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Fertility and climate change*

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Abstract

A quarter of the total increase in emissions is attributable to the growth of emissions per capita, whereas three-quarters are due to population growth. This evidence notwithstanding, demography in climate–economy models typically follows exogenous trends. We develop a climate–economy integrated model with endogenous fertility through a quality–quantity trade-off. The decentralization of the social optimum requires two complementary instruments: a carbon pricing policy and family planning interventions. Global population increases and reaches a peak, depending on the scenario, between 11.6 billion in the social optimum and 14.6 billion if only carbon prices are implemented. Fertility costs (i.e., the net present value of the climate-related costs per child) are in 2020 estimated to be about 22,000 euros in the "social optimum" scenario, and about 88,000 euros in the "second-best with fertility taxes" scenario. Carbon pricing tends to have a rebound effect as it increases population growth leading to higher future emissions. Our results highlight the effects of fertility choices and global population on climate change, quantifying the cost of neglecting the interaction.

Keywords: Carbon tax; climate change; climate-economy models; family planning; fertility; population; population externality

JEL classification: *H*23; *J*11; *J*13; *Q*54; *Q*56

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1. Introduction

The International Energy Agency estimates that world emissions from fossil fuels reached 38 $GtCO_2$ in 2019, up from 15.8 $GtCO_2$ in 1970. Over the same time span, the world's population increased from 3.7 to 7.6 billion people (PBL Netherlands Environmental Assessment Agency, 2020). Decomposing the resulting 108 percent cumulative growth of total emissions into population growth and growth of per capita emissions, we find that global population alone contributed 77 percentage points to emissions. These numbers reveal an inconvenient fact: three-quarters of the rise in emissions is due to the additional people who now populate the world, while one-quarter has come through the growth of per capita consumption of goods and services, and the associated production activities.

This striking evidence notwithstanding, the majority of climate–economic studies and models focus on measures to bring down emissions from production and consumption activities; fertility decisions are typically taken to follow exogenous trends. Yet population growth is a key component of projections of future emissions. Projections suggest that the world's population will rise to around 9.8 billion by 2050 and to 11.2 billion by 2100, with a wide range of uncertainty. Climate economists can contribute to our assessment of these scenarios, bringing the environmental consequences of individuals' reproductive decisions into the picture.

In this paper, we study the interactions between climate change and population dynamics. Because a newborn child increases the competition for space and natural resources on a finite planet, we present a model of endogenous fertility choices where family planning decisions generate external costs to society. These costs are due to the emissions generated by the additional individual, which reduce environmental resources available to the following generations.

Of course, a newborn child also contributes to production when grown up. Through the child's embedded human capital, the child adds to growth opportunities for the whole economy, ultimately contributing to social welfare. The parents provide for education to enhance a child's human capital, which is costly in terms of both time and resources. Our model draws from the literature on optimal fertility, education decisions, and economic growth. We add to those studies a perspective on the environmental externality generated by fertility decisions. That is, we contribute to an emerging literature that connects endogenous fertility decisions, economic growth, and climate–economy interactions. We calibrate the model so as to provide a quantitative estimate for the "climate–population externality" and to assess the quantitative significance of the interaction between emission reductions and family planning policies.

Our results underscore the importance of population policies such as (voluntary) programs that promote women's social status, health, and education. At the COP21 conference on climate held in Paris in December 2015 for the first time in history almost all countries adopted a universal, legally binding global climate deal. Governments agreed on integrating climate change measures into national policies, strategies, and planning, and summarized these in so-called Nationally Determined Contributions (NDCs). The NDCs focus on efficient mechanisms to reduce emissions, but remain silent about population growth, just like the Kyoto Protocol. Yet, the relevance of population dynamics was originally recognized in 1972 during the first Earth Summit.[1] In more recent times, Principle 8 of the 1992 Rio Declaration (United Nations, 1992) highlights that "to achieve sustainable development and a higher quality of life for all people, States should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies."

Thus, demographic and fertility policies should, in principle, be considered when framing national policies and international agreements concerning climate change and sustainability more generally. To that end, it is essential to make an assessment of the population externality. Yet, optimal climate policies and demographic policies interact in various ways, as this paper shows. In this study, we use a climate−population−economy model to ask three broad questions. To what extent can fertility decisions contribute to climate policy? Should climate policy be adjusted if family planning policies cannot decentralize the social optimum? If a planner cannot implement optimal climate policies such as carbon taxes, to what extent does the absence of such climate policies raise the pressure for family planning policies as part of climate policies?

We find that the efficient climate policy requires a substantial reduction in family size. Of course, countries have widely diverging per capita emissions, per capita incomes, and fertility rates, so this result cannot be applied equally across all countries, and it is conceivable that family planning as part of climate policy would be more relevant in the least-developed countries.[2] We come back to this caveat in the conclusions to this paper. As to the second question, the absence of family planning policies leads to a reduction in (second-best) carbon taxes. High carbon taxes potentially exacerbate the

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[1] Actions and proceedings of the Stockholm conference are collected in a Report (United Nations, 1972), and are synthesized in 26 Principles. The 16th Principle states: "Demographic policies which are without prejudice to basic human rights and which are deemed appropriate by Governments concerned should be applied in those regions where the rate of population growth or excessive population concentrations are likely to have adverse effects on the human environment and impede development."

[2] We want to be careful in our interpretation, and we are aware of the tension between developing and developed countries regarding historic and future responsibility for climate change.

population-driven climate problem. Intuitively, it might be expected that by imposing carbon taxes, the climate–population externality is alleviated as the lifetime carbon footprint of each newborn is reduced. But by reducing income, carbon taxes lead to a rise in fertility rates, potentially making climate damages due to fertility worse. Finally, if carbon prices cannot be implemented, the fertility externality becomes very large, leading to a substantial reduction in second-best family size.

The remainder of the paper is organized as follows. In Section 2, we present a few stylized facts that are useful to frame the problem, while in Section 3 we review the relevant literature. In Section 4, we present the model whose calibration is then discussed in Section 5. Scenario results are presented in Section 6. Conclusions, caveats, and future research directions close the paper.

2. Stylized facts

The two options to achieve a reduction in aggregate CO_2 emissions are, respectively, reducing the population size and lowering per capita emissions. These are, in turn, related to the carbon intensity of production and consumption activities. Historically, total emissions and population have steadily grown, as shown in Figure 1. Over the period 1970–2019, total emissions grew 141 percent and population increased by 108 percent. Per capita emissions went up by only 16 percent. Statistical analysis consistently shows the major contribution of population growth to emissions (Ehrlich and Holdren, 1971; O'Neill et al., 2001).[3]

While, historically, industrialized countries have contributed most to emissions, future emissions growth is expected to be mainly driven by lower- and middle-income countries that currently are characterized by significant population growth, and will see a sharp income growth. The global population is currently growing at more than 80 million people per year, despite a declining fertility (Sulston et al., 2012). Uncontrolled population growth increases the level of emissions, worsening the adverse impacts of climate change. Such consequences are not taken into account by households: parents are not fully informed, sometimes have limited access to means for birth control, and

