Environmental Research Letters

LETTER • OPEN ACCESS

The impact of climate change on fertility

Environmental Research Letters

OPEN ACCESS

RECEIVED
25 September 2018

REVISED
18 February 2019

ACCEPTED FOR PUBLICATION
19 February 2019

PUBLISHED
3 May 2019

LETTER

The impact of climate change on fertility*

Gregory Casey[1], Soheil Shayegh[2,3], Juan Moreno-Cruz[4], Martin Bunzl[5], Oded Galor[6,7] and Ken Caldeira[8]

[1] Economics Department, Williams College, Williamstown, MA 01247, United States of America
[2] Bocconi University, Milan, Italy
[3] RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
[4] School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Canada
[5] Department of Philosophy, School of Arts and Sciences, Rutgers University, New Brunswick, NJ 08901, United States of America
[6] Economics Department, Brown University, Providence, RI 02912, United States of America
[7] Population Training and Studies Center, Brown University, Providence, RI 02912, United States of America
[8] Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305, United States of America

E-mail: gpc2@williams.edu

Keywords: climate change, economics, education, fertility, inequality

Supplementary material for this article is available online

Abstract

We examine the potential for climate change to impact fertility via adaptations in human behavior. 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 damage decreases 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 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 [3–5]. Thus, climate change has the potential to affect fertility patterns.[9] 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 [1, 16, 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.

* GC, SS, and JM-C designed the research. GC and SS performed the research. All authors analyzed the results and GC, SS, and JM-C wrote the paper. KC supervised the project and provided feedback on manuscript drafts. We thank two anonymous referees for helpful comments that improved the paper.

[9] 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 [9–12]. While important, these mechanisms are not within the scope of the current study, which focuses on economic mechanisms.

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 behavior resulting from changes in the incentives generated by effective relative prices. 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. Second, we build a model that combines standard economic theory regarding structural transformation and endogenous fertility with existing estimates of the sectoral impacts of climate change. The results suggest that 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 channel 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 modeled after Colombia, for which global temperatures and technology can be treated as exogenous factors. We find that climate damage 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, which 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 important 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.[10]

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 in the tropics, labor is likely to reallocate towards agriculture, where 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 damage decreases 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 [25–27] has been a major driving force in past demographic transitions [15, 28–30]. Agricultural production makes less use of skilled labor compared to other sectors [31, 32], implying that climate damages that raise the return to working in agriculture will also lower the relative return to

[10] 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].

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, 33]. 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 [34, 35]. Thus, when an economy reallocates towards agriculture, the opportunity cost for women to raise children may 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 [1, 16, 17]. The reasoning is straightforward. Crop yields are weather-dependent and thus are highly sensitive to changes in climatic conditions [36–38]. 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 [39]. Increasing temperatures can lower worker productivity or decrease attendance [40]. Moreover, climate change can affect long-term worker health [41], increase the potential for extreme weather [2], and lead to coastal erosion [42, 43], 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 [36–38]. Given the vast difference in temperatures and crops grown around the globe, increasing temperatures will have different effects on agricultural productivity in different regions.

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 [44, 45], 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 [46–48], 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, 49], 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, 49].

Parents may also desire children in order to have a source of support in old age [50]. This theory is known as the old-age security hypothesis [15]. Climate change could impact fertility via the old-age security hypothesis in two main ways. First, if the government must lower social support due to lost revenues, then parents may respond by increasing fertility. Second, if migration increases in response to climate change, then children will not be as strong a source of support, and fertility could decrease. In either case, the strength of the link between fertility and old-age support will be limited by the development of functioning financial systems [15].

In 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, 51]. 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, 29, 30]. If there is a greater return to education in developed

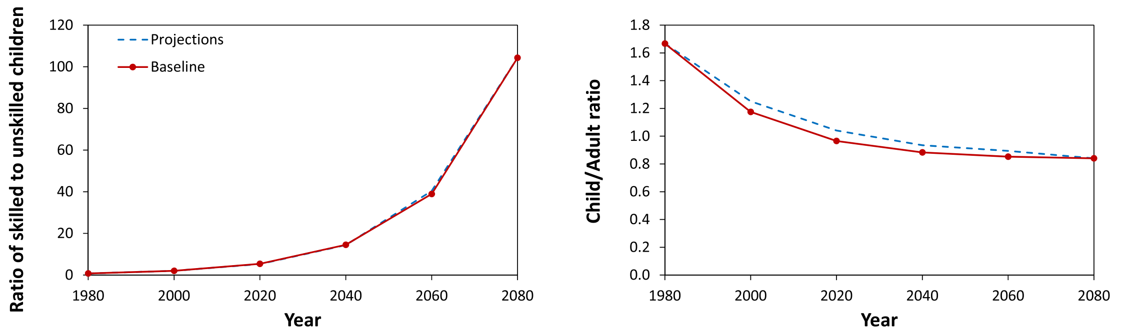

Figure 1. Comparison of the baseline model with the forecast data for Colombia [57]. We assume that the existing projections do not take into account the feedback from climate to demography. As a result, the baseline model assumes a constant climate. The left panel shows the ratio of skilled to unskilled 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.

