords: Migration, Climate Change, Fertility, Population, Wage, Quantity-quality Tradeoff

JEL Classification: F22

Address for correspondence:
Soheil Shayegh
Fondazione Eni Enrico Mattei
Corso Magenta, 63
20123 Milano
Italy
E-mail: soheil.shayegh@feem.it

To go or not to go: migration alleviates climate damages even for those who stay behind

Soheil Shayegh*[1] and Greg P. Casey[2]

[1]Fondazione Eni Enrico Mattei (FEEM), Milan, Italy
[2]Institute at Brown for Environment and Society, Brown University, USA

We examine the effect of climate change on fertility rates and human capital accumulation in developing countries, focusing on the instrumental role of migration. In particular, we investigate how climate-induced migration in developing countries will affect those who do not migrate. Holding all else constant, climate shocks raise the return to acquiring skills, because skilled individuals compared to unskilled ones have greater opportunity to migrate after the shock. In response to this change in incentives, parents choose to invest more in education and have less children, a process known as the 'quantity-quality' trade-off. These effects partially offset the damages of climate change, even for those who do not migrate.

Despite the fact that demography is a primary driver of climate change (Raupach et al., 2007; O'Neill et al., 2012), very little is known about how climate change will affect demography (Casey et al., 2017). The climate-to-population feedback, however, could have substantial consequences. First, by ignoring demographic outcomes, the existing literature only captures some of the dimensions through which climate change will affect human well-being. Second, the climate-to-population feedback – like feedbacks in the natural system – affect the likelihood that the earth will experience extreme increases global temperature. In this paper, we examine the effect of climate change on fertility rates and human capital accumulation in developing countries, focusing on the instrumental role of migration. We find that migration significantly lessens the negative demographic impacts of climate change and also decreases inequality. We focus on the effects among those who do not migrate. This mechanism is distinct from those found in existing work.

Climate damages have two competing impacts of the potential for migration in developing countries. By disproportionately harming developing countries, climate change increases the motivation to emigrate (Desmet and Rossi-Hansberg, 2015). Conversely, negative climate shocks leave poor and agricultural workers unable to afford emigration (Black et al., 2011; Cattaneo and Peri, 2016). Through this mechanism, climate shocks in poor countries raise the return to education by differentially affecting the migration prospects of skilled and unskilled individuals. Moreover empirical evidence demonstrates that human capital accumulation responds to incentives created by migration (Beine et al., 2001, 2008). Thus, climate change is likely to raise human capital accumulation via this migration channel, partially offsetting the direct negative impacts climate damages.

This migration channel will also affect fertility, which is closely linked to human capital accumulation. Parents have limited resources to devote to raising children. Thus, they face a trade-off between having more children and investing more in the education of each child. As a result, when parents are induced to invest more in the education of their children - for example, when responding to climate shocks - they also tend to lower fertility (Becker, 1960; Galor, 2011). There is substantial evidence in economics for the existence of this quantity-quality (Q-Q) trade-off (Bleakley and Lange, 2009; Aaronson et al., 2014). Thus, the migration channel may also lessen direct climate damages by decreasing the fertility rate.

Climate change will also affect inequality via this migration channel. Counterintuitively, the differential improvement in migration prospects for high-skilled individuals leads to lower inequality for those who remain in the sending country. When parents undertake the Q-Q trade-off, they

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*soheil.shayegh@feem.it.

consider potential wages with and without migration. When the high skilled individuals have increased ability to migrate, therefore, parents are willing to invest in child education at lower domestic rates of return. Thus, for those who do not end up migrating, wages between skilled and unskilled individuals become more similar as a result of climate change. Again, this can partially offset the tendency for climate change to disproportionately harm unskilled and low-income individuals (Wheeler and Von Braun, 2013; IPCC, 2014).

We build a dynamic general equilibrium model with endogenous fertility and human capital decisions. In our main quantitative results, we compare the effects of climate change on economic outcomes with and without the potential for migration. In doing so, we demonstrate the role that migration plays in mitigating the negative effects of climate change. In particular, we find that the potential of migration lowers the fertility rate and increases the number of children receiving an education, when compared to a world without climate change. The increase in skilled children almost fully offsets the increased number of skilled individuals who migrate, leaving the skill composition of remaining workers virtually unchanged. The net effect on income per capita of remaining people is also very small. Thus, the mitigating impacts of migration responses occur at the level of individuals, implying that most of the benefit of migration still accrues to those who can leave. Without endogenous migration responses, climate change greatly increases inequality, but the endogenous response significantly mitigates this effect. Even after considering this response, however, inequality increases as a result of climate change.

