The Impact of Climate Change on Fertility

Gregory Casey[a*], Soheil Shayegh[b, c], Juan Moreno-Cruz[d], Martin Bunzl[e], Oded Galor[f,g], and Ken Caldeira[h]

[a]Economics Department, Williams College, Williamstown, MA 01247
[b]Bocconi University, Milan, Italy
[c]RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
[d]School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Canada
[e]Department of Philosophy, School of Arts and Sciences, Rutgers University, New Brunswick, NJ 08901
[f]Economics Department, Brown University, Providence, RI 02912
[g]Population Training and Studies Center, Brown University, Providence, RI 02912
[h]Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305

January 2019

[0]G.C., S.S., and J.M-C designed the research. G.C. and S.S. performed the research. All authors analyzed the results and G.C., S.S., and J.M-C wrote the paper. K.C. supervised the project and provided feedback on manuscript drafts. The authors declare no conflict of interest.
To whom correspondence should be addressed, e-mail: gpc2@williams.edu.

Abstract

We examine the potential for climate change to impact fertility via adaptations in human behaviour. We start by discussing a wide range of economic channels through which climate change might impact fertility, including sectoral reallocation, the gender wage gap, longevity, and child mortality. Then, we build a quantitative model that combines standard economic-demographic theory with existing estimates of the economic consequences of climate change. In the model, increases in global temperature affect agricultural and non-agricultural sectors differently. Near the equator, where many poor countries are located, climate change has a larger negative effect on agriculture. The resulting scarcity in agricultural goods acts as a force towards higher agricultural prices and wages, leading to a labor reallocation into this sector. Since agriculture makes less use of skilled labor, climate damages decrease the return to acquiring skills, inducing parents to invest less resources in the education of each child and to increase fertility. These patterns are reversed at higher latitudes, suggesting that climate change may exacerbate inequities by reducing fertility and increasing education in richer northern countries, while increasing fertility and reducing education in poorer tropical countries. While the model only examines the role of one specific mechanism, it suggests that climate change could have an impact on fertility, indicating the need for future work on this important topic.

Climate change will have a substantial impact on the economy [1, 2]. There is also a broad consensus that economic factors affect fertility [3, 4, 5]. Thus, climate change has the potential to affect fertility patterns.[1] Since higher fertility is linked to negative economic outcomes [13, 14], the climate-to-fertility feedback could substantially alter the economic damages from global climate change. It may also exacerbate the inequity embedded in climate change.

Many economic theories of long-run demographic change emphasize industrialization and the transition out of agriculture [3, 15], known as structural transformation. Meanwhile, there is substantial evidence that climate change affects agricultural and non-agricultural sectors differently [16, 1, 17], thereby altering the transition process. Thus, economic theory suggests that future changes in climate may substantially influence fertility patterns via the process of structural transformation, among other possible avenues.

In this paper, we discuss the potential for human adaptation to climate change to alter long-run fertility patterns. Our primary goal is to highlight this important issue and spur future work in this area. We focus on economic mechanisms, specifically changes in human behaviour resulting from changes in the incentives generated by effective relative prices.

[1] A recent study finds that temperature may have long-run effects on fertility via reproductive health [6], a finding which is consistent with evidence on short-run temperature fluctuations and seasonality [7, 8]. Similarly, climate change can cause other large societal disruptions, such as natural disasters and civil war, that may also impact fertility patterns [9, 10, 11, 12]. While important, these mechanisms are not the focus of the current study, which focuses on economic mechanisms.

We proceed in two steps. First, we discuss a wide range of potential mechanisms — including sectoral reallocation, child mortality, longevity, and the gender wage gap — through which climate change may impact fertility, emphasizing areas of future research. Our second step is to build a model that combines (i) standard economic theory regarding structural transformation and endogenous fertility with (ii) existing estimates of the sectoral impacts of climate change. The results suggest climate change will indeed impact fertility, demonstrating the need for future work on this topic.

Our model examines the relationship between structural transformation and the quantity-quality trade-off, which has played a substantial role in past demographic transitions [3, 15] and is likely to be an important mechanism for future climate impacts. The quantity-quality trade-off refers to the decision faced by prospective parents whether to have fewer children with greater health and education investment per child or more children with less investment per child. To isolate the impact of climate change on demographic outcomes, we focus primarily on a hypothetical economy modelled after Colombia, for which global temperatures and technology can be treated as exogenous factors. We find that climate change leads to higher fertility and lower educational attainment.

We also use our model to perform a number of quantitative experiments. First, we re-examine our hypothetical economy at different latitudes to investigate spatial heterogeneity in the impacts of climate change. We find evidence for substantial inequities: at high latitudes, the demographic effects of climate change are reversed, leading to lower fertility and greater education attainment. Second, we examine whether realistic mitigation policies will substantially alter fertility patterns. We find that feasible but stringent policies can essentially eliminate the demographic impacts of climate change. Finally, we examine how the impacts of climate change differ in rich and poor countries, holding location fixed. We find essentially no difference. This result suggests that location, rather than income, will be the primary source of heterogeneity of climate impacts on fertility.

How climate change may impact fertility

In this section, we discuss how climate change may alter fertility via different economic channels. Clearly, non-economic factors, especially cultural norms, have first order consequences for fertility decisions [18, 19]. It is unclear, however, how climate change might affect cultural norms over the relevant time horizons. Thus, we leave the role of cultural evolution as an open question for future research.

In the economic approach to fertility, parents have a finite set of resources and preferences over various outcomes, as with any other decision. They use these resources to achieve the best possible outcome attainable within their economic constraints. In relation to fertility, the decision has two parts. First, individuals must decide the quantity of resources, both time and money, to devote to childrearing. Second, conditional on the total amount of resources devoted to childrearing, individuals must decide whether to use those resources to have more children or invest more in the future of each child. This latter decision is known as the quantity-quality trade-off. This simple model of choice delivers several insights. First, when the relative cost of having a child increases — either because the absolute cost of having a child increases or the cost of another activity decreases — the fertility rate will fall. Second, when the relative benefit of having another child decreases, then fertility will fall. Thus, the economic model of fertility suggests that climate change will affect fertility decisions by altering the relative costs and benefits of having children and investing in the well-being of each child.[2]

Effects through structural transformation

We start by focusing on how climate change might affect fertility by altering the composition of production within an economy. In response to negative economic impacts from climate change, labor is likely to reallocate towards agriculture, were large climate impacts are expected relative to other sectors. This can occur for two reasons. First, the low elasticity of substitution in the demand for agricultural and non-agricultural goods implies that the scarcity of agricultural goods will increase prices and wages in this sector, creating incentives for labor reallocation [22, 23]. Second, if climate damages decrease income, consumers would have an incentive to spend a greater fraction of their income on agriculture goods when compared to a world without climate change [23, 24]. This would again increase the relative wage of agricultural workers and motivate labor reallocation.

There are many ways that structural transformation can influence fertility. As discussed above, the quantity-quality trade-off [25, 26] has been a major driving force in past demographic transitions [15, 27, 28, 29]. Agricultural production makes less use of skilled labor [30, 31], implying that climate damages that raise the return to working in agriculture will also lower the relative return to education. Economic theory and evidence, therefore, suggest that parents will adapt to these changes in relative prices by spending fewer resources on educating children and more on increasing fertility.