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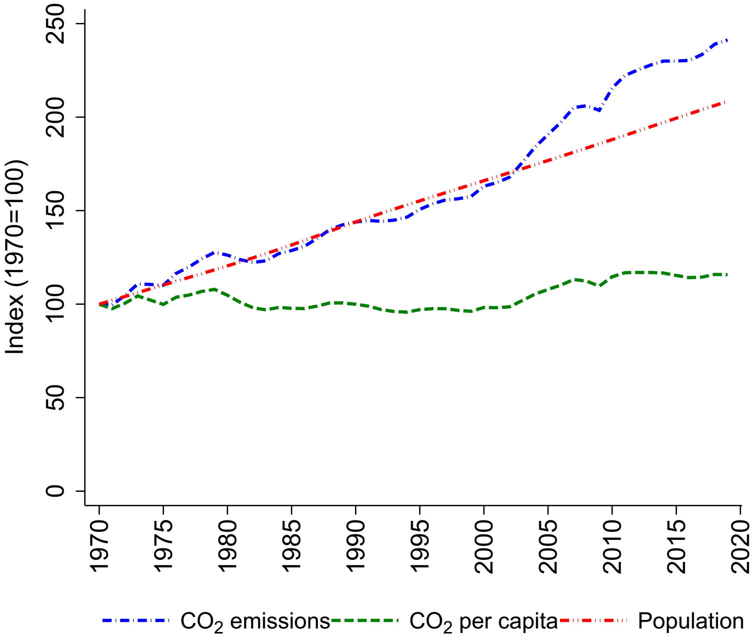
[3] A simple decomposition, according to which total emissions are equal to the product of per capita emissions and population, underlies the trends shown in Figure 1. There is a large econometric literature aiming to estimate the contribution of population to CO_2 emissions. A recent example is Casey and Galor (2017), who show that the elasticity of carbon emissions with respect to population is nearly seven times larger than the elasticity with respect to income per capita. However, the range of estimated population elasticities in the literature is quite large, mostly depending on the controls that are included in the regressions and the statistical methods employed (Liddle, 2015).

Figure 1. World total and per capita emissions from fossil fuel combustion and total population, 1971–2018

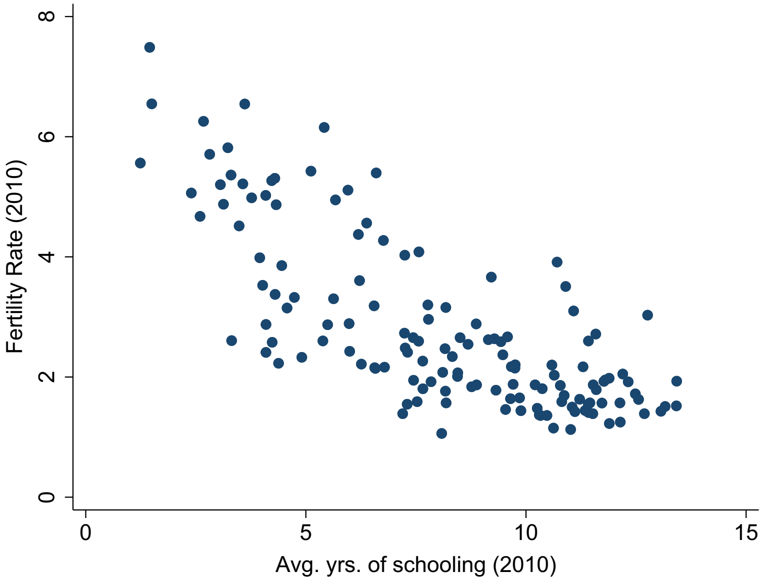


Source: United Nations (2019); PBL Netherlands Environmental Assessment Agency (2020).

retain a more local perspective. As noted by Murtaugh and Schlax (2009), there is a carbon legacy associated with current reproduction decisions due to the additional emissions of children, grandchildren, and so on, which can be sizeable compared with the parents' current emission-generating day-to-day activities. Wynes and Nicholas (2017) go a step forward and calculate the emission reduction potential of a range of individual lifestyle choices. They find that among the most effective decisions is having one fewer child, which would save an average 58.6 tons CO_2eq for individuals living in developed countries.

Because households do not take into account that the available per capita resources decline with the size of the next generation, fertility choices are characterized as a congestion externality. Dealing with this aspect requires accounting for endogenous fertility decisions. In this paper, we borrow from Becker and Barro (1988) where parents obtain satisfaction from having children and supporting their course of studies, as this will enhance the human capital they embody. Because education is expensive, parents face a trade-off between the number of children to have and the amount of education they

Figure 2. Fertility rates and schooling, by countries



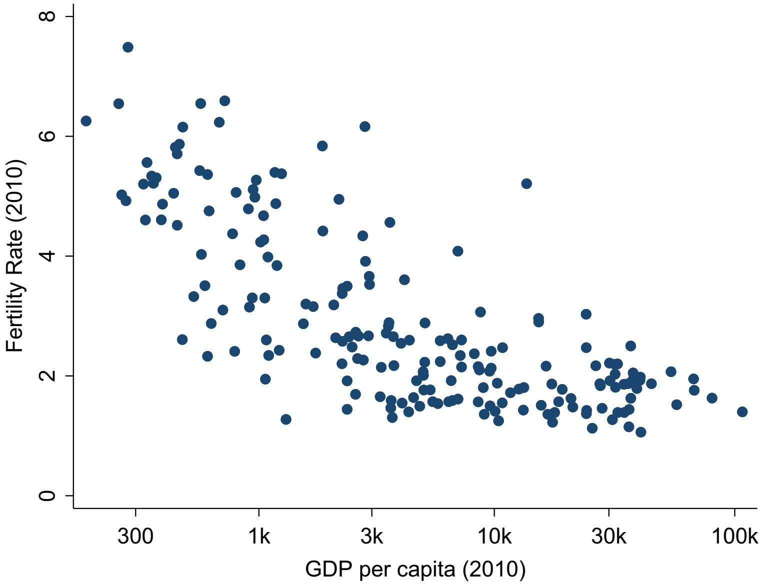
Source: United Nation Population Division database for fertility rates (child per female); database of Barro and Lee (2013) for average years of education.

can provide to each of them (Becker and Lewis, 1973). The trade-off also means that women who are better educated have higher opportunity costs for their time; they tend to have fewer better-educated children (Martin, 1995; Skirbekk, 2008; United Nations, 2017), though this relationship does not always play out as expected, for example, because of an interaction effect with the marriage market (Fort et al., 2016).

The trade-off between fertility and education not only plays out between families, but also leaves its mark when comparing countries. The opportunity cost of child-rearing is higher in high-income countries, especially for women (Jones and Tertilt, 2009), where there are fewer children who receive more schooling (Becker and Barro, 1988; Becker et al., 1990; Hazan and Berdugo, 2002; de la Croix and Doepke, 2003; Moav, 2004). Figure 2 shows the quantity–quality trade-off using the Barro and Lee (2013) dataset.

The quantity–quality family planning model also explains various empirical correlations between inequality and economic growth (de la Croix and Doepke, 2003). Poor parents tend to have many children and invest little in education. A large fertility differential between rich and poor lowers average education leading to less human capital and therefore slower growth. The family planning differential effect accounts for most of the empirical

Figure 3. Fertility rates and income, by countries



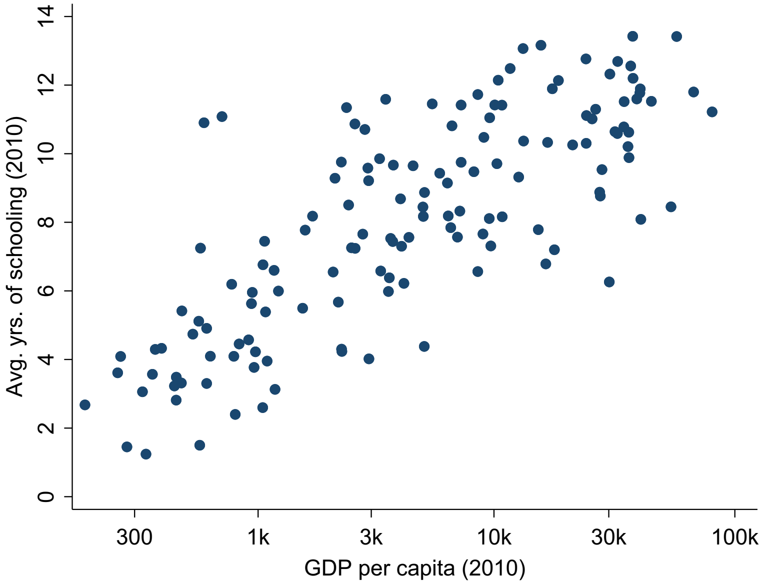
Source: WDI database, World Bank for GDP per capita (constant 2010 EUR); United Nation Population Division database for fertility rates (child per female).

relationship between inequality and growth. Figures 3 and 4 show the correlation between fertility and income in the first figure, and between education and income in the other. Our model is set up to replicate these stylized patterns.