The existing literature on the demographic impacts of climate change generally focused on biological impacts of heat on mortality and fertility(Deschenes, 2014; Barreca et al., 2015). By contrast, we focus on the potential for climate change to impact demographic outcomes via altering economic incentives. To the best of our knowledge, only one existing paper examines such mechanisms and only considers closed economies (Casey et al., 2017). Thus, we build on this literature by considering the role of migration. Of course, a substantial literature focuses on the role of migration in mitigating the damages of climate change (Black et al., 2011; Cattaneo and Peri, 2016; Desmet and Rossi-Hansberg, 2015). This literature, however, focuses on the reallocation of people from more to less vulnerable locations on the planet. We contribute to this literature by considering how migration can mitigate the negative consequences of climate change via demography, rather than the movement of people alone.

Model

We build an overlapping generations (OLG) model with endogenous fertility. The supplementary information appendix contains the key equations for our economic model and the solution method for our approach. In this model, individuals live through two stages of life. In the first stage, they are children who consume parental time. In the second stage, they work, consume goods, and raise children. Parents have preferences over the lifetime income of their children. Skilled children have higher earnings, but also require more parental investment, capturing the quantity-quality trade-off.

We are interested in how migration affects fertility and human capital decisions and, in particular, how the potential for migration alters the effects of climate change. At the beginning of adulthood, each person has an exogenous probability of migration. Every individual has incentive to migrate, so we treat this exogenous probability as a reduced-form stand-in for the complicated array of costs and benefits that go into migration. In future work, we plan to endogenize this probability. Parents take into account this probability when deciding whether to have skilled or unskilled children.

We are interested in how climate change alters the probability of migration from developing to developed countries. Existing research finds two common facts (Black et al., 2011; Cattaneo and Peri, 2016). First, climate shocks increase the incentive to migrate. At the same time, these negative shocks make it more difficult to poor individuals to migrate because of liquidity constraints. We capture these two competing effects in a simple reduced form manner. When temperature increases, high-skill (i.e., richer) individuals have an increased migration probability, while low-skill (i.e., poorer) individuals) have a decreased migration probability. Again, endogenizing these probabilities is a priority for future work.

When temperatures increase, therefore, the relative return to skill increases, holding all else equal. This occurs because skilled individuals have an increased probability of migrating to the more productive country, while poorer individuals have a decreased probability of migration. Thus, temperature increase induce parents to substitute towards child quality and have fewer children. This positive demographic response partially offsets the damages from climate change. Moreover, since the higher return to skill is coming from the increase potential to migrate, parents are willing to invest in education at lower domestic returns. Thus, inequality between skilled and unskilled individuals is also reduced by the migration channel, holding all else constant.

While the focus of our model is on migration, we build a complete dynamic general equilibrium model. Our underlying model of production follows Casey et al. (2017). In particular, we employ a two-sector model of structural transformation. There are two types of goods, agricultural and manufacturing. Existing research like Caselli and Coleman (2001) and Gollin et al. (2014) show that agriculture uses substantially less skilled labor. To simplify the analysis, we assume manufacturing work uses only skilled labor and agricultural work uses only unskilled labor. There is a low substitutability between the two types of goods, implying that workers reallocate towards more damaged sectors after a climate shock. Our specification for climate damages come from Desmet and Rossi-Hansberg (2015).

Casey et al. (2017) use this model to investigate the demographic impacts of climate change in a closed economy. We take their analysis with an exogenous and unchanging migration probability as a baseline case from which to compare our results. In particular, we examine the effects of exogenous differences in emission scenarios, given by Representative Concentration Pathways (RCPs) as described in (Van Vuuren et al., 2011; Meinshausen et al., 2011), on fertility and education decisions. In our model, we find the perfect foresight equilibrium, as is standard in the climate change economics literature. Thus, damages from climate change are anticipated and fertility responds before the damage occurs. We assume that technological progress and global temperature can be taken as exogenous variables.

While we focus on results in the sending country, we also simulate a receiving country, which is necessary to determine the wages for those who migrate. We choose data from a poor region (Africa) and a rich region (west Europe) to calibrate and validate our model. We choose parameters to match demographic projections for both regions. Historical data indicates a constant flow of migrants from Africa to Europe and in particular to western European countries which fits our criteria of a receiving economy that is more developed than the sending countries. Despite its simple nature, our model can recreate the existing demographic projections for both regions. The model fit for the sending region is evaluated in the left panel in Figure 1, and the details of the calibration procedure are discussed in the supplementary information. The impacts of climate change on relative productivity in the sending region is represented on the right panel in Figure 1. As we move to higher RCP scenarios the relative productivity of agricultural sector compared to industrial sector decreases.

