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Outward migration may alter population dynamics and income inequality

Soheil Shayegh*

Climate change impacts may drive affected populations to migrate. However, migration decisions in response to climate change could have broader effects on population dynamics in affected regions. Here, I model the effect of climate change on fertility rates, income inequality, and human capital accumulation in developing countries, focusing on the instrumental role of migration as a key adaptation mechanism. In particular, I investigate how climate-induced migration in developing countries will affect those who do not migrate. I find that holding all else constant, climate change raises the return on acquiring skills, because skilled individuals have greater migration opportunities than unskilled individuals. In response to this change in incentives, parents may choose to invest more in education and have fewer children. This may ultimately reduce local income inequality, partially offsetting some of the damages of climate change for low-income individuals who do not migrate.

Migration is an important adaptation mechanism against negative outcomes of climate change[1,2]. Long-term climate change impacts such as ongoing sea-level rise[3,4] or global mean temperature rise[5] can increase the vulnerability of affected populations and push them to displace in search of better living conditions[6]. The relationship between population dynamics and climate change is, however, a two-way avenue[7,8]. Although demography is a primary driver of climate change[9,10], very little is known about how climate change will affect demography. The climate-to-population feedback in the form of migration may have profound consequences for both sending and receiving regions[5]. Furthermore, the climate-to-population feedback—like feedbacks in the natural system—can affect the likelihood of extreme climate events.

Migration, like many other adaptation strategies, is a local decision that is made at household level to diversify environmental risks within a broader economic context[11]. Therefore, migration decisions 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 change—they also tend to lower fertility[12,13]. There is substantial evidence in economics for the existence of this quantity–quality (Q–Q) trade-off[14–16]. The Q–Q trade-off is based on the assumption that fertility is an economic decision made by individuals who are trying to maximize their utility of consumption. There are other theories that place greater emphasis on the supply side of the fertility decision, focusing on the role of birth control and family planning programs in reducing fertility rates, especially in developing countries[17,18]. In this paper, however, I focus only on the demand side of the fertility and migration decisions to show how the migration channel can also lessen climate damages by decreasing the fertility rate.

Although many studies that have investigated the impact of natural disasters on migration flows have found little evidence to support the direct impact of climate change on mass migration[19,20], they have highlighted two important factors that contribute to possible climate-induced migration: the indirect effect of climate change on migration through income inequality, and the fact that migration rates are significantly different between different income groups. Whereas residents of middle-income countries have higher probability of migration, climate change leaves poor and agricultural workers unable to afford emigration[6,21,22]. Through this mechanism, climate change in poor countries raises the return on 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[23,24]. Thus, climate change is likely to raise human capital accumulation via this migration channel, partially offsetting the negative impacts of climate damages.

The existing literature on the demographic impacts of climate change has generally focused on biological impacts of heat on mortality and fertility[25,26]. By contrast, I focus on the potential for climate change to impact demographic outcomes via altering economic incentives for migration. Of course, a substantial literature focuses on the role of migration in mitigating the damages of climate change[6,21,27]. This literature, however, focuses on the reallocation of people from more vulnerable to less vulnerable locations on the planet. I consider how migration can mitigate the negative consequences of climate change via demography, rather than the movement of people alone.

The results of my research indicate that a higher rate of migration among high-skilled individuals motivates parents to invest in child education at lower domestic rates of return. Thus, for those who do not end up migrating, local income inequality, measured by the wage gap between skilled and unskilled individuals in the sending region, is reduced as a result of climate change. This can partially offset the tendency for climate change to disproportionately harm unskilled and low-income individuals. I have limited the scope of this research to only the sending region and, therefore, I do not investigate the impact of migration on domestic income inequality in the receiving region, which is a topic of a very long and controversial debate among economists and political scientists[28–30].

Integrated model of climate change and migration

I build an overlapping generations (OLG) model with endogenous fertility. 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.

Fondazione Eni Enrico Mattei (FEEM), 20123 Milano, Italy. *e-mail: soheil.shayegh@feem.it

Skilled labour yields higher earnings, but also requires more parental investment during childhood, capturing the quantity–quality trade-off. The model is calibrated to reflect the projection of skilled to unskilled labour ratio in the sending region, taking into account the asymmetric damages from climate change (Supplementary Information 1 and Supplementary Fig. 1).