Structural change can also impact fertility via the gender wage gap. In many societies, women bear most of the responsibility for raising children. Thus, when labor opportunities for women increase, so does the opportunity cost of raising children [3, 15, 32]. Moreover, theory and evidence suggest that, on average, women have a comparative advantage in education-intensive work, while men have comparative advantage in brawn-based modes of production [33, 34]. Thus, when an economy reallocates towards agriculture, the opportunity cost for women to raise children may

[2] Economic theories of fertility focus on the desire for a specific level of fertility. Fertility also depends on access to birth control. It is thus possible for climate change to impact fertility through availability of contraception [20, 21].

decrease, leading to an increase in fertility. Existing evidence suggests that the gender wage gap has been an important factor in long-run demographic change in Europe [3, 15]. Unfortunately, we are not aware of empirical work characterizing the strength of these comparative advantages across the globe.

Sectoral Impacts of Climate Change. The proposed effects of climate change on fertility through structural transformation depend on the assumption of differential impacts of climate change across sectors. In this section, we briefly review the literature on climate damages and, in particular, the differential effect of climate change on agricultural and non-agricultural production. There is a widespread consensus that such a differential effect exists [16, 1, 17]. The reasoning is straightforward. Crop yields are weather-dependent and thus are highly sensitive to changes in climatic conditions [35, 36, 37]. As a result, changes in temperature directly affect the inherent productivity of specific production techniques (e.g., planting maize with certain inputs and a certain amount of labor). The same is not true for production techniques that are not inherently sensitive to weather conditions.

This does not imply that changes in climate do not affect other sectors. Indeed, aggregate economic evidence suggests that such an effect exists [38]. Increasing temperatures can lower worker productivity or decrease attendance [39]. Moreover, climate change can affect long-term worker health [40], increase the potential for extreme weather [2], and lead to coastal erosion [41, 42], all of which would affect production in essentially any industry. Importantly, however, these factors should also affect agricultural production. Thus, in aggregate, agriculture should be more sensitive to changes in temperature as compared to other sectors.

This also does not imply that the all climate impacts are negative or equally distributed across the globe. Existing research also suggests that there is considerable spatial heterogeneity in the impact of climate change on agriculture [35, 36, 37]. Given the vast difference in temperature around the globe, increasing temperatures have differential effects on the suitability of local conditions for growing any particular crop. When considering the impact across all crops, this process will lead to differential effects on overall agricultural productivity.

Potential impacts outside of structural transformation

Many theories of long-run changes in fertility emphasize life expectancy and child mortality. Since climate change will affect mortality [43, 44], this is a potential link from climate to fertility. For example, theory and evidence strongly suggest that increases in life expectancy are associated with greater human capital accumulation and lower fertility [45, 46, 47], because longer life expectancy increases the benefits from early investment in human capital.

Change in child mortality can also be an important driver of long-run changes in fertility [3]. Specifically, parents may increase fertility in the face of high and uncertain mortality rates in order to ensure that they achieve some minimum desired level of fertility [3]. The theoretical relationship between mortality and the number of surviving children, however, is ambiguous [3, 15, 48], and statistical evidence on the effect of mortality on the number of surviving children is mixed [3, 15]. In particular, countervailing forces, such as the increased cost of having surviving children and the increased incentive to invest in the health of each surviving child, create a link between higher mortality and a decrease in fertility, leaving the overall effect uncertain and context-dependent [3, 15, 48].

When examining cross-country data, there is a strong negative correlation between income and fertility levels, which could imply that climate change may directly affect fertility via changes in income. Economic theory and evidence, however, do not suggest a simple causal effect from increasing income to decreasing fertility [4, 49]. In other words, it is not that richer individuals can 'afford' to have fewer children, which seems unlikely given that raising children is resource-intensive. Instead, the simple correlation is best explained by the more nuanced causal mechanisms discussed above. Quantity-quality mechanisms are particularly relevant in this regard [15, 28, 29]. If there is a greater return to education in developed countries, then the quantity-quality trade-off would suggest a negative correlation between fertility and income.

Model

As discussed above, there are many mechanisms that will determine the full strength of the effect of climate change on fertility. We now turn to a examination of one particular mechanism, the interaction of structural transformation and the quantity-quality trade-off. Our goal with this modelling exploration is not to provide a full quantitative accounting of the effects of climate change on demographic outcomes. Instead, by showing the importance of one mechanism, we demonstrate that climate impacts are likely to be significant, highlighting the need to future research. We also stress important sources of heterogeneity that may exacerbate existing inequities.

Our model combines standard economic-demographic theory and existing empirical evidence on the consequences of climate change. We build on the standard overlapping generations (OLG) approach to endogenous fertility [26, 50, 51].[3] We follow individuals through two stages of life. In the first stage of life, they are children who consume parental time. In the second stage, they work, consume goods, and raise children. To capture the quantity-quality trade-off, we assume that parents have preferences over the lifetime earnings of children and that raising a skilled child uses more parental time than raising an unskilled child. Since skilled children earn higher wages, parents face a trade-off between quality and quantity.

We employ a two-sector model of structural transformation. There are two types of goods, agricultural and non-agricultural. Existing research shows that agriculture uses substantially less

[3]The online supplemental material contains the key equations for our economic model and a related discussion.

skilled labor [30, 31]. To simplify the analysis, we assume non-agricultural work uses only skilled labor and agricultural work uses only unskilled labor.

Consistent with empirical evidence, we employ a model with low substitutability between the two types of goods, implying that workers reallocate towards more damaged sectors after a climate shock [22, 23]. Thus, if climate impacts lower the productivity of agricultural production, the scarcity of food leads to an increase in relative food prices. The increase in relative food prices then increases relative wage for agricultural work and lowers the incentive for parents to invest in child quality. As a result, fertility increases and educational attainment decreases. This is the economic mechanism through which climate change affects fertility and human capital in our model.

Our specification for climate damages comes from Desmet and Rossi-Hansberg [17]. These estimates capture the differential effect of climate change on agricultural and non-agricultural industries, as well as the spatial heterogeneity in the impacts of climate change. These estimates are particularly well suited to our application, because they were generated for a two-sector model similar to ours.[4]

Our focus is on the demographic effects of climate change, rather than the causes of climate change or the optimal policy response. As a result, we consider the case of a small economy for which technological progress and global temperature can be taken as exogenous variables. In our primary analysis, we calibrate the model to match demographic features of Colombia. We also present results for Switzerland in the supplemental online material. To ensure that our baseline model is consistent with existing demographic projections used in climate change analysis, we calibrate our model to past demographic trends and the projections embodied in the Shared Socioeconomic Pathways [55]. Specifically, we calibrate the model to SSP2, which serves as a 'middle of the road' scenario.[5] The model fit is evaluated in Figure 1. The demographic projections show the usual trends for developing countries, increasing education and falling fertility. Despite its simplicity, our model captures these patterns well.