Results

To analyze the potential affects of climate change on human capital via emigration from the sending region, we examine the outcomes in this region under four different RCPs as described in Moss et al. (2010). Figure 2 presents the global carbon concentrations and temperatures for the sending region under different RCPs.

It is important to note that throughout our analysis We assume that climate change and its impacts are exogenous to the economies under investigation. In other words, we are not investigate long term climate policies that may alter or reverse the course of climate change and temperature increase in our model. By developing two models of migration (one climate-independent and the other one climate-dependent), we hope to quantify the impact of climate change-induced migration on the sending economy. While our model is quantitative, our primary goal is to provide evidence for our qualitative conclusions.

Figure 3 examines the effect of climate change on economic and demographic outcomes in our model for three RCP scenarios[1]. We analyze and compare two cases of migration regimes here.

First, we assume that the migration probability is constant and independent of climate. In this case, parents in the sending region are taking into account a constant probability child migration. Hence, the decisions on the number of children and their education level will be taken given migration probabilities. The baseline is defined as a case without climate change in the future but with the fixed migration rate from the sending to receiving economy.

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[1] We have not included the RCP 2.6 scenario here since the climate change impacts are minimum and hard to distinguish from the baseline scenario without climate change.

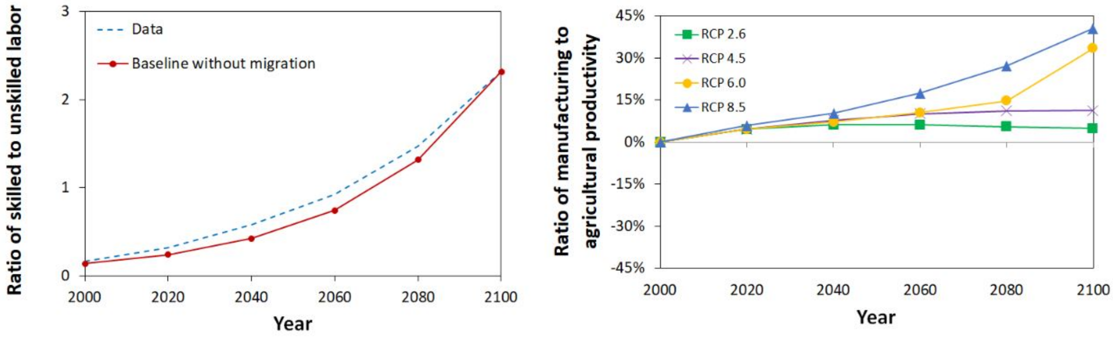

Figure 1: Comparison of the baseline model with the forecast data for Africa based on Lutz et al. (2014) (left panel). The ratio of manufacturing productivity to agricultural productivity under different RCP scenarios (right panel).

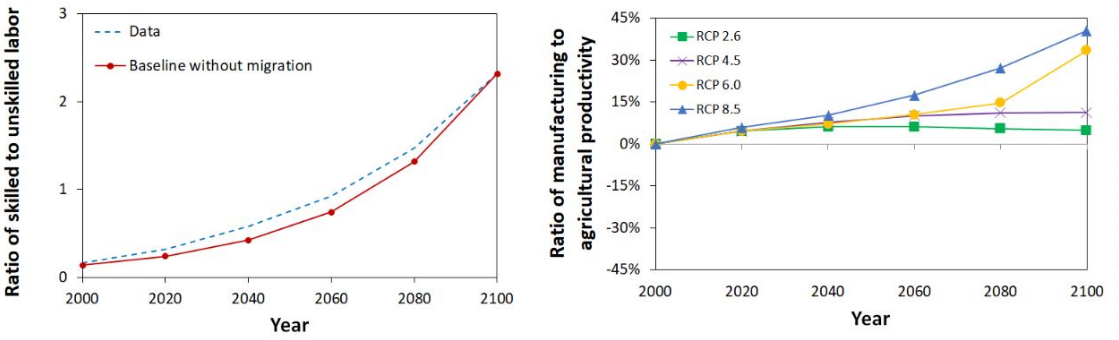

Figure 2: Climate characteristics of the four RCP scenarios. The left panel shows atmospheric CO_2 loadings in GtC from the RCPs from Moss et al. (2010). The right panel shows global mean temperatures projected from combining the RCPs with climate dynamics in Desmet and Rossi-Hansberg (2015). The global temperature data is then combined again with the climate dynamics in Desmet and Rossi-Hansberg (2015) to yield latitude-specific temperatures for Africa. These local temperatures, are used as inputs in our analysis.

Second, we assume that the migration rate is a function of temperature in the sending economy. This is based on the empirical evidence presented in Cattaneo and Peri (2016). We compare the results of this scenario along with the results of the first scenario where the migration rate is fixed. All results are presented as percentage change from the baseline case.