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 modeling 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 substantial, highlighting the need to future research. We also highlight important sources of heterogeneity that may exacerbate existing inequities.

Our model combines standard economic-demographic theory and empirical evidence on the consequences of climate change. We build on the standard overlapping generations (OLG) approach to endogenous fertility [26, 27, 52].[11] 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 skilled labor per unit produced than does non-agricultural production [31, 32]. To simplify 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.[12]

Our focus is on the demographic effects of climate change, rather than the causes of climate change or the optimal policy response. Consequently, 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 base case 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

[11] The online supplementay material is available online: stacks.iop.org/ERL/14/054007/mmedia and contains the key equations for our economic model and a related discussion.

[12] These damage estimates do not allow for 'tipping points' in climate damages [53–55].

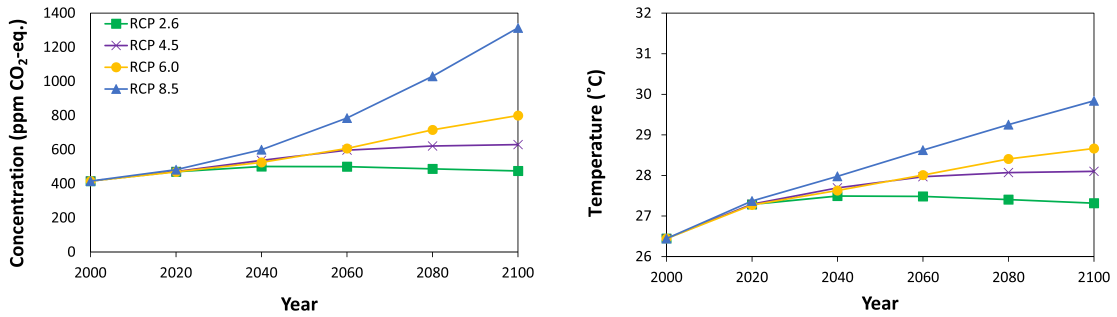

Figure 2. Climate characteristics of the four RCP scenarios. The left panel shows atmospheric concentraition in ppm CO_2 equivalent from the RCPs [60]. The RCP data are combined with the climate dynamics in Desmet and Rossi-Hansberg [17] to yield latitude-specific temperatures for Colombia, which are presented in the right panel.

[56]. Specifically, we calibrate the model to SSP2, which serves as a 'middle of the road' scenario.[13] 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) [58, 59]. Holding the underlying demographic parameters fixed, changes in emissions capture different global mitigation scenarios. Figure 2 presents the global carbon concentrations and temperature for Colombia 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 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. We start by considering effects predicted for Colombia in its true location. We focus on RCP 8.5, a pessimistic scenario without strong mitigation policies. The temperature at 5° latitude will increase by 10% in the year 2100, compared to the baseline scenario with constant climate. 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 15% compared to the baseline. 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). The model suggests that, in the long run, the total child population will be 1.35% 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. Holding the underlying economic-demographic model constant, we examine the effect of exogenous differences in mitigation policies, which result in differences in carbon concentrations.

The RCP 2.6 scenario represents a world with stringent mitigation policies and leads to a 3.3% higher temperature than the baseline scenario of a constant climate. Recall that temperatures were 10% higher in RCP 8.5. The ratio of non-agricultural productivity to agricultural productivity is 5% above baseline, instead of the 45% under RCP 8.5. The model suggests that this effect is too small to have a