At the beginning of adulthood, each person has an exogenous probability of migration that is determined purely by the change in the local temperature[21]. The temperature follows the trajectory of the global carbon concentrations under different Representative Concentration Pathways (RCPs) for the sending region (Supplementary Fig. 2). For my main model, I assume that every individual has an incentive to migrate, so the migration probability can be a reduced-form stand-in for the complicated array of costs and benefits that go into migration. Parents take into account this probability when deciding whether to have skilled or unskilled children. The results of model calibration for labour ratio and adult population are presented in Supplementary Information 2 and Supplementary Fig. 3.

Existing research provides two guidelines on how to define the migration probability[6,21]. First, natural hazards such as climate shocks increase the incentive to migrate, at least for middle-income regions[20]. At the same time, these negative shocks make it more difficult for poor individuals to migrate because of liquidity constraints. I capture these two competing effects in a simple reduced-form manner. When temperature increases, high-skill (that is, richer) individuals have an increased migration probability, while low-skill (that is, poorer) individuals have a decreased migration probability. Some studies have shown temperature rather indirectly induces migration through wages[19,20]. In Supplementary Information 3 and Supplementary Fig. 4, I have included a variation of migration probability that includes the wage ratio between the two regions.

When temperature increases, therefore, the relative return to skill increases, holding all else equal. Thus, temperature increase induces parents to prioritize child quality and have fewer children. This positive demographic response partially offsets the damages from climate change. Moreover, since the higher return on skill is coming from the increase in migration potential, parents are willing to invest in education at lower domestic returns. Thus, local income inequality between skilled and unskilled individuals is also reduced by the migration channel, holding all else constant.

Although the focus of my model is on migration, I build a complete dynamic general equilibrium model. In this model, I 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. I assume that technological progress and global temperature can be taken as exogenous variables. I use a deterministic projection of greenhouse gas (GHG) concentrations and temperature rise. In Supplementary Information 4, I endogenize the impact of population change on the concentration of GHG emissions and the global mean temperature. Due to the small number of immigrants compared to the whole population, such endogenization has a negligible impact on the overall results presented here (see Supplementary Fig. 5).

Although I focus on results in the sending region, I also simulate the demographic dynamics in the receiving region, which is necessary to determine the wages for those who migrate. Despite its simple nature, my model can recreate the existing demographic projections for both regions. It is important to note that throughout my analysis I assume that climate change and its impacts are exogenous to the economies under investigation. In other words, I am not investigating long-term climate policies that may alter or reverse the course of climate change and temperature increase in my model. However, in Methods I have taken into account the change in global carbon concentrations due to the population change as a result of migration. By developing two models of migration (one climate-independent and the other climate-dependent), I hope to quantify the impact of climate-change-induced migration on the sending economy. Although this model is quantitative, my primary goal is to provide evidence for my qualitative conclusions.

Impact of climate change

Figures 1 to 4 examine the effect of climate change on economic and demographic outcomes in the model for three RCP scenarios. I have not included the RCP2.6 scenario here, since the climate change impacts are minimal and the results from two migration cases are hard to distinguish. The baseline is defined as a case with climate change in the future but without the possibility of migration from the sending region to the receiving region. I analyse and compare two cases of migration regimes here.

First, I 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 of child migration. Hence, the decisions on the number of children and their education level will be taken given migration probabilities.

Second, I assume that the migration rate is a function of temperature in the sending economy[21]. I 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 without migration.

Further, I incorporate migration policies into this analysis by investigating three migration policies. The main results are reported as 'Both' where both skilled and unskilled migrants are facing a moderate migration cost that not only affects their probability of migration but also inflicts a spike in the parents' child-rearing expenses. The other two cases are extreme ends of the migration policy spectrum where only one type of labour is allowed to migrate while a migration ban is applied to the other type. These policies are marked as 'Only skilled' and 'Only unskilled' in Figs 1 to 4.

Under the RCP4.5 temperature trajectory, in the absence of any migration cost, the fixed migration probability of skilled labour rises from a fixed rate of 8% under the climate-independent scenario to about 10% under the climate-dependent scenario (see Fig. 1a). On the other hand, the migration probability of unskilled labour drops from a fixed rate of 0.27% under the climate-independent scenario to about 0.11% under the climate-dependent scenario, making it very hard for people with lower education to migrate (see Fig. 1b). A similar pattern can be detected in higher RCP scenarios, where the divergence from the fixed rate migration is even more intensified. The 'Both' scenarios offer milder migration probabilities for both types of labour. However, the overall picture remains the same: climate-dependent migration increases the probability of migration for the skilled individuals and decreases the probability of migration for the unskilled individuals.