We use the calibrated model to examine how demographic outcomes change when global temperature changes. Specifically, we examine how different levels of global mitigation will affect population dynamics by comparing demographic outcomes under different exogenous emissions paths given in the Representative Concentration Pathways (RCPs) [56, 57]. Holding the underlying demographic parameters fixed, changes in emissions capture different global mitigation scenarios. Figure 2 presents the global carbon concentrations and temperatures under the different RCPs.

Results

Figure 3 presents the results of the computational exercises, which are designed to better understand the effects of climate change on fertility via the quantity-quality trade-off and structural

[4]Unfortunately, these damage estimates do not allow for 'tipping points' in climate damages [52, 53, 54].

[5]The details of the calibration procedure are discussed in the online supplemental material.

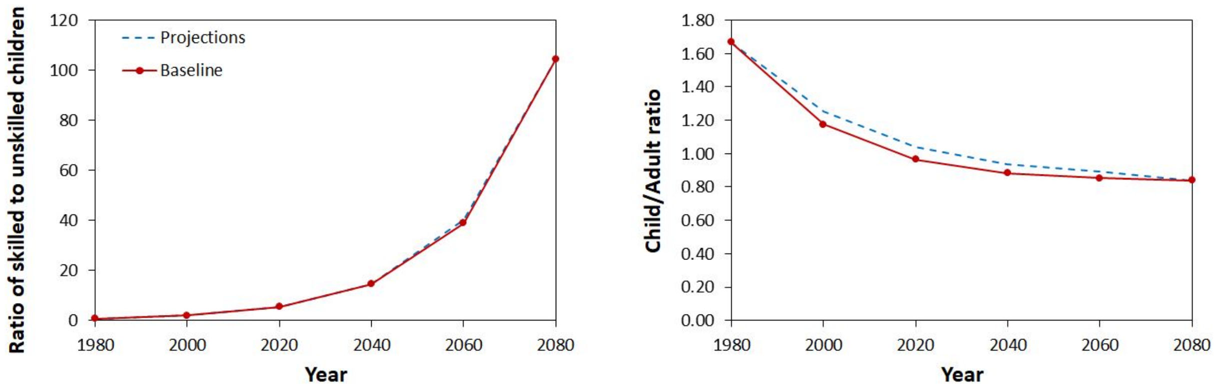

Figure 1: Comparison of the baseline model with the forecast data for Colombia [58]. We assume that the existing projections do not take into account the feedback from climate to demography. As a result, the baseline model assumes a constant climate. The left panel shows the ratio of skilled to unskilled labor. The panel on the right shows the child/adult ratio, a measure of fertility that corresponds directly to the economic-demographic model. We define children as those under 20 years of age. To focus on adults of child-bearing age, we consider individuals aged 20-39.

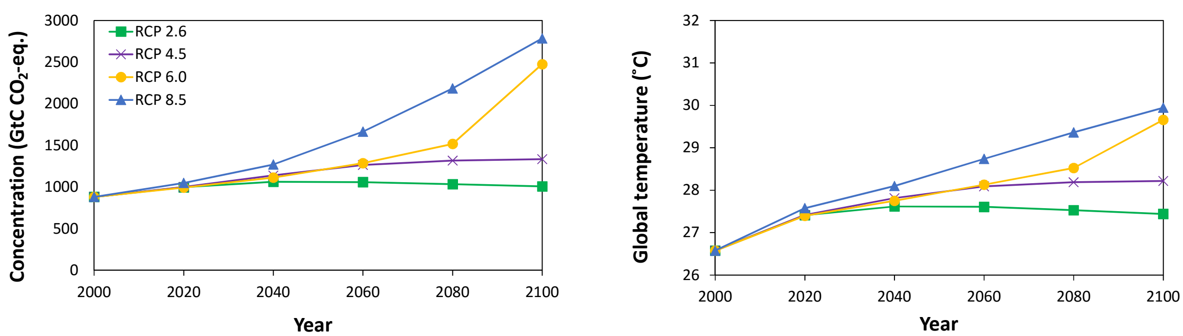

Figure 2: Climate characteristics of the four RCP scenarios. The left panel shows atmospheric CO_2 loadings in GtC from the RCPs [59]. The right panel shows global mean temperatures projected from combining the RCPs with climate dynamics in Desmet and Rossi-Hansberg [17]. The global temperature data is then combined again with the climate dynamics in Desmet and Rossi-Hansberg [17] to yield latitude-specific temperatures. These local temperatures, which are presented in the next figure, are used as inputs in our analysis.

transformation. All results are shown relative to a baseline case with constant climate.

Adaptation. The model captures how adaptation to climate change may include changes in fertility and human capital accumulation via structural transformation and the quantity-quality trade-off. To examine this mechanism, we start by considering the leftmost column, which examines Colombia in its true location. We also report on RCP 8.5, a pessimistic scenario without strong mitigation policies. The top panel shows that temperature at 5 degrees latitude (the actual position of Colombia) will increase by 10% in the year 2100. The damage estimates imply that the relative productivity of the non-agricultural sector will increase by almost 45%.

As described above, this increases 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 skill. The model suggests that ratio of skilled to unskilled children decreases by