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

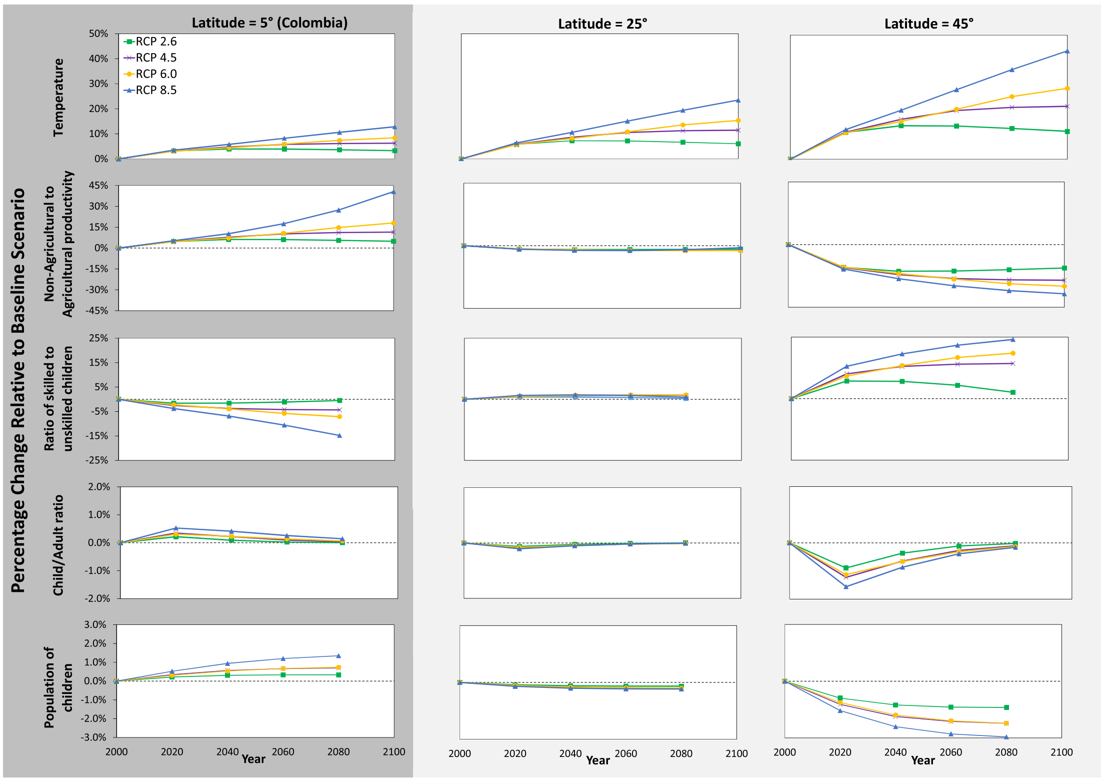

Figure 3. Results from the four RCP scenarios for different latitudes as percentage change compared to the baseline. The baseline scenario assumes a constant climate. The left column presents results for a hypothetical economy like Colombia at its true latitude of 5°. The center and right columns investigate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

meaningful impact on skill accumulation, fertility or the size of the child population 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

Figure 3 also illustrates the importance of spatial heterogeneity. We perform a computational experiment considering an economy identical to Colombia's, but at alternate latitudes. This experiment captures the heterogeneous effects of climate across latitudes, holding all else equal.

The effect of climate change on demographic outcomes differs 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.

We examine the results for an economy like Colombia that is located at 25° of latitude (figure 3). The effect of carbon concentrations on temperature are larger 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 larger changes in temperature.

We also examine the effect of temperature on economic and demographic outcomes for an economy like Colombia at 45° of latitude (figure 3). In this case, higher temperatures increase 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% compared to the baseline, 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 atmospheric carbon dioxide concentrations as exogenous. Results for Switzerland illustrate 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 than 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° latitude), as well as 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 damage 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 damage from these channels implies larger benefits from mitigation policies. Fortunately, the model suggests that stringent mitigation policies can largely eliminate the impacts of climate change on fertility via the quantity-quality trade-off channel.

Our model also has implications for inequality. It is widely acknowledged that poor countries are less capable of adapting to climate change than rich countries [61, 62]. Our results highlight another 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. These forces may increase the income 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. Channels related to health are likely to be of particular importance. Future work could also combine our model with a realistic representation of international trade, since climate change alters patterns of comparative advantage [17].[14] Moreover, our 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. Thus, further work could highlight the potential for international development assistance to bolster climate change adaptation. 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 interactions with the economic mechanisms discussed here. Future work can also expand on our results and discussion by considering non-economic mechanisms.

To understand the full impact of climate change and the benefits of mitigation policy, it is important to consider how adaptations to climate change may include demographic change. Our model suggests that demographic responses to climate change will increase damage in tropical countries and exacerbate existing inequities, increasing the benefit of mitigation policies. These results suggest a need for future work to build on our results by exploring and quantifying other important channels.

[14] 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 [32, 63, 64].

Acknowledgments

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 Community's 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.
- The Canada Research Chairs program of the Social Sciences and Humanities Research Council of Canada.

Conflict of interest

The authors declare no conflict of interest.