In all RCP scenarios, the increase in temperature caused by increasing carbon concentrations decreases the relative productivity of agriculture (see Supplementary Fig. 1). This creates a demand for labour in the agricultural sector to compensate the damages to the productivity in this sector. As a consequence, the wages in the agricultural sector rise. Migration of skilled labour creates an external incentive for parents to educate their children, hoping that migrating children will end up in the receiving region with higher wages. The result of these two competing effects determines the quantity and the quality of children in each generation.

Migration creates an initial increase in the ratio of skilled to unskilled labour, but as time passes, climate change takes a greater toll on agricultural productivity, creating a demand for unskilled labour in this sector (see Fig. 1c). As a result, the increase in skilled to unskilled ratio will be slower in the future. Meanwhile, climate-change-induced migration increases the skilled to unskilled ratio at a faster pace than climate-independent migration does. For example, under RCP6.0 and with only skilled migration, migration

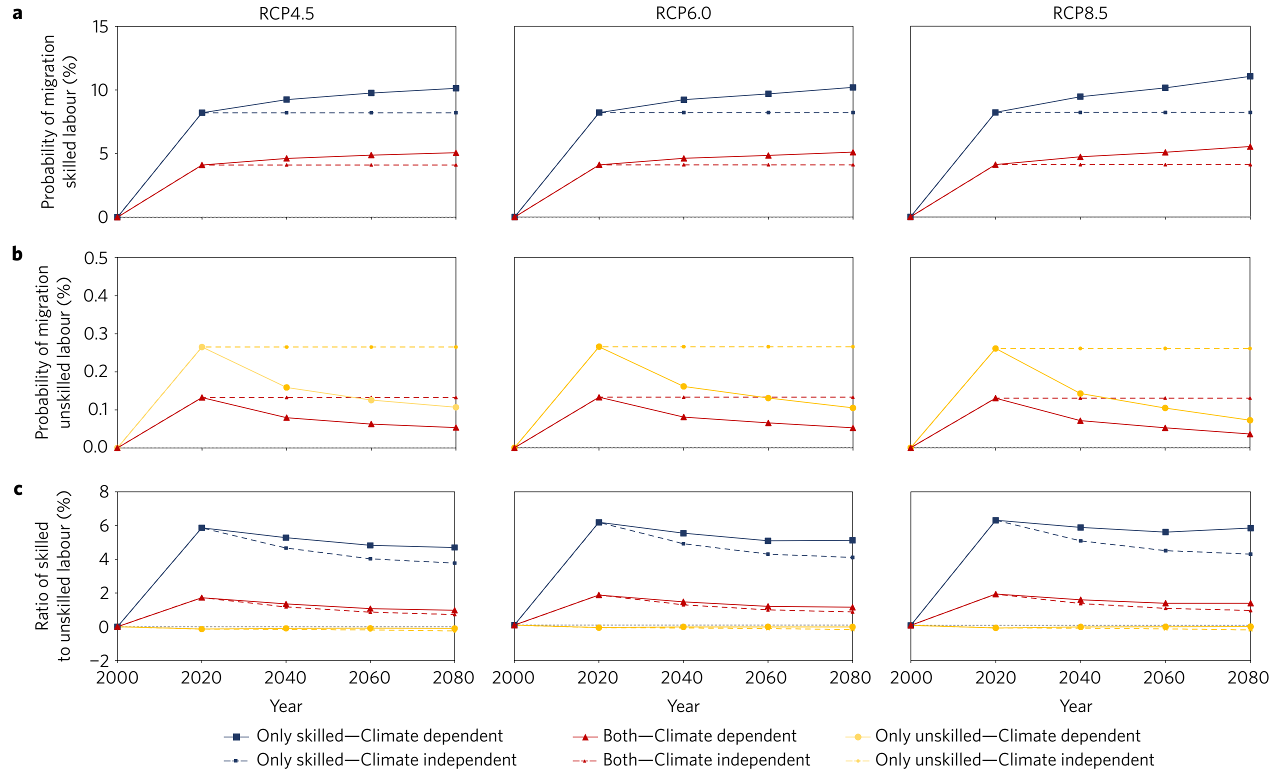

Figure 1 | Impact of migration on labour market in the sending country under three RCP scenarios for two cases of climate-dependent and climate-independent migration. a, Probability of migration for skilled labour. **b**, Probability of migration for unskilled labour. **c**, Skilled to unskilled labour ratio. The results are reported as percentage change compared to the baseline without migration.