We start by considering the first row, which examines the migration probability for the climate-dependent case across different DRC scenarios. The left column shows how this probability is changing for each type of children under RCP 4.5 temperature trajectory. While the migration probability of skilled labor is increasing by about 15% the migration probability of unskilled labor decreases by about 45%, making it very hard for people with lower education to migrate. Similar pattern can be detected in higher RCP scenarios where the divergence from the baseline is even more intensified. The middle column investigate the migration probabilities under the RCP 6.0 scenario and the right column represents the migration probabilities under the RCP 8.5 scenario. In the extreme climate conditions under RCP 8.5, the migration probability of skilled labor increases by about 45% while it falls by more than 80% for unskilled labor.

In all RCP scenarios, the increase in temperature caused by increasing carbon concentrations decreases the relative productivity of agriculture, as shown in the right panel of Figure (2). This increases the wages in the agricultural sector due to the low substitutability between consumption goods. Since agricultural production uses unskilled workers, this lowers the return to acquiring skills and raises the benefit of having unskilled children. Since unskilled children cost less parental time, parents end up having more children with lower education.

The second and the third rows are showing this effect by comparing the ratio of skilled to unskilled children (second row) and labor (third row) Under two cases of climate-dependent migration and climate-independent migration across different RCP scenarios. Climate change induced migration reduces the skilled to unskilled ratio in a smaller pace than climate-independent migration does. For example, under RCP 8.5 the skilled to unskilled ratio of children falls by about 9% in climate-dependent case whereas it reduces by more than 15% in climate-independent case. However, such disparity is less profound among adult population. While under RCP 8.5 scenario, the ratio of skilled to unskilled labor falls by similar 9% in the climate-dependent migration case, it falls only by 10% in climate-independent case.

The fourth row examines the effects of climate change on inequality in the sending region measured by the wage ratio of skilled to unskilled labor. The effects of climate change on wage ratio differ substantially between the two cases of migration. While the overall picture indicates that under all RCP scenarios, migration in general is helping to close the wage gap, the climate-dependent migration demonstrate a far effective way to achieve this goal. Under the RCP 6.0 scenario for example, the wage ratio shrinks by 3% in the climate-dependent migration case while it reduces by less than 1% in the climate-independent case.

The fifth row is dedicated to the total number of children per adult. The graphs in this row show the change in population growth rate from the baseline case without climate change. When we allow for climate change, the fertility rates increase in response to climate damages to the agricultural sector and increase in return to unskilled labor. However and in all RCP scenarios, climate-dependent migration increases fertility rate in a slower pace than climate-independent migration does. While fertility rate increase by 2% under RCp 8.5 in the climate-independent migration case, it goes up only by about 1% in the climate-dependent migration case.

In the last row, we examine the change in output per capita across different RCP scenarios. As in the other rows, the effects of temperature are more extreme at higher RCP scenarios. Output per capita in the sending region is decreasing as more skilled people are immigrating to the receiving region. However, the discrepancy between two cases of migration (climate-dependent and climate-independent) is much smaller. In both cases the output per capita decreases by more than 20% under RCP 8.5 scenario.

Discussion and conclusion

We examine how climate-induced migration can influence economic and demographic outcomes for non-migrants in developing countries. In response to climate shocks, high-skill individuals have an increased probability of migration, while low-skill individuals have a decreased probability. This occurs because climate shocks have two conflicting effects: they increase the incentive to migrate but also lower incomes, leaving poorer individuals without sufficient funds to relocate. The differential effect of climate shocks on migration opportunities raises the relative return to acquiring skills. This, in turn, will induce parents to spend more resources on children's education and therefore, have fewer children. Also, since parents will be more willing to invest in education, the wage gap between skilled and unskilled individuals in the sending country will decrease, closing the inequality gap between these two populations.

Our results demonstrate the potential for migration to alleviate the negative economic and demographic impacts of climate change. A large existing literature focuses on the role of migration in lessening such negative effects by moving people from one country to another (Black et al., 2011; Desmet and Rossi-Hansberg, 2015). To the best of our knowledge, we are the first to examine the effect of migration on demographic outcomes, specifically fertility and human capital accumulation. Moreover, we focus on the well-being of those who remain in the sending country. Thus, our study adds new insight into the role of migration in climate change adaptation.

More generally, our work contributes to the very small but important literature examining the demographic impacts of climate change (Barreca et al., 2015; Casey et al., 2017). This literature is important for two key reasons. First, by ignoring demographic outcomes, the existing literature only captures some of the dimensions through which climate change will affect human well-being. Second, the climate-to-population feedback – like feedbacks in the natural system – affect the likelihood that the earth will experience extreme increases global temperature. Existing work treats such demographic factors as exogenous or excludes them altogether, abstracting from this important feedback mechanism.