ORCID iDs

Gregory Casey https://orcid.org/0000-0002-2674-357X
Ken Caldeira https://orcid.org/0000-0002-4591-643X

References

[1] Tol R S J 2009 The economic effects of climate change *J. Econ. Perspect.* **23** 29–51
[2] Stern N 2013 The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models *J. Econ. Literature* **51** 838–59
[3] Guinnane T W 2011 The historical fertility transition: a guide for economists *J. Econ. Literature* **49** 589–614
[4] Bryant J 2007 Theories of fertility decline and the evidence from development indicators *Population Dev. Rev.* **33** 101–27
[5] Shenk M K, Towner M C, Kress H C and Alam N 2013 A model comparison approach shows stronger support for economic models of fertility decline *Proc. Natl Acad. Sci.* **110** 8045–50
[6] Barreca A, Deschenes O and Guldi M 2015 Maybe next month? Temperature shocks, climate change, and dynamic adjustments in birth rates *NBER* working paper
[7] Lam D A and Miron J A 1994 Global patterns of seasonal variation in human fertility *Ann. New York Acad. Sci.* **709** 9–28
[8] Lam D A and Miron J A 1996 The effects of temperature on human fertility *Demography* **33** 291–305
[9] Zhang D D, Lee H F, Wang C, Li B, Pei Q, Zhang J and An Y 2011 The causality analysis of climate change and large-scale human crisis *Proc. Natl Acad. Sci.* **108** 17296–301
[10] Hsiang S M, Meng K C and Cane M A 2011 Civil conflicts are associated with the global climate *Nature* **476** 438
[11] Nobles J, Frankenberg E and Thomas D 2015 The effects of mortality on fertility: population dynamics after a natural disaster *Demography* **52** 15–38
[12] Skjsjj N and Nobles J 2017 Post-disaster fertility: hurricane Katrina and the changing racial composition of new orleans *Population Environ.* **38** 1–26
[13] Solow R M 1956 A contribution to the theory of economic growth *Q. J. Econ.* **70** 65–94
[14] Ashraf Q H, Weil D N and Wilde J 2013 The effect of fertility reduction on economic growth *Population Dev. Rev.* **39** 97–130
[15] Galor O 2012 The demographic transition: causes and consequences *Cliometrica* **6** 1–28
[16] Nordhaus W D and Boyer J 2003 *Warming the World: Economic models of global warming* (Cambridge, MA: MIT Press)
[17] Desmet K and Rossi-Hansberg E 2015 On the spatial economic impact of global warming *J. Urban Econ.* **88** 16–37
[18] Hirschman C 1994 Why fertility changes *Annu. Rev. Sociol.* **20** 203–33
[19] Lesthaeghe R 2014 The second demographic transition: a concise overview of its development *Proc. Natl Acad. Sci.* **111** 18112–5
[20] Joshi S and Schultz T P 2013 Family planning and womenas and childrenas health: long-term consequences of an outreach program in matlab, Bangladesh *Demography* **50** 149–80
[21] Canning D and Schultz T P 2012 The economic consequences of reproductive health and family planning *Lancet* **380** 165–71
[22] Ngai L R and Pissarides C A 2007 Structural change in a multisector model of growth *Am. Econ. Rev.* **97** 429–43
[23] Herrendorf B, Rogerson R and Valentinyi Á 2013 Two perspectives on preferences and structural transformation *Am. Econ. Rev.* **103** 2752–89
[24] Alvarez-Cuadrado F and Poschke M 2011 Structural change out of agriculture: labor push versus labor pull *Am. Econ. J.: Macroeconomics* **3** 127–58
[25] Becker G S 1960 An economic analysis of fertility *Demographic and Economic Change in Developed Countries* (New York: Columbia University Press) pp 209–40
[26] Galor O and Mountford A 2008 Trading population for productivity: theory and evidence *Rev. Econ. Stud.* **75** 1143–79
[27] Galor O 2011 *Unified Growth Theory* (Princeton, NJ: Princeton University Press)
[28] Aaronson D, Lange F and Mazumder B 2014 Fertility transitions along the extensive and intensive margins *Am. Econ. Rev.* **104** 3701–24
[29] Vogl T S 2015 Differential fertility, human capital, and development *Rev. Econ. Stud.* **83** 365–401
[30] Chatterjee S and Vogl T 2017 Escaping malthus: economic growth and fertility change in the developing world *Am. Econ. Rev.* **108** 1440–67
[31] Caselli F and Coleman W J 2001 The U.S. structural transformation and regional convergence: a reinterpretation *J. Political Econ.* **109** 584–616
[32] Gollin D, Lagakos D and Waugh M E 2014 The agricultural productivity gap *Q. J. Econ.* **129** 939–93