3. Related literature

This paper lies at the intersection between two large bodies of literature. The first strand of literature integrates climate change in the Ramsey–Cass–Koopmans theory of economic growth. Nordhaus (1994) is a founding paper, developing the first integrated climate-growth model, and receiving the Nobel prize in recognition (Barrage, 2019). This is a well-established literature; recent papers develop calibrated analytical models that allow for closed-form solutions supplemented with quantitative assessment. These help to precisely identify mechanisms and suggest the appropriate level for optimal carbon prices (Golosov et al., 2014), and their adjustment, for example, for non-standard time preferences (Gerlagh and Liski, 2017), catastrophic risk (Gerlagh and Liski, 2018), innovation externalities (Fried, 2018), and distortionary fiscal policies (Barrage, 2020).

Figure 4. Schooling and income, by countries



Source: WDI database, World Bank for GDP per capita (constant 2010 EUR); database of Barro and Lee (2013) for average years of education.

Our study fits into this series, adding fertility into a stylized model that provides intuitive analytics and quantitative solutions.[4]

This brings us to the second strand of literature: the economics of family planning. When presenting stylized facts, we have mentioned the ground-breaking papers by Becker and Lewis (1973) and Becker et al. (1990). Another paper related to ours is Shi and Zhang (2009). They showed that an optimal policy taxes births and uses the revenues to subsidize education, resembling China's recent moves in population policies. Xue and Yip (2017) examined the effects of the One Child Policy (OCP) in China in a Galor and Weil (2000) model with a population constraint, and showed that investments in the education of children increased after the OCP intervention. Birth control methods were analyzed in a model of family planning by Becker (1960). Strulik (2017) and Bhattacharya and Chakraborty (2017) investigated the role of contraception in models of economic growth.

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[4] The few integrated assessment models that consider endogenous population growth do so through distinct scenarios (Weyant et al., 1996). This contrasts with another complex modeling topic: technological change. This has been taken up early by a number of climate–economy models including Buonanno et al. (2000) and van der Zwaan et al. (2002).

Cavalcanti et al. (2021) built a model of growth and development with both endogenous fertility and contraceptive choices. In our paper, we study a policy of fertility reduction that does not take a specific form of family planning policy. It could be contraception, the worldwide legalization of abortion, education subsidies, or any other relevant mechanisms involved in family planning.

It must be recognized, however, that there is a nearly universal aversion to viewing childbearing in purely economic terms. This makes population control controversial. To many, the free choice (not) to procreate is an inviolable right (Dillard, 2007). We need to tread carefully. There is evidence that population policies can lead parents to freely choose lower fertility (Abel et al., 2016). Moreover, slower population growth in developing countries is also likely to increase the ability of societies to adapt to the impacts of climate change (O'Neill et al., 2001).

Various philosophers and economists have considered the idea of "optimal population" (Zimmermann, 1989), and economists have extended the Pareto principles for efficiency to economies with endogenous populations (Golosov et al., 2007). In the climate context, such questions require an explicit treatment of the interests of various generations (Howarth, 1998). Our aim is modest. We add structure by considering dynasties as units of decision-making (rather than individuals), and assume rational family planning. In our context, the size of a generation is efficient apart from climate externalities. That is, we are focused on the question of whether fertility decisions by one dynasty affect the utilities of other dynasties. We do not touch on existing inequalities between dynasties (Bretschger and Valente, 2011) or between generations (Andersen et al., 2020).

Our ambition is to integrate in this paper, in a tractable analytical framework, the two above-mentioned bodies of literature, one on climate and economic growth, and the other on the economics of family planning. A handful of papers have studied the same nexus. Population features prominently in "the tragedy of the commons" where Hardin (1968) writes: "to couple the concept of freedom to breed with the belief that everyone born has an equal right to the commons is to lock the world into a tragic course of action". When a common good externality, such as climate change, is present in a model with endogenous fertility choice, Harford (1998) shows that two instruments are needed for Pareto efficiency: a Pigouvian tax on pollution and a tax per child. This tax equals the present discounted value of pollution taxes each descendant will pay. Our model computes these two externalities. In addition, we allow for education and human capital as crucial elements of family decisions, and we consider the environmental externality in a rigorous set-up of integrated assessment models of climate change. O'Neill and Wexler (2000) estimate the environmental cost of childbearing through its impact on climate. They run exogenous emissions and population scenarios to artificially construct a negative externality whose size is found to range from several hundred to several thousand dollars per birth. We consider endogenous emission and population scenarios. Schou (2002) studies endogenous fertility decisions in a long-run growth model with production-related environmental externalities. While he derives qualitatively similar solutions, our set-up enables a more complete characterization of the full dynamic path. Our model shares elements on fertility with de la Croix and Gosseries (2009), but we add production and climate details that provide meaningful quantitative estimates, in the tradition of Golosov et al. (2014). Our paper is close in spirit to de la Croix and Gosseries (2012), who argue that climate policies provide an implicit subsidy on fertility, and state that "further research is needed to assess the impact of using population and pollution capping schemes either alternatively or complementarily" (de la Croix and Gosseries, 2012, p. 284). We take up the challenge. Bohn and Stuart (2015) quantitatively assess the population externality in a balanced growth setting. Our dynamic paths show the importance of non-stationary dynamics: the population externality rises and falls.

Before turning to the description of the model in the next section, we note that, for reasons of tractability, this paper shares two limitations common to the aforementioned studies. First, we keep the rich cultural and economic context in which family planning decisions are made implicit. Male and female parents have different preferences regarding family planning (Alger and Cox, 2013), and women's career opportunities are a major source of variation in fertility (Voigtländer and Voth, 2013; Low et al., 2018) – and socially embedded preferences just as much (Fernández and Fogli, 2006; Dasgupta and Dasgupta, 2017). None of these aspects is tackled explicitly in our model, where our policy instrument "fertility costs" is to be interpreted as a broad description of measures such as childcare costs (Ebenstein et al., 2015; Bauernschuster et al., 2016) and parental leave (Olivetti and Petrongolo, 2017), but also includes change in laws (Godefroy, 2018) that affect economic and social structures and their effects on fertility.[5] Second, we acknowledge that the environmental externality to childbearing considered here is but one of a wide range of impacts, both positive and negative, that the birth of an additional child will have on society. For example, one the one hand, when grown up, children enlarge the tax base and can help pay for public pensions to the elderly (Blake and Mayhew, 2006), or share the burden of public goods, such as national defense or publicly funded research, or again produce scale/spillover effects in human capital formation, thus increasing the rate of technological improvement (Simon, 1996; Bretschger, 2020). On the other hand, children can receive transfers from the working-age population

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[5] We acknowledge that general population policies can be inefficient tools compared with the theoretical first-best fertility tax. This could increase social costs.

for publicly funded education and health programs, and therefore increase the burden on society. Furthermore, each additional child dilutes the value of commonly held resources such as public lands, publicly owned mineral or fishing rights, and parks. Kruse-Andersen (2019) shows that even if all research is directed towards green technologies, population growth still harms the environment. We expect that endogenous innovations and the direction of technical change will not overturn the main findings of our study.