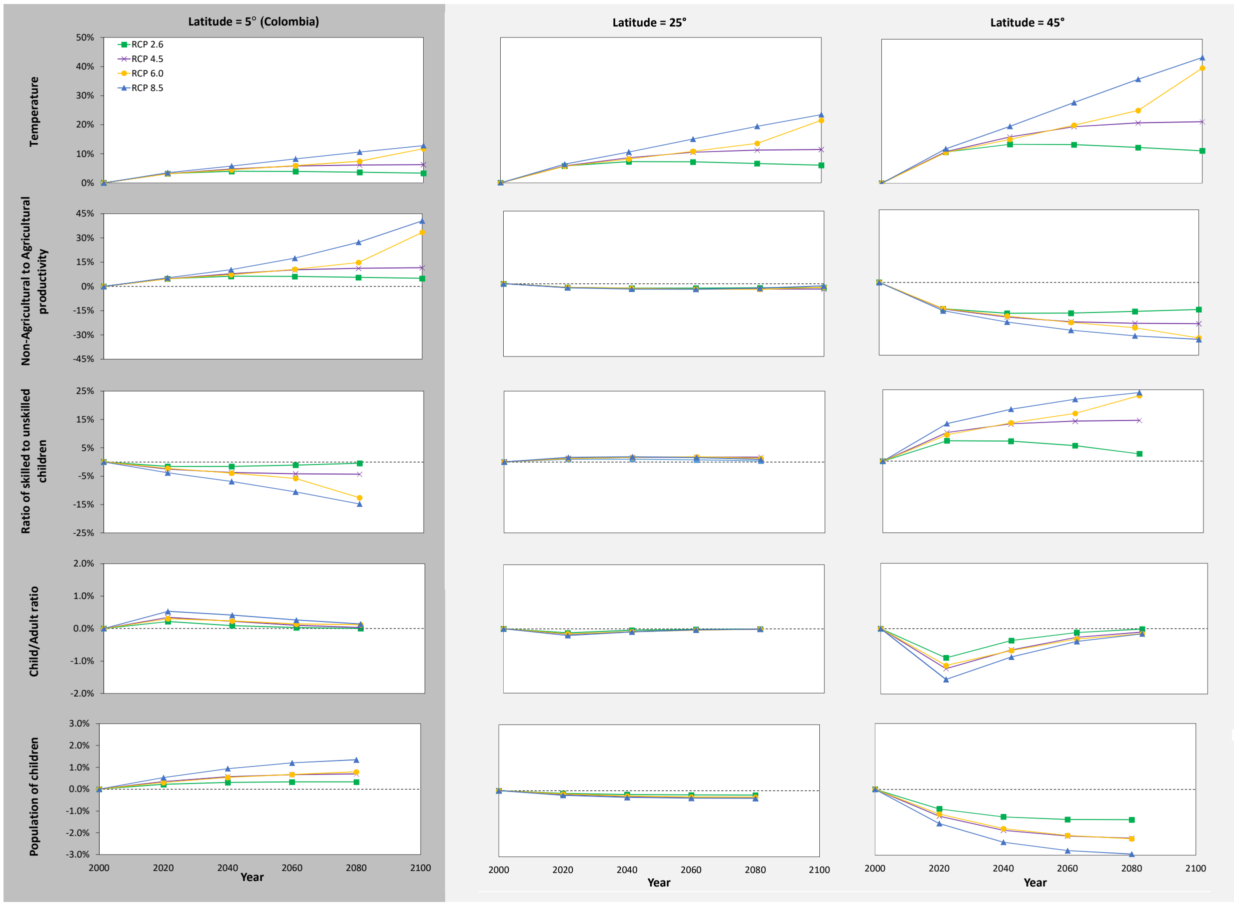

Figure 3: Results from the four RCP scenarios for different latitudes as percentage change compared to the baseline. The baseline scenario assumes a constant climate. The leftmost column presents results for a hypothetical economy like Colombia at its true latitude of 5 degrees. The next two columns investigate the role of spatial heterogeneity by considering the same hypothetical economy at alternate locations.

15%. The quantity-quality trade-off implies that fertility will rise when education falls. Consistent with the economic model, we measure fertility via the child-to-adult ratio. As education decreases, fertility increases, but then converges back to the baseline level. This convergence occurs because the baseline model predicts that developing countries will experience rapidly falling fertility independently of other forces (see Figure 1). To gauge the magnitude of the fertility decline, the last row shows the impact on total child population. The model suggests that the long-run population will be 1% higher due to the transitory changes in fertility. Overall, climate change leads to less education and greater fertility, when compared to a world with a constant climate.

Mitigation. The above results demonstrate that standard economic theory, when combined with existing estimates of the impact of climate change, predicts that changes in climate will affect fertility and human capital accumulation, when compared to a world with a constant climate. We now turn to investigating the role of mitigation policies. In particular, we hold the underlying economic-demographic model constant and examine the effect of exogenous differences in mitigation policies, which will result in differences in carbon concentrations.

The RCP 2.6 scenario represents a world with stringent mitigation policies and leads to a 3.3% increase in temperature, compared to 10% in RCP 8.5. The ratio of non-agricultural productivity increases by 5% relative to the baseline, instead of the 45% increase under RCP 8.5. The model suggests that this effect is too small to have a meaningful impact on skill accumulation (row 3), fertility (row 4) or the size of the child population (row 5) over the next 60 years. In other words, strict mitigation policies can essentially eliminate the demographic consequences of climate change at low latitudes, at least when restricting attention to the quantity-quality mechanism our model investigates.

Spatial Heterogeneity. The remaining two columns examine the role of spatial heterogeneity. In particular, we perform a computational experiment where we consider an economy identical to Colombia's, but at alternate locations. This experiment captures the heterogeneous effects of climate across latitudes, holding all else equal.

The effects of climate change on demographic outcomes differ substantially across latitudes. This occurs for two main reasons. First, the relationship between global and local temperature depends on latitude. Second, changes in temperature have non-linear effects on agricultural and non-agricultural productivity. As a result, both the direction and magnitude of the effect on differential productivities – which drives demographic outcomes – differ across latitudes.

In the second column, we examine the results for an economy like Colombia that is located at twenty-five degrees of latitude. The top row demonstrates that the effect of carbon concentrations on temperature are more extreme at this higher latitude. The effect on relative productivity, however, is smaller. As a result, the effect on fertility and skill accumulation is smaller, despite bigger changes in temperature.

In the third column, we examine the effect of temperature on economic and demographic outcomes for an economy like Colombia at forty-five degrees of latitude. In this case, higher temperature increases the relative productivity of agriculture, pushing workers into other sectors and inducing parents to substitute toward child education. Thus, population decreases and skill acquisition increases as a result of climate change. The magnitudes are large. Under RCP 8.5, the ratio of skilled to unskilled children increases by almost 25%, and the child population falls by 3%. Once again, lower carbon concentrations lead to smaller demographic impacts, but there are still meaningful changes under RCP 2.6.

Heterogeneity by Levels of Development. In the supplemental material, we re-calibrate the model and repeat all of the exercises for Switzerland, another small economy for which it is appropriate to take technology and global carbon concentrations as given. By examining results for Switzerland, we can analyze how climate change might affect demographic outcomes in a richer country. Switzerland has both a higher ratio of skilled children and a lower fertility rate when compared to Colombia. This is consistent with known demographic patterns in developed and developing countries and is well described by the calibrated model. We examine Switzerland at its true location (45 degrees of latitude), as well as the alternate locations given in Figure 3. By comparing the two different hypothetical countries at the same latitude, we can isolate the partial impact of development. The outcomes for Switzerland and Colombia are nearly identical at all latitudes, suggesting that location, rather than development, is the primary source of heterogeneity in the climate-fertility relationship captured by our model.

Discussion and Conclusion

Our model suggests that the damages from climate change for countries at low latitudes may be substantially larger than previously estimated. In particular, by changing the return to acquiring skills, climate change can induce parents to have more children and invest less in the education of each child. The increased damages from these channels imply larger benefits from mitigation policies. Fortunately, the model suggests that stringent but realistic mitigation policies can essentially eliminate the impacts of climate change on fertility via the quality-quantity trade-off.

Our model also has important implication for inequality. It is widely acknowledged that poor countries are less capable of adapting to climate change [60, 61]. Our results highlight a new potential source of spatial inequality in vulnerability to climate change: the differential effect of climate change on relative sectoral productivity will affect parental decisions about fertility levels and education for children. In high latitude countries, which tend to be richer, climate change may lead to lower fertility and higher skill accumulation, the reverse of what we find for low latitude countries. Thus, these forces may increase the gap between the richer high-latitude countries and poorer equatorial countries. We find little heterogeneity in impacts when considering differences in levels of development independently of differences in location.

Our model focuses on a single channel. As a result, it is necessarily preliminary, and there are many ways that future work can build on our results to provide a more complete quantitative accounting of the impacts of climate change on demographic outcomes. Most immediately, future studies can quantify the other economic channels discussed in the earlier sections of this paper. Mechanisms related to health and mortality are likely to be of particular importance.