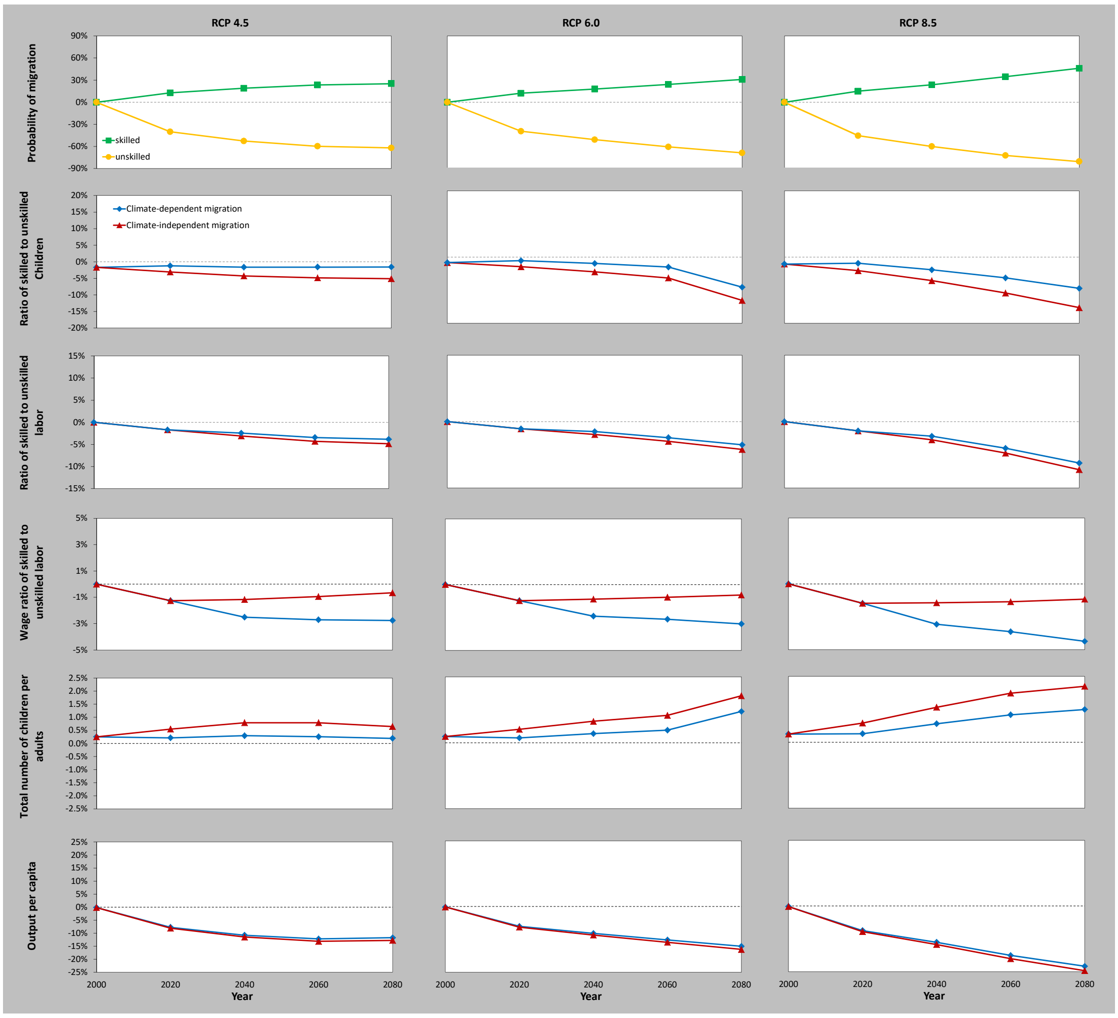

Figure 3: Results from the three RCP scenarios for two cases of climate-dependent and climate-independent migration as percentage change compared to the baseline. The baseline scenario assumes a constant climate with a constant migration rate. The columns present the RCP scenarios.

In most approaches to climate change economics, individuals passively react to damages inflicted by climate change (Nordhaus and Boyer, 2003; Golosov et al., 2014). Yet, there are solid reasons to believe that climate change may influence individual behavior in substantial ways. We have focused on demographic decisions and hope that our work will spur further research in this direction. Recent evidence from the field of economic growth suggests that three factors - human capital, population, and technology - drive long-term economic outcomes (Jones and Romer, 2010). Thus, examining how climate change interacts with these factors is of first-order importance to establishing how climate change will affect human well-being. We have taken steps in this direction by investigating two components, human capital and population.