In principle, if the different external costs and benefits to childbearing could be identified and estimated, they would all be part of the design of optimal family policy. In practice, externalities to childbearing are difficult to measure and to allow for in dynamic general equilibrium models. Therefore, here we study only the externality arising from the climate damage associated with childbearing. As our quantitative estimates show, this is a very important external effect.

4. An endogenous fertility climate–economy model

We start by considering a simple model featuring the trade-off between quality and quantity of children. The Unified Growth Theory (Galor and Weil, 2000; de la Croix and Doepke, 2003) puts this trade-off at the heart of the explanation of long-run growth and development. We then add a climate description that enables us to investigate the inter-relationship between fertility decisions and climate change. In this respect, we aim to describe the relevant mechanisms while keeping the model simple. For this reason, we abstract from life-cycle savings, various energy sources, and complex climate emissions-response functions. As in standard growth models, lower-case variables denote variables in intensive form; variables are normalized per size of the parent population N_t. Thus, $y_t = Y_t/N_t$ is output per worker, $k_t = K_t/N_t$ is capital intensity, $e_t = E_t/N_t$ is emissions per worker, and $h_t = H_t/N_t$ is human capital intensity. We assume that only parents work, whereas children are inactive. Thus, $l_t = L_t/N_t$ is the employment rate, and $c_t = C_t/N_t$ is consumption per parent. Current education expenditures are expressed per child, $s_t = S_t/N_{t+1}$.

4.1. Households

Our representation of the household sector borrows from de la Croix and Doepke (2003). Parents make decisions concerning the level of consumption c_t, the number of children f_t, and the level of spending on education s_t. We measure fertility as child per parent so that the next generation's cohort size is

$$N_{t+1} = f_t N_t. \tag{1}$$

As household income increases, the level of education expenditures increase as parents can afford more education. At the same time, the number of children for each family decreases, because rearing children is time costly (i.e., there is an opportunity cost in terms of missed labour income that is increasing with wages). For the convenience of analysis, we abstract from economic activity and consumption of the old generation N_{t-1}, and only consider the "adult" generation N_t as economically active. That is, we consider saving for the next generation and abstract from savings for future consumption when old, while we focus on the costs of rearing and educating children.[6] Households derive utility from consumption c_t, and parents enjoy having children as in Brunnschweiler et al. (2021), with f_t the fertility level chosen by parents.

Let $u_t = \ln(c_t) + \gamma \ln(f_t)$ be the direct utility of parents, and v_t recursive altruistic welfare:

$$v_t = \ln(c_t) + \gamma \ln(f_t) + \beta v_{t+1}. \tag{2}$$

While models with exogenous population tend to define welfare in aggregate terms, models with endogenous fertility usually describe altruism through offspring's average utility (e.g., de la Croix and Doepke, 2003; Shi and Zhang, 2009).[7] We assume that parents can only increase the welfare of their children by increasing bequests of human capital, h_{t+1}, and, in turn, parents' utilities depend on the amount of human capital they received.[8] The parameter $\gamma > 0$ weighs the utility derived from family size, while β is the (altruistic) weight associated with children's (average) utility.[9]

Through altruism, each generation positively weighs future consumption and fertility. As we will see below equation (6), real income depends on the per-worker capital k_t and human capital h_t, so that we can rewrite equation (2) as

$$v_t(k_t, h_t) = \sum_{i=0}^{\infty} \beta^i (\ln(c_{t+i}) + \gamma \ln(f_{t+i})), \tag{3}$$

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[6] We keep the old generation in the model while inactive as they play a role in the calibration of population numbers in Section 5.

[7] Average utility is used to support closed-form results (Golosov et al., 2014). Moreover, this formulation keeps solutions away from the repugnant conclusion (see the end of Section 6.2).

[8] Utility also depends on macro variables, such as the state of technology and climate, but these are beyond the decisions of individual families.

[9] The model in de la Croix and Doepke (2003) assumes $\gamma = \beta$, and considers two-period consumption. We abstract from consumption by the old generation but we keep the two parameters separate as each of them is essential to our quantitative calibration exercise.

where we write $v_t(k_t, h_t)$ to emphasize that, at the individual level, welfare depends (only) on per-worker (human) capital inherited. Parents can transmit wealth to children by providing them with financial bequests – as in Eckstein and Wolpin (1985) and Becker and Barro (1988) – and education. Children's human capital h_{t+1} is built through schooling s_t and does not directly depend on the level of human capital of parents h_t,

$$h_{t+1} = (\chi + s_t)^{\eta}, \tag{4}$$

where $\chi > 0$ is a base (free) level of knowledge, s_t is education investment, and $\eta \in (0, 1)$ is the elasticity of human capital to expenditures in education. If parents decide not to invest in the quality of their children, χ guarantees a minimum level of quality.[10]

Parents are endowed with one unit of time, which they allocate to child rearing and labour supplied to firms. The time parents spend raising their offspring, $\phi f_t < 1$, is deducted from labour supply,

$$l_t = 1 - \phi f_t, \tag{5}$$

where ϕ is the time needed to raise a child.

Finally, we consider family policies in place such as subsidized childcare, education, and other forms of support for parents, but also "girl power" policies such as girls' education and the creation of better career opportunities for young women. For convenience of the analysis, we catch all these measures into one bin that we label "fertility costs" ξ_t per child.[11] The household budget constraint becomes

$$c_t + s_t f_t + k_{t+1} f_t + \xi_t f_t = w_t h_t l_t + r_t k_t + T_t, \tag{6}$$

where income consists of labour income $w_t h_t l_t$, capital income $r_t k_t$, and transfers T_t. It is spent on consumption, education s_t, capital investments k_{t+1}, and fertility costs, the latter three multiplied by the number of children f_t.

Parents maximize their utility (3) subject to labour supply (5), the budget constraint (6) and human capital production (4).[12] The first-order conditions for consumption c_t, fertility f_t, schooling s_t, and capital investments k_{t+1} give the following expressions:

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[10] In studies that focus on between-family differences, the parameter χ can also be considered as compulsory education provided for free.

[11] This variable could, in principle, be both positive and negative. It is modeled as a cost as the optimal solution suggests that there should be a tax on newborns.

[12] The household's optimal problem is solved in detail in Online Appendix A.1.

$$(s_t + k_{t+1} + \xi_t + \phi w_t h_t)\frac{1}{c_t} = \frac{\gamma}{f_t}; \tag{7}$$

$$\frac{f_t}{c_t}(\chi + s_t) = \eta\beta\frac{w_{t+1}h_{t+1}l_{t+1}}{c_{t+1}}; \tag{8}$$

$$\frac{f_t}{c_t} = \beta\frac{r_{t+1}}{c_{t+1}}. \tag{9}$$

Equation (7) equates the marginal cost (left-hand side) to the marginal utility of having an extra child (right-hand side). Costs come from education, fertility costs, and opportunity costs of time (i.e., forgone income) – all valued at the marginal utility of consumption. Equation (8) presents total expenditures on education on the left, which equals the next-period discounted income produced by human capital, scaled by the elasticity of education in human capital. Both terms of the equation are evaluated at the marginal utility of consumption. Finally, the left-hand side of equation (9) presents the marginal costs of investments in capital (per child), which is proportional to the number of children and evaluated at the marginal utility of consumption. The right-hand side shows the next-period returns on investments, discounted and evaluated with the marginal utility of income.