[33] Schultz T P 1985 Changing world prices, women's wages, and the fertility transition: Sweden, 1860–1910 *J. Political Econ.* **93** 1126–54
[34] Galor O and Weil D N 1996 The gender gap, fertility, and growth *Am. Econ. Rev.* **86** 374–87
[35] Olivetti C and Petrongolo B 2016 The evolution of gender gaps in industrialized countries *Annu. Rev. Econ.* **8** 405–34
[36] Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci.* **111** 3268–73
[37] Deryng D, Conway D, Ramankutty N, Price J and Warren R 2014 Global crop yield response to extreme heat stress under multiple climate change futures *Environ. Res. Lett.* **9** 034011
[38] Challinor A J, Watson J, Lobell D B, Howden S M, Smith D R and Chhetri N 2014 A meta-analysis of crop yield under climate change and adaptation *Nat. Clim. Change* **4** 287–91
[39] Dell M, Jones B F and Olken B A 2014 What do we learn from the weather? The new climate-economy literature *J. Econ. Literature* **52** 740–98
[40] Cachon G, Gallino S and Olivares M 2012 Severe weather and automobile assembly productivity *Columbia Business School* research paper (12/37) (https://doi.org/10.2139/ssrn.2099798)
[41] Deschenes O 2014 Temperature, human health, and adaptation: a review of the empirical literature *Energy Econ.* **46** 606–19
[42] Bosello F, Nicholls R J, Richards J, Roson R and Tol R S J 2012 Economic impacts of climate change in europe: sea-level rise *Clim. Change* **112** 63–81
[43] McNamara D E and Keeler A 2013 A coupled physical and economic model of the response of coastal real estate to climate risk *Nat. Clim. Change* **3** 559–62
[44] Patz J A, Campbell-Lendrum D, Holloway T and Foley J A 2005 Impact of regional climate change on human health *Nature* **438** 310–7
[45] Deschênes O and Greenstone M 2011 Climate Change, mortality, and adaptation: evidence from annual fluctuations in weather in the us *Am. Econ. J.: Appl. Econ.* **3** 152–85
[46] Kalemli-Ozcan S, Ryder H E and Weil D N 2000 Mortality decline, human capital investment, and economic growth *J. Dev. Econ.* **62** 1–23
[47] Cervellati M and Sunde U 2005 Human capital formation, life expectancy, and the process of development *Am. Econ. Rev.* **95** 1653–72
[48] Cervellati M and Sunde U 2015 The economic and demographic transition, mortality, and comparative development *Ame. Econ. J.: Macroeconomics* **7** 189–225
[49] Doepke M 2005 Child mortality and fertility decline: does the barro-becker model fit the facts? *J. Population Econ.* **18** 337–66
[50] Caldwell J C 1976 Toward a restatement of demographic transition theory *Population Dev. Rev.* **2** 321–66
[51] Jones L E, Schoonbroodt A and Tertilt M 2010 Fertility theories: can they explain the negative fertility-income relationship? *Demography and the Economy* ed John B Shoven (Chicago, IL: University of Chicago Press) pp 43–100
[52] Galor O and Weil D N 2000 Population, technology, and growth: from malthusian stagnation to the demographic transition and beyond *Am. Econ. Rev.* 806–28
[53] Stern N 2008 The economics of climate change *Am. Econ. Rev.* **98** 1–37
[54] Taylor M S 2009 Innis lecture: environmental crises: past, present, and future *Can. J. Econ.* **42** 1240–75

[55] Lenton T M 2011 Early warning of climate tipping points *Nat. Clim. Change* **1** 201

[56] Samir K C and Lutz W 2017 The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100 *Glob. Environ. Change* **42** 181–92

[57] Lutz W, Butz W P and Samir K C 2014 *World Population and Human Capital in the Twenty-First Century* (Oxford: Oxford University Press)

[58] Vuuren D P Van *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

[59] Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* **109** 213–41

[60] Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56

[61] Wheeler T and Von Braun J 2013 Climate change impacts on global food security *Science* **341** 508–13

[62] Intergovernmental Panel on Climate Change 2014 *Climate Change 2014-Impacts, Adaptation and Vulnerability: Regional Aspects* (Cambridge: Cambridge University Press)

[63] Lagakos D and Waugh M E 2013 Selection, agriculture, and cross-country productivity differences *Am. Econ. Rev.* **103** 948–80

[64] Tombe T 2015 The missing food problem: trade, agriculture, and international productivity differences *Am. Econ. J.: Macroeconomics* **7** 226–58