Methods

Our model builds on the standard overlapping generation (OLG) framework (Diamond, 1965; Galor, 2011). In our model, individuals can reside in two countries (country I and country II). They live for 2 periods and can be skilled (s) or unskilled (u). For the first period of life, individuals are children who make no decisions and consume only parental time. In the second period of life, individuals will be assigned to their country of residency (i.e. either to stay where their parents are or to immigrate to the other country) at the beginning of their adulthood period. Wherever they live, they will work, consume goods, and have children for the next period of their life. Individuals make consumption and fertility decisions to maximize lifetime utility. In the empirical application, we use period lengths of 20 years.

Preferences

The adult utility function nests two components. The outer nest is given by:

$$v(c_t, n_t^s, n_t^u) = (1-\gamma)ln(c_t) + \gamma\mathbf{E}\big[ln(n_t^s w_{t+1}^s + n_t^u w_{t+1}^u)\big], \tag{1}$$

where n_t^j, $j = u, s$ is the number of children of skill level j, c_t is consumption of a bundle of physical goods, and $\mathbf{E}$ is the expected utility from the future wages of children. In other words, parents have preferences over own consumption and the expected lifetime earnings of their children depending on where the children will earn their income. We assume two cases for calculating migration rate. First, we assume that the probability of a child of skill level j to migrate from country 1 to country 2 as an adult is a function of the current temperature in the sending country 1 (climate-dependent migration):

$$\beta_{12}^j = \exp(\eta_j + \Psi_j \times \log(T_1)), \tag{2}$$

where η_j and Ψ_j are the coefficients from the empirical studies by Cattaneo and Peri (2016). In the second case (climate-independent migration), we fix the temperature T_1 at its current level for all the modeling horizon.

The expected utility from the wage of a child of skill level j is therefore calculated as

$$\begin{aligned} &\mathbf{E}\big[ln(n_t^s w_{t+1}^s + n_t^u w_{t+1}^u)\big] = \\ &\quad \beta_{12}^s \beta_{12}^u ln(n_t^s w_{t+1}^{2,s} + n_t^u w_{t+1}^{2,u}) \\ &\quad + (1-\beta_{12}^s)\beta_{12}^u ln(n_t^s w_{t+1}^{1,s} + n_t^u w_{t+1}^{2,u}) \\ &\quad + \beta_{12}^s(1-\beta_{12}^u) ln(n_t^s w_{t+1}^{2,s} + n_t^u w_{t+1}^{1,u}) \\ &\quad + (1-\beta_{12}^s)(1-\beta_{12}^u) ln(n_t^s w_{t+1}^{1,s} + n_t^u w_{t+1}^{1,u}), \end{aligned} \tag{3}$$

where $w_{t+1}^{i,j}$ is the future wage of a child of skill level j in country i. For simplicity of the equations, we will use country indices only when it is necessary to emphasis the difference between two countries. Children consume only parental time Galor (2011). In particular, a child of type j consumes τ^j units of time. The child rearing costs are different for children with different skill levels in different countries. We normalize the price index of the consumption composite to one. Thus, the budget constraint corresponding to (1) for every adult in each country is given by:

$$c_t = [1 - \tau^u n_t^u - \tau^s n_t^s] w_t. \tag{4}$$

The maximization of (1) subject to (4) yields:

$$\begin{aligned} c_t &= (1-\gamma) w_t \\ \tau^u n_t^u + \tau^s n_t^s &= \gamma. \end{aligned} \tag{5}$$

Equation (5) encapsulates the quantity-quality trade-off. Because $\tau^s > \tau^u$ and the total time devoted to raising children is fixed, individuals must decide between investing in higher skilled children – who will earn more income – and having a greater number of total children.

Also, for individuals in country 1 to have both types of children, it must be the case that:

$$\frac{\tau^{1,s}}{\tau^{1,u}} = \frac{\displaystyle\sum_{i\in\{1,2\}} \left(\beta_{1i}^s \sum_{j\in\{1,2\}} \frac{\beta_{1j}^u w_{t+1}^{i,s}}{n_t^s w_{t+1}^{i,s} + n_t^u w_{t+1}^{j,u}}\right)}{\displaystyle\sum_{i\in\{1,2\}} \left(\beta_{1i}^u \sum_{j\in\{1,2\}} \frac{\beta_{1j}^s w_{t+1}^{i,u}}{n_t^s w_{t+1}^{j,s} + n_t^u w_{t+1}^{i,u}}\right)}, \tag{6}$$

and since we do not allow for migration from country 2 to 1 in this model, for individuals in country 2 to have both types of children, we must have:

$$\frac{\tau^{2,s}}{\tau^{2,u}} = \frac{w_{t+1}^{2,s}}{w_{t+1}^{2,u}}. \tag{7}$$

As in any investment decision, individuals make decisions to equate relative marginal benefits and relative marginal costs. If this equation did not hold, parents would have only a single type of child. Under the assumptions of our model, this situation never occurs in equilibrium.