For this economy, it is not possible to find closed-form solutions for fertility and schooling choices, independent of the future state of the world. That is, future policies affecting returns on capital and wages, such as climate policies, will affect future fertility choices, the share of schooling in expenditures, and thereby also present fertility and schooling choices. For the long run, when total factor productivity and the social cost of carbon become very large, the economy converges to a balanced growth supported by closed-form solutions for the fertility rate and expenditures on capital and education investments (see Online Appendix A.4).[13]

On the transition path, the model captures the quality–quantity children's trade-off highlighted by Becker and Lewis (1973) and our simulations will show this feature to have substantial consequences for efficient policy choices. In our model, education affects fertility through income, $w_t h_t l_t$, as seen in equation (8). There is no direct effect of education on variables such as

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[13] These show that investments in capital follow the Brock and Mirman (1972) model, being proportional to the capital income share α and the future welfare weight β. Investments in education are proportional to the labour income share $1 - \alpha$, the elasticity of human capital for education η, and the future welfare weight β. Fertility f_t increases with preferences γ and decreases with the time costs of raising children ϕ. An increased capital income share α and increased weight for the future β share induce parents to save more for their children, increasing the cost per child and reducing the number of children.

family-size preferences, knowledge of contraception, and delayed start to motherhood. In this respect, while following standard practice, our model is by construction limited in its ability to describe the full breadth of the effects of education effects on fertility, as the focus is on the interplay between fertility choices and climate change. Also, our model does not describe the effects of climate change on fertility and mortality through the sectoral structure of climate damage (Casey et al., 2019).

4.2. Production

Following Nordhaus and Sztorc (2013), we distinguish gross output, Q_t, from net output, Y_t, the latter obtained after subtracting costs of abatement and climate damages. Thus,

$$Y_t = (1 - d_t)(1 - a_t)Q_t, \tag{10}$$

where d_t is the relative loss of output due to climate damages and a_t is the relative costs of abatement. The production technology is

$$Q_t = A_t K_t^{\alpha} (h_t L_t)^{1-\alpha}, \tag{11}$$

where $K_t = k_t N_t$ is aggregate capital, $H_t = h_t L_t$ is aggregate human capital (or effective labour supply) expressed in quality-adjusted or efficiency units (Lucas, 1988), $L_t = l_t N_t$ is labor supply, and A_t is total factor productivity, which evolves over time with an exogenous constant growth rate $\widehat{A}$ (hats denote rates of change):

$$A_{t+1}/A_t = \widehat{A}. \tag{12}$$

Emissions are assumed to increase proportionally with gross output, with benchmark carbon intensity σ_t to exogenously decline over time, as in Nordhaus and Sztorc (2013). We denote by μ_t the (endogenous) emission control rate. Per-worker emissions, e_t, are then given by

$$e_t = (1 - \mu_t)\sigma_t q_t, \tag{13}$$

where $q_t = Q_t/N_t$ is per-worker gross output. The parameter σ_t describes the emission intensity of the economy consistent with the economy's dependence on, for instance, fossil fuels, absent climate policies. It tends to decline over time for two main mechanisms. First, goods tend to become of better quality and are more diversified, and along this transformation material and energy throughput per produced value declines. Second, the energy mix shows a switch from cheap coal to more versatile oil and gas. On top of these autonomous trends, μ_t represents the enhanced energy savings and fuel switching induced by climate policies.[14] Unit costs of abatement are given by

$$a_t = \theta_1 \mu_t^{\theta_2}, \tag{14}$$

where $0 < \theta_1 < 1$ and $0 < \theta_2$ are parameters.[15] Firms maximize profits in a competitive market

$$\Pi_t = Y_t - w_t h_t L_t - r_t K_t - \tau_t E_t, \tag{15}$$

subject to equations (10) and (11), where w_t is the wage rate expressed in per quality workers, r_t is the return to capital, and τ_t is a tax on emissions $E_t = e_t N_t$. The first-order conditions give the abatement intensity μ_t and emissions through equation (13), as well as the capital and wage income shares $r_t K_t, w_t H_t$:[16]

$$\mu_t = \min\left\{1, \left(\frac{\tau_t \sigma_t}{(1 - d_t)\theta_1 \theta_2}\right)^{1/(\theta_2 - 1)}\right\}; \tag{16}$$

$$r_t k_t = \alpha(y_t - \tau e_t); \tag{17}$$

$$w_t h_t = (1 - \alpha)(y_t - \tau_t e_t). \tag{18}$$

4.3. Climate damages

Climate damages d_t are assumed to depend on cumulative emissions,

$$d_t = 1 - \exp(-\delta Z_t), \tag{19}$$

$$Z_{t+1} = Z_t + M e_t N_t, \tag{20}$$

where Z_t represents cumulative emissions up to the start of period t. Output, labour, and emissions variables are measured per year, so that we multiply emissions by $M = 30$, the number of years within a period.

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[14] We note that the above representation of the determinants of emissions is recurring in all versions of the Dynamic Integrated Climate Economy (DICE) model and the Regional Integrated model of Climate and the Economy (RICE), and we keep it for simplicity. A richer specification of the climate abatement module is typical for models that focus on endogenous technological change but this is not the main focus of this paper.

[15] To obtain total abatement costs, multiply equation (14) by gross output per worker, q_t, which yields a convex abatement cost function in abatement levels.

[16] The firm's optimal program is solved in detail in Online Appendix A.2.

The effect of cumulative emissions on damages per period (19) reflects the parametric form of Golosov et al. (2014), but it deviates importantly in the sense that it assumes that emissions lead to immediate and lasting temperature changes that do not decrease over time.[17]

The climate damage dynamics implies that future damages tend to increase with current labor supply and, thus, with population size. This is an important feature of the model. The equation thus represents the channel through which fertility decisions affect emissions and the economy.

4.4. Competitive equilibrium

The economy produces one homogeneous good that can be used for consumption, education, and investments. Because each period lasts 30 years, we assume that capital fully depreciates and the price of this final good is normalized to one. Thus,

$$N_t c_t + N_t s_t f_t + N_t k_{t+1} f_t = Y_t. \tag{21}$$

Given the description of the behavior of households and firms, we can now define the competitive equilibrium of this model economy. Given technology A_t, initial values of population N_1, capital K_1, and human capital h_1, a competitive equilibrium consists of sequences for parents' sizes, capital and human capital, (N_t, K_t, h_t), consumption, schooling, investment, fertility and labour decisions $(c_t, f_t, s_t, k_t, l_t)$, firms' emissions and output decisions (e_t, y_t), supported by rents, wages, carbon, and fertility costs $(r_t, w_t, \tau_t, \xi_t)$, such that (a) households maximize utility subject to their budget constraint, (b) firms maximize profits, and (c) markets clear.

4.5. Welfare

The competitive equilibrium takes carbon and fertility costs as given, and the equilibrium conditions then define wage, output, consumption, labour, fertility, and schooling choices. Households and firms do not consider the

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[17] In Golosov et al. (2014), long-term damages caused by one unit of emissions are about 20 percent of short-term damages caused by that unit of emissions, because of the decay of atmospheric CO_2. The reason is that they assume damages to be proportional to atmospheric CO_2 concentrations, rather than to temperatures. If we consider a more complete emissions–concentrations–temperature model, we find that the depreciation of atmospheric CO_2 and the slow temperature adjustment almost exactly cancel each other out. This finding enables us to use a very simple model where damages and temperature rise only depend, linearly, on cumulative emissions (Dietz and Venmans, 2019). That is, emissions cause an almost immediate and permanent temperature rise.

externalities they generate. We now consider a planner who maximizes welfare of the first generation v_1, expressed by equation (3).[18] The main analytical result is summarized by the following proposition.