increases the skilled to unskilled ratio of children by about 5.8% in the year 2020 compared to the baseline case without migration. However, as the demand for unskilled labour increases in later years, this increase amounts to around 4.8% in the climate-dependent case versus only 3.8% in the climate-independent case in the year 2080. When both type of labour are allowed to migrate, the skilled to unskilled ratio still follows a similar pattern of increase, but at a smaller pace. Finally, and when only unskilled migration is possible, both migration pull and climate change damages act in the same direction, creating a demand for unskilled children that decreases the skilled to unskilled ratio compared to the baseline case without migration.

Migration of skilled labour reduces the income inequality gap and climate-change-induced migration can amplify this effect. Similar to the previous row, migration of only unskilled labour leads to an opposite effect and increases (slightly) the income inequality gap. Although the overall picture indicates that, under all RCP scenarios, migration in general is helping to close the wage gap, the climate-dependent migration demonstrates a more effective way to achieve this goal. For example, under the RCP6.0 scenario and with both types of labour migrating, the wage ratio, compared to the baseline case without migration, shrinks by about 3.3% in the year 2020 but levels off in the year 2080, when it reaches 2.0% reduction under the climate-dependent migration case and only 1.5% reduction under the climate-independent migration case (see Fig. 2a).

Skilled labour migration increases global income inequality among skilled labour, whereas it decreases global income inequality among unskilled labour (see Figs 2b and 2c). If only unskilled labour migration is allowed, global income inequality will improve among skilled labour, but will be worsened among unskilled labour. However, such an effect is pretty negligible compared to the baseline case without migration. For example, under the RCP6.0 scenario and with both types of labour migrating, the ratio of skilled labour wages in the receiving region to skilled labour wages in the sending region, compared to the baseline case without migration, increases by about 2.3% in the year 2020 but levels off in the year 2080, when it reaches 0.4% increase under the climate-dependent migration case and only 0.3% increase under the climate-independent migration case. These findings are in line with recent studies that show only a modest effect of migration on global income inequality[31].

As shown in Fig. 3, migration reduces population growth when the migration of skilled labour is allowed; however, as the impact of climate change becomes more profound in later years, the fertility rates increase in response to climate damages to the agricultural sector and increases in return to unskilled labour. In all RCP scenarios, climate-dependent migration decreases the fertility rate at a faster pace than climate-independent migration does. For example, under RCP8.5 and with only skilled labour migration allowed, the fertility rate decreases by 2.6% in the year 2020 in the climate-dependent migration case, whereas it decreases by only 2.2% in the climate-independent migration case.

As shown in Fig. 4, output per capita in the sending region is increasing as more skilled people are migrating to the receiving region and the fertility rate decreases in the sending region. However, the discrepancy between the two cases of migration (climate-dependent and climate-independent) is larger in the higher RCP scenarios. In both cases the output per capita increases by more than 2.9% under the RCP8.5 scenario when migration of both types of labour is allowed.

Discussion and conclusion

In this paper, I developed an integrated assessment model of climate change, demographic change, and migration. My model takes the question of climate-induced migration beyond empirical studies and places it within a broader socioeconomic context[11,32]. I examined the effect of climate change on fertility rate, income inequality, and human capital accumulation in developing countries, focusing on the instrumental role of migration as adaptation. In doing