Consumption

The inner level of utility is a constant elasticity of substitution (CES) function given by:

$$c = \{\alpha(c_a^k)^{\frac{\epsilon-1}{\epsilon}} + (1-\alpha)(c_m^k)^{\frac{\epsilon-1}{\epsilon}}\}^{\frac{\epsilon}{\epsilon-1}}, \tag{8}$$

where ϵ is the elasticity of substitution, c_a is consumption of the agricultural good, c_m is consumption of the manufacturing good, and the time subscripts have been suppressed for convenience. As ϵ approaches zero, consumers get less satisfaction from substituting manufacturing goods for agricultural goods. In the limit, there is no substitution and the goods are consumed in fixed proportions.

Climate and Damages

To analyze the effect of carbon concentrations in our model, we combine data on the RCPs Moss et al. (2010) with the simplified climate model of Desmet and Rossi-Hansberg Desmet and Rossi-Hansberg (2015). We calculate the temperature given the latitude and carbon concentration as follows:

$$T(l,t) = T(l,0) + \nu_1 P(t)^{\nu_2}(1 - \nu_3 T(l,0)), \tag{9}$$

where $T(l,t)$ is the temperature at latitude l at time t, $P(t)$ is the carbon concentration, and ν_j is a constant for $j = 1,2,3$. Specifically, $\nu_1 = 0.21$, $\nu_2 = 0.5$ and $\nu_3 = 0.0238$. Based on the temperature, we then calculate sector specific impact function:

$$D^k(T) = max\{g_{k,0} + g_{k,1}T + g_{k,2}T^2, 0\},\ k = a, m, \tag{10}$$

where $g_{m,0} = 0.3$, $g_{m,1} = 0.08$ $g_{m,2} = -0.0023$, $g_{a,0} = -2.24$, $g_{a,1} = 0.308$, and $g_{a,2} = -0.0073$.

Production

There are two sectors, agriculture (a) and manufacturing (m). We adopt a linear production functions that captures the fact that agricultural production is relatively less skill-intensive Caselli and Coleman (2001); Gollin et al. (2014). Specifically,

$$\begin{aligned} Y_m &= D^m(T)A_m H \quad (11) \\ Y_a &= D^a(T)A_a L, \quad (12) \end{aligned}$$

where Y_j, $j = a, m$ is output in sector j, H and L are total skilled and unskilled labor, respectively, A_j is productivity in sector j, and $D^j(T)$ is the climate impact function for sector j at temperature T.

Technological progress evolves exogenously according to:

$$A_{k,t} = (1 + g_k)A_{k,t-1},\ k = a, m. \tag{13}$$

Total skilled and skilled workers are calculated by taking into account the possibility of labor movement to and from the country of interest. For example for country I we have:

$$\begin{aligned} H^I &= n_t^{I,s} N_t^I (1 - \beta^s_{I\to II}) + n_t^{II,s} N_t^{II} \beta^s_{II\to I} \quad (14) \\ L^I &= n_t^{I,u} N_t^I (1 - \beta^u_{I\to II}) + n_t^{II,u} N_t^{II} \beta^u_{II\to I}, \quad (15) \end{aligned}$$

Similarly for country II we have:

$$\begin{aligned} H^{II} &= n_t^{II,s} N_t^{II} (1 - \beta^s_{II\to I}) + n_t^{I,s} N_t^I \beta^s_{I\to II} \quad (16) \\ L^{II} &= n_t^{II,u} N_t^{II} (1 - \beta^u_{II\to I}) + n_t^{I,u} N_t^I \beta^u_{I\to II}, \quad (17) \end{aligned}$$

where N_t^I and N_t^{II} are adult populations in country I and country II at time t. The consumption of manufacturing and agricultural goods in country I by adults of each skill level is calculated by following equations:

$$\begin{aligned} c_m^{I,u} &= \frac{Y_m^I}{H^I \frac{\tau^{I,s}}{\tau^{I,u}} + L^I} \quad (18) \\ c_a^{I,u} &= c_m^{I,u} \frac{\tau^{I,s}}{\tau^{I,u}}. \quad (19) \end{aligned}$$

Equilibrium

Combining individual maximization and production yields the following equilibrium result for each country:

$$
\begin{aligned}
ln\left(\frac{w^s_{t+1}}{w^u_{t+1}}\right) = ln\left(\frac{1-\alpha}{\alpha}\right) - \frac{1}{\epsilon}ln\left(\frac{H}{L}\right) - \frac{1-\epsilon}{\epsilon}ln\left(\frac{D^m(T)}{D^a(T)}\right) \\
- \frac{1-\epsilon}{\epsilon}ln\left(\frac{A_m}{A_a}\right).
\end{aligned}
\tag{20}
$$