Future work could also expand the model presented here to incorporate multiple regions. Such an analysis could provide several interesting insights. First, it would be interesting to combine our model with a realistic representation of international trade, since climate change alters patterns of comparative advantage [17]. As in other studies that look at structural transformation, we chose to focus on a closed economy for our analysis, because the data suggest that the allocation of workers between agricultural and manufacturing sectors in rich and poor countries is inconsistent with the forces of comparative advantage that govern standard trade theory [62, 31, 63]. Second, A globalscale model would also be able to make endogenous the temperature and technology dynamics that we take as exogenous to highlight our question of interest, the impact of climate change on demographic outcomes. Third, the mechanisms in our model highlight the importance of scarce food resources and corresponding increases in wages and prices. These results suggest that foreign aid targeted to improve agricultural productivity or improve food availability might be effective at lessening the negative demographic consequences of climate change. Further work in this area could highlight the potential for international development assistance to bolster climate change adaptation.

Finally, future work can expand on our results and discussion by considering non-economic mechanisms. As discussed above, both cultural factors and large-scale disruptions, such as natural disasters and civil wars, can also be affected by climate change, resulting in significant impacts on fertility that may have important interactions with the economic mechanisms discussed here.

Acknowledgements

This project has received funding from the following sources:

- The European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 703399 for the project "Robust Policy".
- The European Research Council under the European Communitys Programme "Ideas" - Call identifier: ERC-2013-StG / ERC grant agreement n 336703 project RISICO "Risk and uncertainty in developing and implementing climate change policies".
- The Fund for Innovative Climate and Energy Research.

References

[1] Richard SJ Tol. The economic effects of climate change. *Journal of Economic Perspectives*, 23(2):29–51, 2009.

[2] Nicholas Stern. The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3):838–859, 2013.

[3] Timothy W Guinnane. The historical fertility transition: A guide for economists. *Journal of Economic Literature*, 49(3):589–614, 2011.

[4] John Bryant. Theories of fertility decline and the evidence from development indicators. *Population and Development Review*, 33(1):101–127, 2007.

[5] Mary K Shenk, Mary C Towner, Howard C Kress, and Nurul Alam. A model comparison approach shows stronger support for economic models of fertility decline. *Proceedings of the National Academy of Sciences*, 110(20):8045–8050, 2013.

[6] Alan Barreca, Olivier Deschenes, and Melanie Guldi. Maybe next month? Temperature shocks, climate change, and dynamic adjustments in birth rates. *NBER Working Paper*, 2015.

[7] David A Lam and Jeffrey A Miron. Global patterns of seasonal variation in human fertility. *Annals of the New York Academy of Sciences*, 709(1):9–28, 1994.

[8] David A Lam and Jeffrey A Miron. The effects of temperature on human fertility. *Demography*, 33(3):291–305, 1996.

[9] David D Zhang, Harry F Lee, Cong Wang, Baosheng Li, Qing Pei, Jane Zhang, and Yulun An. The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences*, 108(42):17296–17301, 2011.

[10] Solomon M Hsiang, Kyle C Meng, and Mark A Cane. Civil conflicts are associated with the global climate. *Nature*, 476(7361):438, 2011.

[11] J Nobles, E Frankenberg, and D Thomas. The effects of mortality on fertility: Population dynamics after a natural disaster. *Demography*, 52(1):15–38, 2015.

[12] Nathan Seltzer and Jenna Nobles. Post-disaster fertility: Hurricane Katrina and the changing racial composition of New Orleans. *Population and Environment*, pages 1–26, 2017.

[13] Robert M Solow. A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70(1):65–94, 1956.

[14] Quamrul H Ashraf, David N Weil, and Joshua Wilde. The effect of fertility reduction on economic growth. *Population and Development Review*, 39(1):97–130, 2013.

[15] Oded Galor. The demographic transition: Causes and consequences. *Cliometrica*, 6(1):1–28, 2012.

[16] William D Nordhaus and Joseph Boyer. *Warming the World: Economic models of global warming*. MIT press, 2003.

[17] Klaus Desmet and Esteban Rossi-Hansberg. On the spatial economic impact of global warming. *Journal of Urban Economics*, 88:16–37, 2015.

[18] Charles Hirschman. Why fertility changes. *Annual Review of Sociology*, 20:203–233, 1994.

[19] Ron Lesthaeghe. The second demographic transition: A concise overview of its development. *Proceedings of the National Academy of Sciences*, 111(51):18112–18115, 2014.

[20] Shareen Joshi and T Paul Schultz. Family planning and womens and childrens health: Long-term consequences of an outreach program in matlab, bangladesh. *Demography*, 50(1):149–180, 2013.

[21] David Canning and T Paul Schultz. The economic consequences of reproductive health and family planning. *Lancet*, 380(9837):165–171, 2012.

[22] L Rachel Ngai and Christopher A Pissarides. Structural change in a multisector model of growth. *American Economic Review*, 97(1):429–443, 2007.

[23] Berthold Herrendorf, Richard Rogerson, and Ákos Valentinyi. Two perspectives on preferences and structural transformation. *American Economic Review*, 103(7):2752–2789, 2013.

[24] Francisco Alvarez-Cuadrado and Markus Poschke. Structural change out of agriculture: Labor push versus labor pull. *American Economic Journal: Macroeconomics*, 3(3):127–158, 2011.

[25] Gary S. Becker. An economic analysis of fertility. In *Demographic and Economic Change in Developed Countries*, pages 209–240. Columbia University Press, 1960.

[26] Oded Galor. *Unified Growth Theory*. Princeton University Press, 2011.

[27] Daniel Aaronson, Fabian Lange, and Bhashkar Mazumder. Fertility transitions along the extensive and intensive margins. *American Economic Review*, 104(11):3701–3724, 2014.

[28] Tom S Vogl. Differential fertility, human capital, and development. *Review of Economic Studies*, 83(1):365–401, 2015.

[29] Shoumitro Chatterjee and Tom Vogl. Escaping malthus: Economic growth and fertility change in the developing world. *American Economic Review*, 2017.

[30] Francesco Caselli and Wilbur John Coleman. The U.S. structural transformation and regional convergence: A reinterpretation. *Journal of Political Economy*, 109(3):584–616, 2001.

[31] Douglas Gollin, David Lagakos, and Michael E Waugh. The agricultural productivity gap. *Quarterly Journal of Economics*, 129(2):939–993, 2014.

[32] T Paul Schultz. Changing world prices, women's wages, and the fertility transition: Sweden, 1860-1910. *Journal of Political Economy*, 93(6):1126–1154, 1985.

[33] Oded Galor and David N Weil. The gender gap, fertility, and growth. *American Economic Review*, 86(3):374–387, 1996.

[34] Claudia Olivetti and Barbara Petrongolo. The evolution of gender gaps in industrialized countries. *Annual Review of Economics*, 8:405–434, 2016.

[35] Cynthia Rosenzweig, Joshua Elliott, Delphine Deryng, Alex C Ruane, Christoph Müller, Almut Arneth, Kenneth J Boote, Christian Folberth, Michael Glotter, Nikolay Khabarov, et al. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, 111(9):3268–3273, 2014.