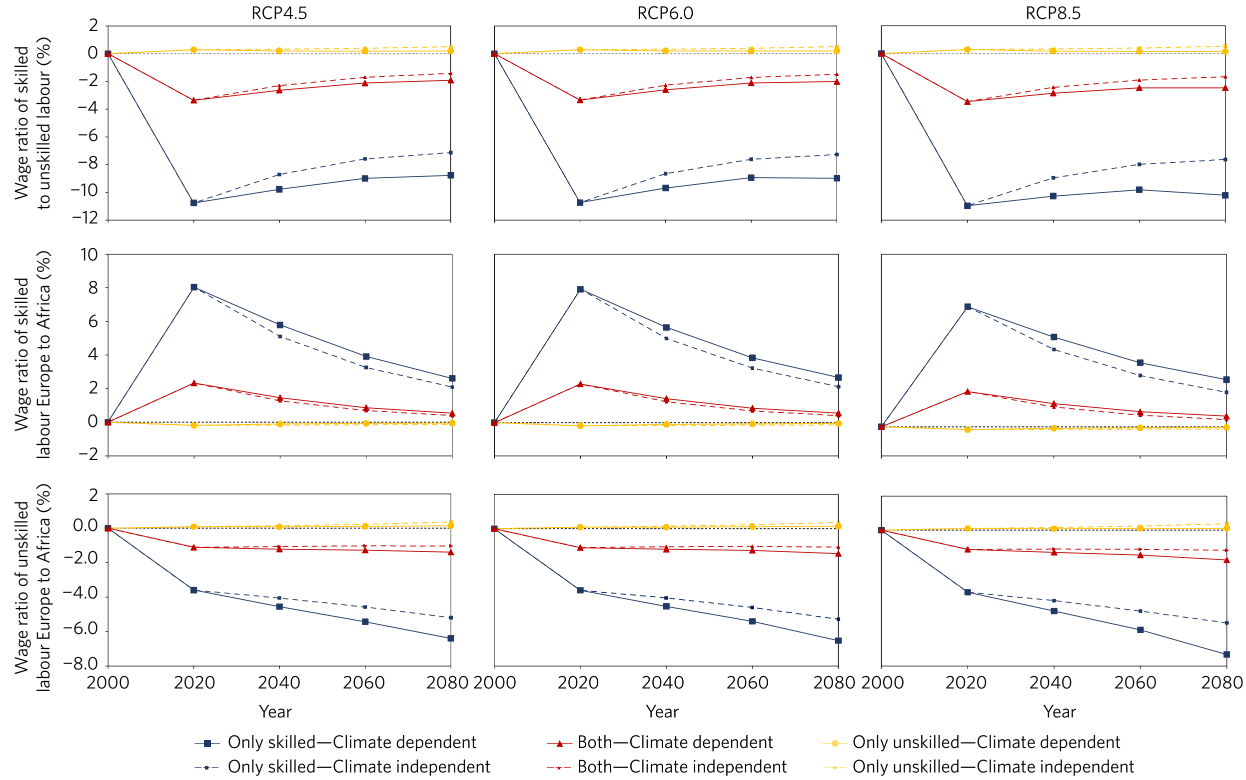

Figure 2 | Impact of migration on income inequality under three RCP scenarios for two cases of climate-dependent and climate-independent migration. **a**, Wage ratio of skilled to unskilled labour in the sending region. **b**, Wage ratio of skilled labour in the receiving region to the sending region. **c**, Wage ratio of unskilled labour in the receiving region to the sending region. The results are reported as percentage change compared to the baseline without migration.

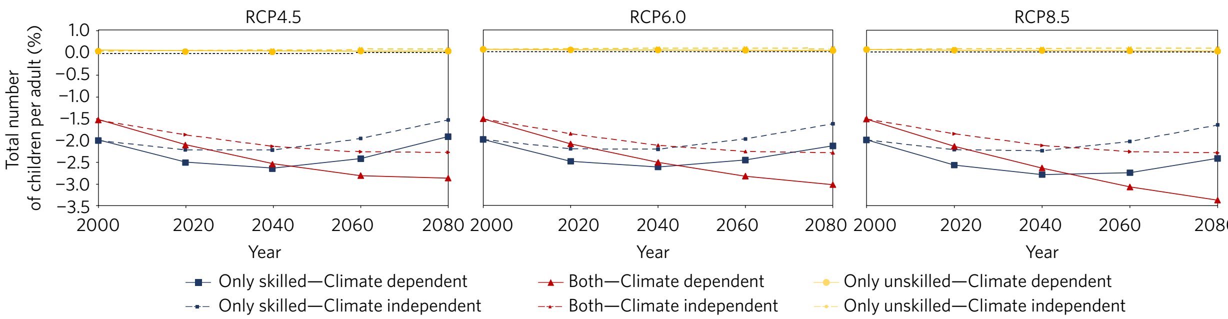

Figure 3 | Impact of migration on fertility rate under three RCP scenarios for two cases of climate-dependent and climate-independent migration. The results are reported as percentage change compared to the baseline without migration.

so, I demonstrate the role that migration plays in mitigating the negative effects of climate change. In particular, I 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 migration. Skilled individuals have more means and opportunities to migrate compared to unskilled individuals whose migration probability decreases as climate change looms. Even in the ideal case with no migration cost for skilled children, only a portion of skilled children actually emigrate. This will increase the skill composition of remaining workers and cause the wages for skilled labour in the sending region to decline, closing the income inequality gap in the sending region. The wages of unskilled labour increase as the population of this group shrinks, closing the global unskilled income inequality gap. 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. Migration, even without endogenous climate response, closes the income inequality gap in the sending region, but the endogenous response significantly amplifies this effect. Even after considering this response, however, in most scenarios global income inequality for skilled labour increases as a result of climate change.