Proposition 1. *The social optimum can be implemented by two instruments:* (1) *a carbon tax* τ_t*, equal to the net present value of future marginal damages, given by*

$$\tau_t = \delta M N_t c_t \sum_{i=1}^{\infty} \beta^i \frac{y_{t+i}}{c_{t+i}}; \tag{22}$$

and (2) *a fertility cost* ξ_t*, which corrects for damages caused by extra future emissions per child*,

$$\xi_t = \frac{1}{N_{t+1}} \sum_{i=1}^{\infty} \frac{\tau_{t+i} E_{t+i}}{R_t^{t+i}} \tag{23}$$

where for ease of notation the returns on investments are compounded into $R_t^{t+i} = r_{t+1} r_{t+2} \ldots r_{t+i}$. *The planner returns lump-sum carbon tax and fertility cost revenues to current households*:

$$T_t = \tau_t e_t + \xi_t f_t. \tag{24}$$

This ensures that the current value of output equals the income of the current adult generation, which is equal to its expenditures, as given by equation (6).[19]

As the consumption share tends to remain stable over time, expression (22) shows that the optimal carbon tax approximately follows the time path of income. Indeed, with a constant consumption share in output c_t/y_t, the carbon tax formula collapses to the one in Golosov et al. (2014):[20]

$$\tau_t \approx \frac{\beta \delta}{1-\beta} M Y_t. \tag{25}$$

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[18] Scovronik et al. (2017) explore the consequences for a mitigation policy of assuming different exogenous population paths. In a normative analysis, taking aggregate utility with endogenous fertility can lead to a "repugnant conclusion" (Parfit, 2016) with high fertility levels and low consumption. Indeed, at the end of Section 6.2, we see that aggregate income is maximal in scenarios with high fertility. Using average utility does not lead to preferences for very low populations, as congestion externalities disappear long before the population becomes very small.

[19] In Online Appendix A.3, we provide the full welfare program with all constraints and optimality conditions and we prove the propositions.

[20] The model is written in annual output so that, over a period, emissions cumulate over M years. This explains the M in the formula. Another way to understand the factor M is: the term $1-\beta$ measures the time preference rate per period, which is about proportional to the number of years per period. The outcome of the formula is thus more or less independent of the number of years within a period, apart from the change in temperature delay explaining the β in the numerator.

That is, the carbon tax grows proportional to output, a feature our model shares with Golosov et al. (2014) and Gerlagh and Liski (2017). The intuition for this result is that damages tend to increase proportionally with output, while the Ramsey rule tells us that the discount factor decreases inversely proportional with consumption growth. As a result of the two opposing forces, and for a constant consumption share, the net present value of damages associated with one unit of CO_2 is independent of future technology, productivity, and labor supply.[21]

The fertility cost ξ_t in equation (23) measures the fertility externality (i.e., the decrease in welfare of other dynasties) per increase in the number of children f_{t+1}, and it has a simple intuition. The term within the summation aggregates all climate change damages caused by all descendants, valued at current prices. The scaling with the next-period cohort size divides these damages by the size of the immediate offspring, so that the fertility costs equal the value of externalities caused per child.

The proposition highlights that household education decisions need no correction, but that, in addition to carbon taxes, fertility decisions also need a correction to achieve the social optimum. The question is, on the one hand, how second-best carbon taxes respond if fertility choices cannot be adapted to climate policy goals and, on the other hand, how family planning policy must correct for missing carbon taxes. To answer this question, we calibrate the model and run four scenarios detailed in Section 6 and Online Appendix B.

5. Calibration

Calibration entails determining the starting values of a few key variables for our policy simulations and the values of the relevant parameters. In discussing our calibration procedure, we follow the order of presentation of the model equations in the previous section.

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[21] Both mentioned papers build their carbon tax formulas on parametric choices that guarantee a constant investment and consumption share in income, independent of climate policy. See also the Brock and Mirman (1972) model, where full capital depreciation and Cobb–Douglas production result in a constant savings rate along the transitionary path. Our model adds investments in education to the list of expenditures. That is, to support closed-form (25) as the solution, we would have to impose a constant value share for both capital and human capital, independent of the level of emissions, and a constant elasticity of human capital with respect to education ($\chi = 0$). The production function set out in Section 4.2 produces a hump-shaped value share of emission allowances; the value share is zero for high emission levels if carbon prices are zero, and for zero emissions supported by high carbon prices. Because the capital and human capital value shares are a constant fraction of the remaining part (see equations (17) and (18)), they are not constant.

We measure all flow variables per year. One period lasts 30 years in our model. When results are presented in terms of volumes per period, aggregates are multiplied by $M = 30$. The first year of our model, $t = 1$, is labeled "2020" and runs from 2005 to 2035.

5.1. Demographics and households

We first determine the starting cohort size N_1. Within a single period, parents are aged 15–45, which is the range that corresponds to the fertility period of a woman. Generations overlap as, at each point in time, adults, the old, and children are alive. The total population as observed in the data, P_t, is given by

$$P_t = \nu_{t-1} N_{t-1} + N_t + \epsilon N_{t+1}, \tag{26}$$

where old parents are represented by N_{t-1}, ν_{t-1} is the survival rate of the old, and the current generation of parents is given by N_t. The current generation of children N_{t+1} is multiplied by $\epsilon = 1/2$, as babies are born uniformly over the period.[22]Life expectancy in years is given by $(1 + (1/2) + \nu_{t-1})M$.[23]

We begin by determining the initial number of parents, N_1, using equation (26). We start the first period with $P_1 = 7.8$ billion people (United Nations, 2019). Cohort N_0 is born between 1945 and 1975, and we take the life expectancy in 2010 of 73 years, when this cohort was, on average, 50 years of age. We then conclude that $\nu_0 = 28/30 = 0.93$.[24] Fertility of that cohort when they were, on average, 30 years of age, around 1990, was close to 1.6, so that $N_1 = 1.6 N_0$. Fertility f_1 in 2020 is around 1.2. Using equations (1) and (2), we obtain[25]

$$N_1 = \frac{P_1}{1 + \nu_0 / f_0 + \epsilon f_1} = \frac{7.8}{1 + 0.93/1.6 + 0.5 \times 1.2} = 3.57. \tag{27}$$

Turning to the household parameters, based on a 1 percent pure discount rate per year, we exogenously set the altruism preference parameter equal to $\beta = 0.74$. In Section 6.2, we also show results for pure discount rates

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[22] This is the expected value of a uniform distribution. We do not exploit the possibility to consider delayed fertility as a population control measure, described in equation (26) by a reduction of ϵ.

[23] This is relevant to the calibration of N_t, but life expectancy does not play a role in our analysis. See Gerlagh et al. (2017) for an extensive analysis of the implications of increasing life expectancy for optimal climate policies.

[24] Setting $(1 + (1/2) + \upsilon_0)M = (1 + (1/2) + \upsilon_0)30 = 73$ and solving for υ_0 yields the value 0.93.