[36] Delphine Deryng, Declan Conway, Navin Ramankutty, Jeff Price, and Rachel Warren. Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*, 9(3):034011, 2014.

[37] AJ Challinor, J Watson, DB Lobell, SM Howden, DR Smith, and Netra Chhetri. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4:287–291, 2014.

[38] Melissa Dell, Benjamin F Jones, and Benjamin A Olken. What do we learn from the weather? The new climate–economy literature. *Journal of Economic Literature*, 52(3):740–798, 2014.

[39] Gerard Cachon, Santiago Gallino, and Marcelo Olivares. Severe weather and automobile assembly productivity. *Columbia Business School Research Paper*, (12/37), 2012.

[40] Olivier Deschenes. Temperature, human health, and adaptation: A review of the empirical literature. *Energy Economics*, 46:606–619, 2014.

[41] Francesco Bosello, Robert J Nicholls, Julie Richards, Roberto Roson, and Richard SJ Tol. Economic impacts of climate change in europe: Sea-level rise. *Climatic Change*, 112(1):63–81, 2012.

[42] Dylan E McNamara and Andrew Keeler. A coupled physical and economic model of the response of coastal real estate to climate risk. *Nature Climate Change*, 3(6):559–562, 2013.

[43] Jonathan A Patz, Diarmid Campbell-Lendrum, Tracey Holloway, and Jonathan A Foley. Impact of regional climate change on human health. *Nature*, 438(7066):310–317, 2005.

[44] Olivier Deschênes and Michael Greenstone. Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the us. *American Economic Journal: Applied Economics*, 3(4):152–185, 2011.

[45] Sebnem Kalemli-Ozcan, Harl E Ryder, and David N Weil. Mortality decline, human capital investment, and economic growth. *Journal of Development Economics*, 62(1):1–23, 2000.

[46] Matteo Cervellati and Uwe Sunde. Human capital formation, life expectancy, and the process of development. *American Economic Review*, 95(5):1653–1672, 2005.

[47] Matteo Cervellati and Uwe Sunde. The economic and demographic transition, mortality, and comparative development. *American Economic Journal: Macroeconomics*, 7(3):189–225, 2015.

[48] Matthias Doepke. Child mortality and fertility decline: Does the barro-becker model fit the facts? *Journal of Population Economics*, 18(2):337–366, 2005.

[49] Larry E Jones, Alice Schoonbroodt, and Michèle Tertilt. Fertility theories: Can they explain the negative fertility-income relationship? In *Demography and the Economy*, pages 43–100. University of Chicago Press, 2010.

[50] Oded Galor and David N Weil. Population, technology, and growth: From malthusian stagnation to the demographic transition and beyond. *American Economic Review*, pages 806–828, 2000.

[51] Oded Galor and Andrew Mountford. Trading population for productivity: Theory and evidence. *Review of Economic Studies*, 75(4):1143–1179, 2008.

[52] Nicholas Stern. The economics of climate change. *American Economic Review*, 98(2):1–37, 2008.

[53] M Scott Taylor. Innis lecture: Environmental crises: past, present, and future. *Canadian Journal of Economics*, 42(4):1240–1275, 2009.

[54] Timothy M Lenton. Early warning of climate tipping points. *Nature Climate Change*, 1(4):201, 2011.

[55] KC Samir and Wolfgang Lutz. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, 42:181–192, 2017.

[56] Detlef P Van Vuuren, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C Hurtt, Tom Kram, Volker Krey, Jean-Francois Lamarque, et al. The representative concentration pathways: An overview. *Climatic Change*, 109:5–31, 2011.

[57] Malte Meinshausen, Steven J Smith, K Calvin, John S Daniel, MLT Kainuma, JF Lamarque, K Matsumoto, SA Montzka, SCB Raper, K Riahi, et al. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, 109(1-2):213–241, 2011.

[58] Wolfgang Lutz, William P Butz, and KC Samir. *World Population and Human Capital in the Twenty-First Century*. OUP Oxford, 2014.

[59] Richard H Moss, Jae A Edmonds, Kathy A Hibbard, Martin R Manning, Steven K Rose, Detlef P Van Vuuren, Timothy R Carter, Seita Emori, Mikiko Kainuma, Tom Kram, et al. The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282):747–756, 2010.

[60] Tim Wheeler and Joachim Von Braun. Climate change impacts on global food security. *Science*, 341(6145):508–513, 2013.

[61] Intergovernmental Panel on Climate Change. *Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects*. Cambridge University Press, 2014.

[62] David Lagakos and Michael E Waugh. Selection, agriculture, and cross-country productivity differences. *American Economic Review*, 103(2):948–80, 2013.

[63] Trevor Tombe. The missing food problem: Trade, agriculture, and international productivity differences. *American Economic Journal: Macroeconomics*, 7(3):226–58, 2015.

[64] Brian C ONeill, Elmar Kriegler, Keywan Riahi, Kristie L Ebi, Stephane Hallegatte, Timothy R Carter, Ritu Mathur, and Detlef P van Vuuren. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3):387–400, 2014.

Supplemental Online Material

Economic Model

Given that two-sector models and endogenous fertility are uncommon in the climate change economics literature, we explain the model in some detail. Our model builds on the standard overlapping generation (OLG) framework [26, 51]. We follow individuals through two periods life. For the first period of life, individuals are children who make no decisions. In the second period of life, individuals work, have children and make household decisions. Individuals make consumption and fertility decisions to maximize lifetime utility, which depends on the well-being of their familial dynasty. Individuals can be skilled (s) or unskilled (u). In the empirical application, we use a period length of 20 years.[6]

Preferences

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

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

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 w_{t+1}^j is the future wages of a child of skill level j. In other words, parents have preferences over own consumption and the lifetime earnings of their children, which will determine future consumption by the family. The parameter γ captures cultural factors that influence parental decisions. In the model, we assume that these are not affected by climate and focus on the quantity-quality trade-off.

Raising children is time-intensive [26, 50]. In particular, a child of type j consumes τ^j units of parents time. This implies that parents must forgo time spent working and current period familial consumption to raise children.[7] The consumption composite is the numeraire and, therefore, we normalize its price to one. Thus, the budget constraint corresponding to (1) is given by:

$$c_t = [1 - \tau^u n_t^u - \tau^s n_t^s] w_t. \tag{2}$$

[6]Thus, we capture individuals in childhood (0-19 years of age) and childbearing/childrearing years (20-39). As our model is not meant to capture changes in life expectancy or retirement decisions, we do not model individuals at later stages of life. As noted above, extending our model to examine the impacts of changes in health and life expectancy is a particularly promising avenue for future research.

[7]This set-up is isomorphic to one in which parents pay for other individuals to help raise children, as long as the other individuals are paid the market wage. If raising children was good-intensive, then fertility would rise over time, which is at odds with the data.