My results demonstrate the potential for migration to alleviate the negative economic and demographic impacts of climate change. This is important, in particular, for adaptation policies in regions affected most by the negative outcomes of climate change. In designing migration regulations, policy makers should take into account the broader consequences of restrictive migration policies, not only for the receiving countries but for the sending countries as well[33]. In the face of unprecedented changes in my climate system, a policy that allows for skilled labour migration can significantly reduce income inequality in the sending country by creating a demand for skilled labour. However, if a policy allows or motivates only unskilled labour to migrate, the gains will be negligible or even slightly reversed.

In most approaches to climate change economics, individuals passively react to damages inflicted by climate change[34,35]. Yet, there are reasons to believe that climate change may influence individual behaviour in substantial ways. Recent evidence from the field of

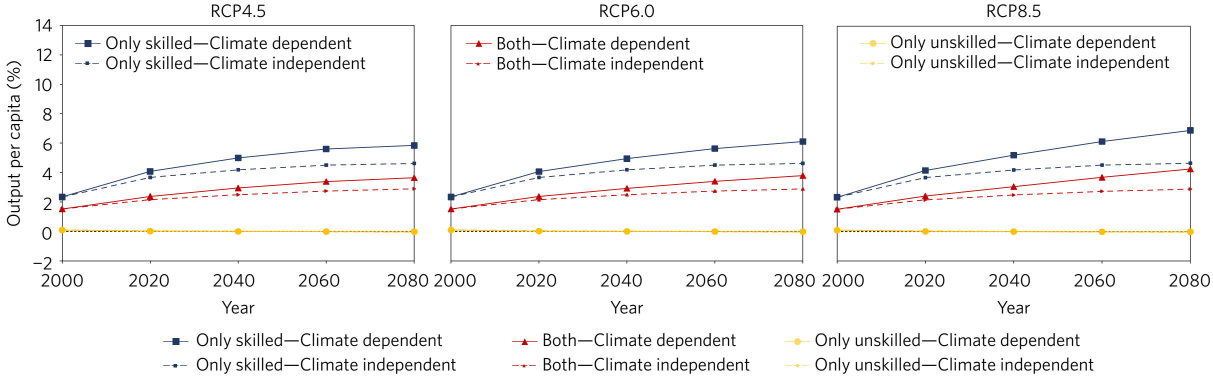

Figure 4 | Impact of migration on output per capita under three RCP scenarios for two cases of climate-dependent and climate-independent migration. The results are reported as percentage change compared to the baseline without migration.

economic growth suggests that three factors—human capital, population, and technology—drive long-term economic outcomes[36]. Thus, examining how climate change interacts with these factors is of first-order importance to establishing how climate change will affect human well-being. I have taken steps in this direction by investigating two components, human capital and population. My model paves the way for a new approach in integrated assessment modelling of climate change and economy where both emissions and population can be modelled endogenously and, therefore, the optimal climate policy can be expanded beyond traditional mitigation efforts to include fertility decisions and migration regulations.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Competing financial interests

The author declares no competing financial interests.

Methods

Economic model. My model builds on the standard overlapping generation (OLG) framework[13,37]. In particular, I employ a two-sector model of structural transformation. The current model does not include a service sector, but this can be added to the model as a potential for future transitions from industry to service. Existing research[38,39] shows that agriculture uses substantially less skilled labour. To simplify the analysis, I assume manufacturing work uses only skilled labour and agricultural work uses only unskilled labour. There is low substitutability between the two types of goods, implying that workers reallocate towards more damaged sectors after a climate shock. My specification for climate damages come from ref. 27. There are two types of goods, agricultural and manufacturing. I evaluate this model without the possibility for migration as a baseline case from which to compare my results. In particular, I examine the effects of exogenous differences in emission scenarios, given by Representative Concentration Pathways (RCPs) as described in refs 40,41, on fertility and education decisions.

In this model, individuals can reside in two regions (region 1 and region 2). They live for two 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 region of residency (that is, either to stay where their parents are or to migrate to the other region) 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, I use period lengths of 20 years. Children consume only parental time[13]. 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.