[25] If we count the number of people younger than 30 years by 2005 (United Nations, 2019), we find 3.54 billion, which confirms our approach and resulting figure of 3.57 as a reasonable proxy.

ranging from 0.5 to 2 percent per year. Parameter ϕ represents the time-cost of children. In the literature, the value chosen for ϕ is between 15 and 30 percent (Haveman and Wolfe, 1995; de la Croix and Doepke, 2003). We set $\phi = 0.2$, implying that a couple spends about 20 percent of its time raising two children.

In order to determine the other parameters, we assume that, in the long run, population slowly decreases so that fertility converges to a value close to one (i.e., $f_\infty = 0.95$), consistent with observations for high-income countries (see Figures 2 and 3), while we set the long-run education share to 20 percent of income.

There is no need for fertility costs or income transfers in the long run, $\xi_t = T_t = 0$. Then, we can rewrite equation (6) and specify the income shares for consumption and educational expenses as

$$\frac{c_t}{y_t l_t} + \frac{k_{t+1} f_t}{y_t l_t} + \frac{s_t f_t}{y_t l_t} = 1. \tag{28}$$

For calibration purposes, we consider the long-run balanced growth of the economy. In Online Appendix A.4, we derive the shares of investments and education expenditures in income, together with fertility levels:

$$i \equiv \frac{k_{t+1} f_t}{y_t} = \alpha\beta; \tag{29}$$

$$j \equiv \frac{s_t f_t}{y_t} = (1-\alpha)\eta\beta; \tag{30}$$

$$f = \frac{1}{\phi}\frac{\gamma - (1+\gamma)(i+j)}{1-\alpha+\gamma-(1+\gamma)(i+j)}. \tag{31}$$

We note that the investment share exactly replicates the Brock and Mirman (1972) model. The last two equations are inverted to compute $\eta = 0.38$ and $\gamma = 1.014$ based on the assumed values $j_\infty = 0.2$ and $f_\infty = 0.95$.[26] The last parameter related to education, χ, is calibrated such that the "business as usual" scenario reproduces first-period fertility f_1 and is set equal to 0.00078.

5.2. Production and climate

We set the capital elasticity of output equal to $\alpha = 0.3$. A declining share of labour income over the past decades suggests a higher value. However, the very long periods in our model partly relabel investment in capital as an intermediate good; the initial capital stock earns a smaller value

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[26] The value for $\eta = 0.386$ that we consider falls within the range of estimates of returns to education (see de la Croix and Doepke, 2003).

share of aggregate production over the full period compared with an annual model. To cover both sides, in Section 6.2 we vary its value over the range 0.2–0.4.

Consider the long-run balanced growth of the economy. The fundamental driver of long-run growth is technology, which evolves according to some exogenous growth factor:

$$A_t = A_0 \widehat{A}^t. \tag{32}$$

In the social optimum, long-run emissions are zero and damages are a constant fraction of output.[27] All long-run growth properties are independent of the level of damages so that, for convenience, we abstract from damages when we calibrate these parameters, implying that we can write $y_t = q_t$, $e_t = 0$, and $\chi \ll s_t$. As fertility is constant, consumption, investments, and schooling expenditures increase proportionally with output, that is, $\widehat{c} = \widehat{k} = \widehat{s} = \widehat{y}$. In turn, output increases with capital and human capital: $\widehat{A}\widehat{k}^{\alpha}\widehat{h}^{1-\alpha} = \widehat{y}$. The long-run human capital build-up (4) yields $s_t = h_{t+1}^{1/\eta}$, which in growth factors gives $\widehat{h} = \widehat{s}^{\eta}$. Combining all these linkages, we obtain $\widehat{A}\widehat{y}^{\alpha+\eta(1-\alpha)} = \widehat{y}$, resulting in the long-run growth dependence on technology:

$$\widehat{y} = \widehat{A}^{1/(1-\eta)(1-\alpha)}. \tag{33}$$

We assume a long-run income growth of 1.5 percent per year, that is, by a factor of 1.56 per period, which defines technological growth $\widehat{A}$.

We next consider climate damages. The pre-industrial level of greenhouse gas concentrations in the atmosphere was 280 ppm (parts per million) of carbon (IPCC, 2014), which corresponds to 2.17 $TtCO_2$ (teratonnes). Doubling this value might lead to irreversible climate events due to the subsequent increase in temperature. According to IPCC (2014), about 20 percent of an increase in CO_2 emissions will stay in the atmosphere for many thousands of years depending on the amount of carbon emitted. New evidence is more pessimistic, however, indicating that between 20 and 35 percent of CO_2 remains in the atmosphere for centuries. To calibrate the damage parameter δ, we assume that about 30 percent of cumulated emissions remain in the atmosphere for thousands of years. The amount of cumulated emissions necessary to double the concentration level of CO_2 in the atmosphere is equal to 2.17 $TtCO_2/0.30 = 7.23$ $TtCO_2$. Early estimates project that a

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[27] Indeed, it can be shown analytically that the social optimum will converge to such a balanced growth path. Carbon taxes increase with output to infinity as seen from equation (22) or, more clearly, in equation (25). In response to rising carbon taxes, abatement (16) increases to 100 percent, and emissions (13) become zero in finite time. Then, given our assumption of damages dependent on cumulative emissions (19), d_t will become a constant value.

doubling of atmospheric concentrations would yield damages equal to a few percentage points of GDP. In his paper, Tol (2009) collects the most recent impact estimates of climate change on GDP. Depending on the temperature increase, we might have a loss in GDP between 1 and 5 percent. In their more recent review of climate damage estimates, Howard and Sterner (2017) indicate a higher percentage of GDP losses from increases in temperature. Based on that evidence, we assume that doubling concentration levels in the atmosphere, by emitting 7.23 TtCO$_2$, reduces world output by 7 percent. We can then calibrate δ by solving equation (19); that is, given $\exp(-\delta Z) = 1 - d$, we obtain

$$\delta = -\frac{\ln(1-d)}{Z} = -\frac{\ln(0.93)}{7.23} = 0.010. \tag{34}$$

Turning to abatement cost parameters, we begin by noting that the DICE 2013 model (Nordhaus and Sztorc, 2013) assumes that 100 percent of abatement (zero net CO$_2$ emissions) costs 7 percent of aggregate GDP. We assume higher abatement costs in the very short term and at current levels of technology, and we assume rapidly declining costs as renewable energy develops. On this basis, we set $\theta_1 = 0.10$, $\theta_2 = 2$, with θ_1 halving every 50 years, so that the rate of change equals $\widehat{\theta_1} = 0.5^{30/50} = 0.66$.

5.3. Initial values

We complete our discussion of calibration with the specification of the initial values of a few key values. We use trend-based values for 2020 as a target (i.e., without the effects of the COVID-19 pandemic). We determined N_1 as described in Section 5.1. In 2018, world GDP was about 83 trillion euros per year (at constant 2010 prices), increasing at about 3 percent per year, so that we target $Y_1 = 0.088$ (quadrillion euros). As $\phi = 0.2$ and $f_1 = 1.2$ from Section 5.1, labour supply is $l_1 = 1 - \phi f_1 = 0.76$. We calibrate h_1, k_1, and A_1, to reproduce annual income in the first period and education and savings consistent with expenditures in the previous period (i.e., 1990). World cumulative emissions between 1750 and 2005 (the first year of our first period) amounted to about 355 GtC (gigatonnes), corresponding to 1.3 TtCO$_2$ (teratonnes) (IPCC, 2014). Total world industrial emissions from fossil fuels in 2019 were equal to 38 GtCO$_2$; extrapolating past trends of 1.8 percent growth, we consider $E_1 = 0.0387$ TtCO$_2$ for 2020. Without abatement, emissions per unit of output are $\sigma_1 = e_1/q_1$ (13), so that

$$\sigma_1 = \frac{E_1}{\exp(\delta Z_1) Y_1} = \frac{0.0387}{1.013 \cdot 0.088} = 0.434, \tag{35}$$

measured in kgCO$_2$ per euro. Nordhaus and Sztorc (2013) suggests a decline of 1.5 percent per year in emission intensity in the business as usual scenario,