The maximization of (1) subject to (2) yields:

$$\begin{aligned} c_t &= (1-\gamma)w_t \\ \tau^u n_t^u + \tau^s n_t^s &= \gamma. \end{aligned} \tag{3}$$

Equation (3) 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 to have both types of children, it must be the case that:

$$\frac{\tau^s}{\tau^u} = \frac{w_{t+1}^s}{w_{t+1}^u}. \tag{4}$$

As in any investment decision, individuals make decisions to equate relative marginal benefits (w_{t+1}^j) and relative marginal costs (τ^j). 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.

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

$$c = \{\alpha(c_a)^{\frac{\epsilon-1}{\epsilon}} + (1-\alpha)(c_m)^{\frac{\epsilon-1}{\epsilon}}\}^{\frac{\epsilon}{\epsilon-1}}, \tag{5}$$

where ϵ is the elasticity of substitution, c_a is consumption of the agricultural good, c_m is consumption of the non-agricultural good, and the time subscripts have been suppressed for convenience. As ϵ approaches zero, consumers get less satisfaction from substituting non-agricultural goods for agricultural goods.

Production

There are two sectors, agriculture (a) and 'manufacturing' (m), which encompasses all other sectors. We adopt linear production functions that captures the fact that agricultural production is relatively less skill-intensive [30, 31]. Specifically,

$$Y_m = D^m(T)A_m H \tag{6}$$

$$Y_a = D^a(T)A_a L, \tag{7}$$

where Y_k, $k = a, m$ is output in sector k, H and L are total skilled and unskilled labor, respectively, A_k is productivity in sector k, and $D^k(T)$ is the climate impact function for sector k evaluated at temperature T. The dynamics for temperature and the impact function are described in the next section. Technological progress evolves exogenously according to:

$$A_{k,t} = (1 + g_k)A_{k,t-1},\ k = a, m. \tag{8}$$

Equilibrium

Combining individual maximization and production yields the following equilibrium result:

$$\begin{aligned} ln\left(\frac{H}{L}\right) = \epsilon ln\left(\frac{1-\alpha}{\alpha}\right) - \epsilon ln\left(\frac{\tau^s}{\tau^u}\right) - (1-\epsilon)ln\left(\frac{D^m(T)}{D^a(T)}\right) \\ - (1-\epsilon)ln\left(\frac{A_m}{A_a}\right). \end{aligned} \tag{9}$$

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. This raises the relative return to working in agriculture, causing parents to have relatively more unskilled children. Thus, total fertility increases following equation (3).

Climate and Damages

To analyze the effect of carbon concentrations in our model, we combine data on the RCPs [59] with the simplified climate model of Desmet and Rossi-Hansberg [17]. We calculate the temperature given the latitude and carbon concentration as follows:

$$T(l,t) = \ T(l,0) + \nu_1 P(t)^{\nu_2}(1 - \nu_3 T(l,0)), \tag{10}$$

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:

$$D^k(T) = \max\{g_{k,0} + g_{k,1}T + g_{k,2}T^2, 0\},\ k = a, m, \tag{11}$$

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 $g_{a,2} = -0.0073$.

Solving the Model

The model allows for a simple computational solution, wherein 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 (10) and (11). Next, we calculate the exogenous component of technology using equation (8).

All of the economic decisions are captured by equation (9), which can now be solved for the ratio of skilled to unskilled individuals in every period. We can then solve for the number of children 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 $\epsilon = 0.5$ and $\alpha = 0.55/2$ from [17]. We also take the temperature and impact functions from [17] 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 [59].

Calibration of remaining parameters

Economic Variables

We then 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. Our goal is to understand how changes in climate will affect future demographic outcomes. Thus, we calibrate the model to historical data and demographic projections from SSP2 [58, 55]. We label anyone between the ages of 20 and 40 with a upper-secondary education or higher as skilled labor, and we label people younger than 20 as children.

We start by taking the ratio of surviving children to adults between the ages of 20 and 40 for years 2000 and 2100 from the historical and forecast data. This is equivalent to the growth rate of people aged 20 to 39. We refer to these growth rates as r_{2000} and r_{2100} below. This yields

$$r_{2000} = \frac{P_{2000}}{P_{1980}} - 1, \tag{12}$$

$$r_{2100} = \frac{P_{2100}}{P_{2080}} - 1. \tag{13}$$

where P is the population of adults between the ages of 20 and 40 from the data. We also use the data to calculate the ratio of skilled to unskilled individuals in each period, h_{2000} and h_{2100}. We can find the number of skilled and unskilled children in years 1980 and 2080 using these ratios:

$$n^u_{1980} = \frac{1 + r_{2000}}{1 + h_{2000}}, \quad n^s_{1980} = n^u_{1980} \times h_{2000}, \tag{14}$$

$$n^u_{2080} = \frac{1 + r_{2100}}{1 + h_{2100}}, \quad n^s_{2080} = n^u_{2080} \times h_{2100}. \tag{15}$$

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):

$$\gamma = \tau^u \times n^u_{1980} + \tau^s \times n^s_{1980}, \tag{16}$$

$$\gamma = \tau^u \times n^u_{2080} + \tau^s \times n^s_{2080}. \tag{17}$$

Next, we use equation (9) to solve for the ratio of the initial and final technology levels, $\frac{A_{m,2000}}{A_{a,2000}}$ and $\frac{A_{m,2100}}{A_{a,2100}}$. We then find the technology growth rates. By assumption, the growth rate of $\frac{A_m}{A_a}$ is constant:

$$\frac{A_{m,2100}}{A_{a,2100}} = (1 + g_r)^{\frac{(2100-2000)}{20}} \frac{A_{m,2000}}{A_{a,2000}}, \tag{18}$$

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,

$$1 + g_r = \frac{1 + g_m}{1 + g_a}, \tag{19}$$

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. Now, g_a can be extracted from equation (19).

Data

All data used in this study are publicly available.

Figure 1: Model Calibration. To calibrate the model, we require past and projection data for the fertility rate and the ratio of skilled to unskilled children. To measure fertility in a manner consistent with the model, we divide the number of children (age 0-19) by the number of adults of child-bearing age (20-39). This corresponds to the two periods of life tracked in the OLG model. We label anyone with upper-secondary education as skilled.

The projection data are from the Shared Socioeconomic Pathways (SSPs). These scenarios investigate alternative pathways of socioeconomic development in order to lay the foundations for investigating the impacts of climate change, as well as adaptation and mitigation [64]. Samir and Lutz use the SSPs to develop detailed demographic predictions about fertility and skill accumulation [55]. To calibrate the model, we use their projections from SSP2, which is the middle of the road

scenario with medium fertility, mortality and and the Global Education Trend (GET) education scenario.
All population data was accessed via the Wittgenstein Center, and is available at:
`http://www.oeaw.ac.at/fileadmin/subsites/Institute/VID/dataexplorer/index.html`.

Figures 2 & 3: Carbon Concentrations. To simulate the model, we require projections for latitude-specific temperatures. Holding the parameters of the underlying economic-demographic model fixed, differences in global carbon concentration can capture differences in mitigation strategies undertaken by countries around the world. As shown in Figure 2, we take global carbon concentrations from the Representative Concentration Pathways [59]. The RCP scenarios explore the possible development trajectories of radiative forcing that drives climate change [56]. We then translate RCPs to latitude-specific temperate using the simple climate model in [17]. We then use [17] to translate latitude-specific temperatures into sector-specific damages. These data are used for the simulations in Figure 3. RCP data are available from the International Institute for Applied Systems Analysis and were accessed via
`http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome`.