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

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

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 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. For my main analysis I assume that the probability of a child of skill level j migrating from region 1 to region 2 as an adult is a function of the current temperature in the sending region 1 (T_1) (climate-dependent migration):

$$\beta_{12}^j = \exp(\eta_j + \Psi_j \times \log(T_1)) \times (1-\zeta^j) \quad (2)$$

where η_j and Ψ_j are the coefficients from the empirical studies by ref. 21 and $0 \le \zeta^j \le 1$ is the relative cost of migration as a portion of child-rearing cost. It also reflects the migration policies in the receiving region. When ζ^j is zero, it implies free mobility between the regions and the migration probability will only be a function of temperature in the sending region. In contrast, when ζ^j approaches one, it implies a restrictive migration policy that bans immigration and, therefore, the migration probability will approach zero.

In the case of climate-independent migration, I fix the temperature T_1 at its current level for all the modelling horizon. Other studies show the impact of the temperature increase on migration probability is rather nonlinear[42]. However, those results may be driven by the fact that migrant population was taken as a whole instead of looking into differentiated migration probabilities for individuals with different incomes.

The expected utility from the future wages of children is therefore calculated as

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

where $w_{t+1}^{i,j}$ is the future wage of a child of skill level j in region i. For simplicity of the equations, I will use region indices only when it is necessary to emphasis the difference between two regions. I normalize the price index of the consumption composite to one. Thus, the budget constraint corresponding to (1) for every adult in each region is given by:

$$c_t = \left[1 - \tau^u n_t^u (1 + \beta_{12}^u \zeta^u) - \tau^s n_t^s (1 + \beta_{12}^s \zeta^s)\right] w_t \quad (4)$$

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

$$c_t = (1-\gamma) w_t$$

$$\tau^u n_t^u (1 + \beta_{12}^u \zeta^u) + \tau^s n_t^s (1 + \beta_{12}^s \zeta^s) = \gamma \quad (5)$$

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 total number of children.

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

$$\frac{\tau^{1,s}(1+\beta_{12}^s \zeta^s)}{\tau^{1,u}(1+\beta_{12}^u \zeta^u)} = \frac{\sum_{i\in\{1,2\}}\left(\beta_{1i}^s \sum_{j\in\{1,2\}} \frac{\beta_{1j}^u w_{t+1}^{i,s}}{n_t^s w_{t+1}^{i,s} + n_t^u w_{t+1}^{j,u}}\right)}{\sum_{i\in\{1,2\}}\left(\beta_{1i}^u \sum_{j\in\{1,2\}} \frac{\beta_{1j}^s w_{t+1}^{i,u}}{n_t^s w_{t+1}^{j,s} + n_t^u w_{t+1}^{i,u}}\right)} \quad (6)$$

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

$$\frac{\tau^{2,s}}{\tau^{2,u}} = \frac{w_{t+1}^{2,s}}{w_{t+1}^{2,u}} \quad (7)$$

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 my model, this situation never occurs in equilibrium.

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

$$c = \left\{\alpha (c_a^k)^{\frac{\epsilon-1}{\epsilon}} + (1-\alpha)(c_m^k)^{\frac{\epsilon-1}{\epsilon}}\right\}^{\frac{\epsilon}{\epsilon-1}} \quad (8)$$

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. For further analysis of the impact of this parameter on the model see Supplementary Information 5 and Supplementary Fig. 6.

Climate and damages. To analyse the effect of carbon concentrations in my model, I combine data on the RCPs[43] with a simplified climate model[27]. I calculate the temperature given the latitude and carbon concentration as follows:

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

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 $\nu_3 = 0.0238$. The concentrations are exogenous and taken from RCP scenarios (see Supplementary Fig. 2). In Supplementary Information 4 I have developed an alternative model with endogenous emissions from migration. The results do not show any significant change compared to the original model. In this model, I use deterministic projections of concentrations and temperature rise. Such projections are subject to uncertainties from socioeconomic and climate systems. There are several sources of uncertainty in this model: uncertainty over the key parameters of the model, uncertainty over the RCP and concentration scenarios, and finally uncertainty about the social response to climate change. Therefore, the findings of this model are subject to change if the underlying assumptions about concentration and temperature pathways change in the future. Once the temperature is calculated (see Supplementary Fig. 2), sector-specific impact function can be obtained from:

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

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). I adopt a linear production functions that captures the fact that agricultural production is relatively less skill-intensive[38,39]. Specifically,

$$Y_m = D^m(T) A_m H \quad (11)$$

$$Y_a = D^a(T) A_a L \quad (12)$$

where Y_j, $j=a,m$ is output in sector j, H and L are total skilled and unskilled labour, 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:

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

Total numbers of skilled and skilled workers are calculated by taking into account the possibility of labour movement to and from the region of interest. For example for region 1 (sending region) I have:

$$H^1=n_t^{1,s}N_t^1(1-\beta_{12}^s) \tag{14}$$

$$L^1=n_t^{1,u}N_t^1(1-\beta_{12}^u) \tag{15}$$

Similarly for region 2 (receiving region) I have:

$$H^2=n_t^{2,s}N_t^2+n_t^{1,s}N_t^1\beta_{12}^s \tag{16}$$

$$L^2=n_t^{2,u}N_t^2+n_t^{1,u}N_t^1\beta_{12}^u \tag{17}$$

where N_t^1 and N_t^2 are adult populations in region 1 and region 2 at time t. The consumption of manufacturing and agricultural goods in region 1 by adults of each skill level is calculated by following equations:

$$c_m^{1,u}=\frac{Y_m^1}{H^1\frac{w^{1,s}}{w^{1,u}}+L^1},\qquad c_m^{1,s}=c_m^{1,u}\frac{w^{1,s}}{w^{1,u}} \tag{18}$$

$$c_a^{1,u}=\frac{Y_a^1}{H^1\frac{w^{1,s}}{w^{1,u}}+L^1},\qquad c_a^{1,s}=c_a^{1,u}\frac{w^{1,s}}{w^{1,u}} \tag{19}$$

Equilibrium. Combining individual maximization and production yields the following equilibrium result for each region:

$$\ln\left(\frac{w_{t+1}^s}{w_{t+1}^u}\right)=\ln\left(\frac{1-\alpha}{\alpha}\right)-\frac{1}{\epsilon}\ln\left(\frac{H}{L}\right)-\frac{1-\epsilon}{\epsilon}\ln\left(\frac{D^m(T)}{D^a(T)}\right)$$
$$-\frac{1-\epsilon}{\epsilon}\ln\left(\frac{A_m}{A_a}\right) \tag{20}$$

At each time period the parents in both countries solve this equation simultaneously taking into account the actions of the adults in the other region. The Nash equilibrium generates the optimal number of children of each skill level in each region. If an increase in temperature negatively affects agriculture more than manufacturing, then the ratio $\ln(D^m(T)/D^a(T))$ is an increasing function of temperature T. If $\epsilon<1$ (that is, 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 regions from the region with lower wages to the one with higher wages. The interaction of these two inter- and intra-region movements defines the optimal level of population at the end of each period.

This result is reminiscent of the literature on directed technical change (DTC)[44]. The DTC literature focuses on the endogenous technological change resulting from exogenous changes in production inputs. Here, I am 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, I calculate the temperature and damage functions using equations (9) and (10). Next, I 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. I 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. The model was calibrated with forecast data on the population growth and the ratio of skilled to unskilled labour in the twenty-first century. The calibration results and the error measures are provided in Supplementary Information 1 and 2. I choose data from a poor region (Africa) and a rich region (west Europe) to calibrate and validate my model. I 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 my criteria of a receiving economy that is more developed than the sending countries.

External parameters. I take several parameter values from ref. 27. First, I take $\epsilon=0.5$ and $\alpha=0.55/2$. I also take the temperature and impact functions as described above.

I normalize the total time spent on raising children to 50% of total adult time. This assumption does not affect my results since the time cost of raising children is calibrated relative to total time spent parenting. I take the path of carbon emissions (an input into the temperature functions) from the RCPs[43].

Calibration of remaining parameters. I 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, I use historical and projected population data from the Wittgenstein Centre[45]. I treat anyone with a high school education as skilled.

I start by calculating the projected population growth rate for years 2000 and 2100 from the historical and forecast data. I refer to these growth rates as r_{2000} and r_{2100} below. I also use the data to calculate the ratio of skilled to unskilled adults in each period, h_{2000} and h_{2100}. I denote $\tau_r=(\tau^s/\tau^u)$. Since I know that total time spent raising children is equal to γ, I 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, I use equation (20) to solve for the ratio of the initial and final technology levels, $(A_{m,2000}/A_{a,2000})$ and $(A_{m,2100}/A_{a,2100})$.

Finally, I find the technology growth rates. By assumption, the growth rate of (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), I 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).

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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