At each time period the parents in both countries solving this equation simultaneously taking into account the actions of the adults in the other country. The Nash equilibrium generates the optimal number of children of each skill level in each country. If an increase in temperature negatively affects agriculture more than manufacturing, then the ratio $ln\big(\frac{D^m(T)}{D^a(T)}\big)$ is an increasing function of temperature T. If $\epsilon < 1$ (i.e., the substitution between goods is sufficiently low), then the relative wages of skilled individuals decrease as a result of these climate damages. Without migration, this raises the relative return to working in agriculture, causing parents to have relatively more unskilled children. Thus, total fertility increases following equation (5). However, when migration possibility is taken into account, there will be a parallel movement of human capital between two countries from the country with lower wages to the one with higher wages. The interaction of these two inter- and intra- country movements defines the optimal level of population at end of each period.

This result is reminiscent of the literature on directed technical change (DTC) Acemoglu (2002). The DTC literature focuses on the endogenous technological change resulting from exogenous changes in production inputs. Here, we are considering the opposite effect of endogenously changing inputs as a result of exogenous shocks to relative productivities.

Solving the Model

The model emits a simple computational solution, where a series of dynamic equations can be solved in order. First, given the carbon concentrations and latitude, we calculate the temperature and damage functions using equations (9) and (10). Next, we calculate the exogenous component of technology using equation (13).

All of the economic decisions are captured by equation (20), which can now be solved for the ratio of skilled to unskilled individuals in every period. We can then solve for the level of the population such that total parenting costs are equal to γ. Again, this can be found starting in the first period and working forward.

Calibration

External Parameters

We take several parameter values from Desmet and Rossi-Hansberg (Desmet and Rossi-Hansberg, 2015). First, we take $\epsilon = 0.5$ and $\alpha = 0.55/2$. We also take the temperature and impact functions as described above.

We normalize the total time spent on raising children to 50% of total adult time. This assumption does not affect our results since the time cost of raising children is calibrated relative to total time spent parenting. We take the path of carbon emissions (an input into the temperature functions) from the RCPs Moss et al. (2010).

Calibration of remaining parameters

We calibrate the model to find the ratio of productivities in the beginning and end years, 2000 and 2100, as well as τ^s, τ^u, g_m, and g_a. To do so, we use historical and projected population data from the Wittgenstein Centre Lutz et al. (2014). We treat anyone with a high school education as skilled.

We start by calculating the projected population growth rate for years 2000 and 2100 from the historical and forecast data. We refer to these growth rates as r_{2000} and r_{2100} below. We also use the data to calculate the ratio of skilld to unskilled adults in each period, h_{2000} and h_{2100}. We denote $\tau_r = \frac{\tau^s}{\tau^u}$. Since we know that total time spent raising children is equal to γ, we use the data to solve the following two equations to obtain the time cost of raising children, (τ^u) and (τ^s):

$$\tau^u = \gamma \frac{1 + h_{2000}}{(1 + r_{2000})(1 + h_{2000}\tau_r)}, \tag{21}$$

$$\tau^u = \gamma \frac{1 + h_{2100}}{(1 + r_{2100})(1 + h_{2100}\tau_r)}. \tag{22}$$

Next, we use equation (20) to solve for the ratio of the initial and final technology levels, $\frac{A_{m,2000}}{A_{a,2000}}$ and $\frac{A_{m,2100}}{A_{a,2100}}$.

Finally, we find the technology growth rates. By assumption, the growth rate of $\frac{A_m}{A_a}$ is constant:

$$\frac{A_{m,2100}}{A_{a,2100}} = (1 + g_r)^{\frac{(2100-2000)}{20}} \frac{A_{m,2000}}{A_{a,2000}}, \tag{23}$$

where g_r is the growth rate of the technology ratio. It is also the only unknown variable in this equation and is now observable. Also,

$$1 + g_r = \frac{1 + g_m}{1 + g_a}, \tag{24}$$

where g_m is the growth rate of A_m and g_a is the growth rate of A_a. Noting that large developed countries, which have nearly all production in manufacturing, grow at 2% per year (a very common approximation), we set $g_m = 0.02$ per year for the receiving region and $g_m = 0.0$ for the sending region. Now, g_a can be extracted from equation (24).

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Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02.520.36934
Fax. +39.02.520.36946

E-mail: letter@feem.it
www.feem.it

Fondazione Eni
Enrico Mattei