Additional Results

In this section, we repeat the exercises from main text focusing on Switzerland, instead of Colombia. Figure 4 shows is the analog to Figure 1. It shows the demographic data together with the fit of the model. As expected, Switzerland has a higher ratio of skilled children at the beginning of the period and lower fertility. Over time, the existing projections suggest that fertility will stay close to replacement level and education will increase. Once again, our simple economic-demographic model captures these trends well.

Figure 5 recreates figure 3 focusing on Switzerland. The quantitative results are quite similar. In particular, the model suggests that (a) climate change will impact fertility and human capital accumulation, (b) stringent mitigation policies can almost eliminate these effects, and (c) there is considerable spatial heterogeneity.

By using the model to compare Switzerland and Colombia at the same latitude, we can perform an experiment that isolates the role of development. The fact that the outcomes are so similar suggests that the location will be dominant driver of heterogeneity in the demographic impacts of climate change.

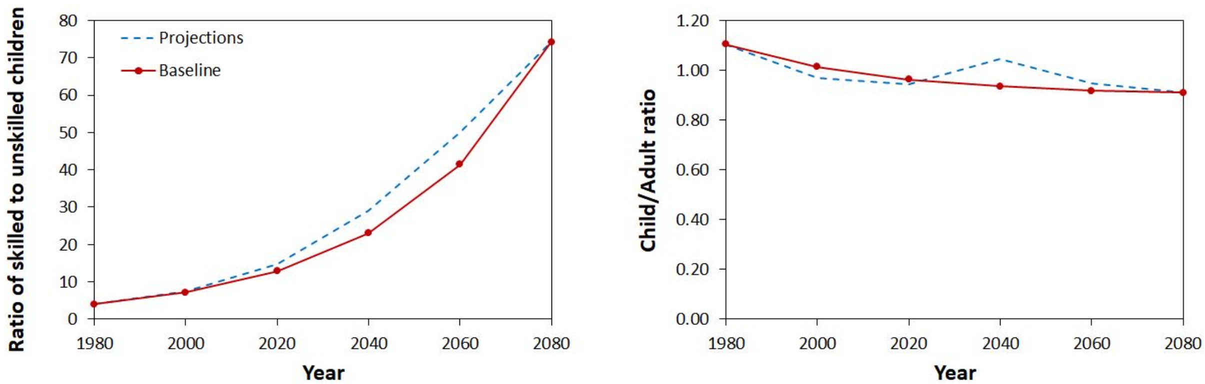

Figure 4: Comparison of the baseline model with the forecast data for Switzerland [58]. We assume that the projections do not take into account the feedback from climate to demography. As a result, the baseline model assumes a constant climate. The left panel shows the ratio of skilled to unskilled labor. The panel on the right shows the child/adult ratio, a measure of fertility that corresponds directly to the economic-demographic model. We define children as those under 20 years of age. To focus on adults of child-bearing age, we consider individuals aged 20-40.

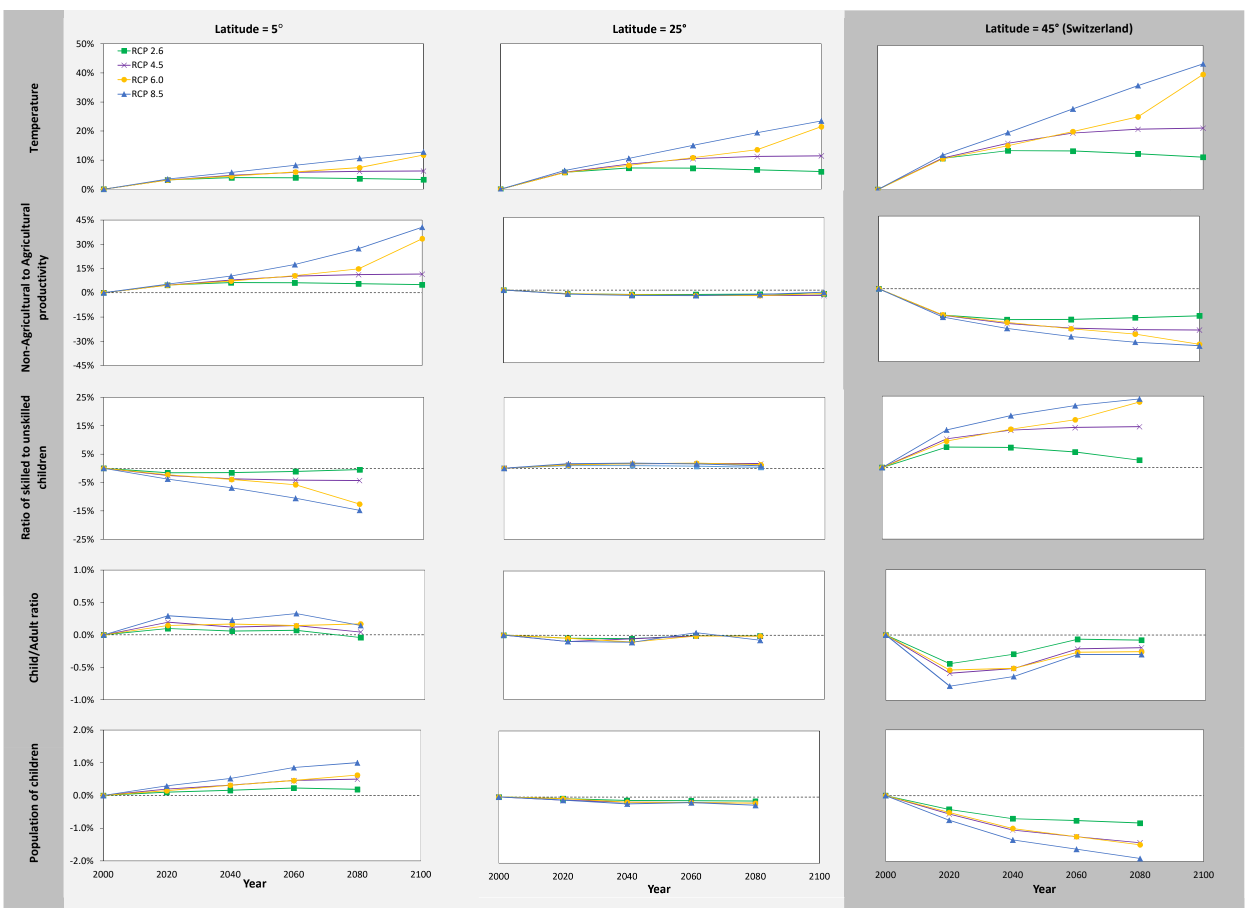

Figure 5: Results from the four RCP scenarios for different latitudes as percentage change compared to the baseline. The baseline scenario assumes a constant climate. The rightmost column presents results for a hypothetical economy like Switzerland at its true latitude of 45 degrees. The next two columns investigate the role of spatial heterogeneity by considering the same hypothetical economy at alternate locations.