Table 1. Parameters

Parameter	Description	Value	Reference and targets
Constant parameters			
β	Altruism	0.74	Discount rate (1 percent per year)
ϕ	Opportunity cost of children	0.2	Literature
γ	Fertility preferences	1.014	Long-run fertility ($f_\infty = 0.95$)
η	Elasticity of human capital to education	0.386	Share of education ($i_\infty = 0.2$)
χ	Compulsory school	0.00077	First-period fertility ($f_1 = 1.2$)
α	Value share of capital	0.3	Literature
δ	Exponent in damage equation	0.010	Long-run climate damages
θ_2	Abatement exponent	2	Literature
Initial values for state variables and dynamic parameters			
N_0	Old-age population	2.23	See text
N_1	Parents	3.57	See text
K_1	Capital stock	8.44	Investments in previous period
Z_1	Cumulative emissions	1.3	Historic emissions in TtCO$_2$
A_1	Productivity	0.957	First-period GDP (75 tn per euro per year)
θ_1	Abatement coefficient	0.10	See text
σ_1	Baseline emission intensity	0.434	See text
Dynamic parameters			
$\widehat{A}$	TFP growth	1.21	Long-run economic growth (1.5 percent per year)
$\widehat{\theta}_1$	Decline in costs of abatement	0.66	See text
$\widehat{\sigma}_1$	Decline in baseline emission intensity	0.64	Data 1990–2018 (1.5 percent per year)

which is consistent with historical emission trends (before there were climate policies), so that the rate of change equals $\widehat{\sigma}_1 = (0.985)^{30} = 0.64$.[28]

Table 1 summarizes the parameters and initial values we used to calibrate our model and carry out the simulations presented in the next section.

6. Scenarios and results

6.1. Central results

We use our integrated climate–fertility model to evaluate the interplay between climate and fertility policies by considering four scenarios. The first scenario is the baseline run, or business as usual (BAU), where there are no

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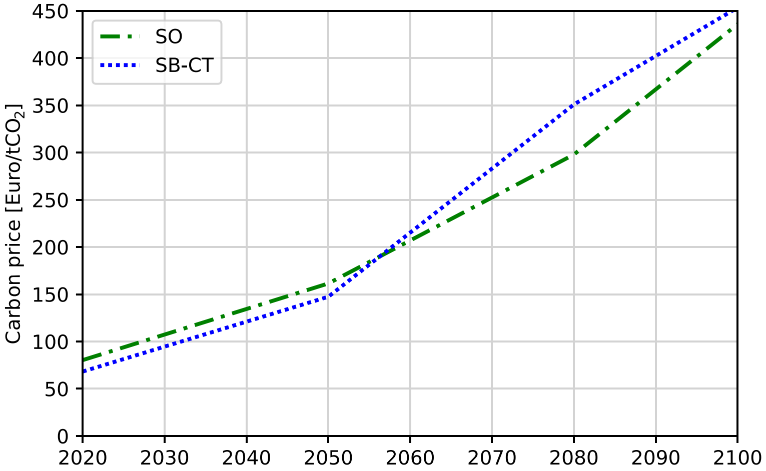
[28] See the database https://data.worldbank.org/indicator/EN.ATM.CO2E.PP.GD.KD.

Figure 5. Carbon taxes



deliberate policies affecting either climate or family planning. For the BAU scenario, it is important to impose the capital investment first-order conditions as part of the scenario calculations, otherwise the scenario tends to internalize the climate externality (which contrasts the BAU assumption) by reducing climate damages through lower investments in capital (Rezai, 2011). The next scenario is the social optimum (SO), where welfare is maximized, and the policymaker implements the optimum through carbon and family policies. The third scenario is the second-best with carbon taxes (SB-CT), where the policymaker cannot steer family planning. In the model, we set fertility costs equal to zero and the regulator chooses a carbon tax that maximizes welfare. The last scenario is the second-best with fertility taxes (SB-FT), where the carbon tax is set equal to zero and fertility costs adjust to maximize welfare. Below we present all results for the central parameter values listed in Table 1. In Section 6.2, we sample parameters and macro targets over intervals around the central values to verify the robustness of the results.

Figure 5 shows the optimal carbon tax. Only the SO and the SB-CT cases are depicted, as the carbon tax is zero in the other two scenarios. In the SO and SB-CT runs, the carbon tax starts at 80 and 68 euros per tCO$_2$, respectively. In the next periods, it tends to rise approximately with income.[29] The tax is relatively high compared to the estimates of Tol (2009), because of the more pessimistic damages (parameter δ).

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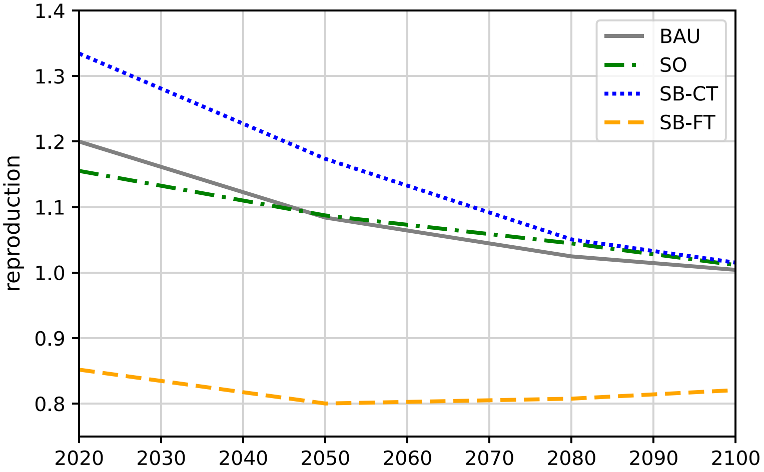
[29] See the end of Section 6.2 for further clarifications about the mechanism behind this result.

Figure 6. Fertility



It stands out that the carbon tax is lower in the SB-CT scenario in the first periods, but then overcomes the carbon tax set in the SO scenario. The explanation is twofold. First, carbon taxes reduce income and thereby increase fertility, increasing future emissions. Thus, this second-best climate policy without family planning will find it optimal to diminish the carbon tax as an indirect tool to reduce future emissions. Second, carbon taxes tend to scale with income (Golosov et al., 2014; Gerlagh and Liski, 2017). In the SB-CT scenario, fertility is higher, the future population is larger (as seen in Figure 7), aggregate income is higher, and thus the carbon tax is higher. We see that the second mechanism outweighs the first from 2070 onward. This naturally leads to Figures 6 and 7.

Figures 6 and 7 show, respectively, fertility (child per parent) and population. Here we see that the social optimum indeed reduces fertility, from 2.4 children per family in the BAU scenario down to 2.3 children per family, while carbon taxes without complementary family policies tend to increase fertility up to 2.7 children per household in the SB-CT scenario. The SB-FT scenario, instead, very strongly reduces fertility, down to 1.7 children per family. Figure 7 shows that contemporary changes in fertility have lasting consequences on future population size. In the BAU and the SB-CT scenarios, population stabilizes below 12 billion and above 14 billion, respectively. In the SO run, instead, population growth is reduced compared with the BAU scenario. The SB-FT run reduces fertility so much that the population level peaks by the middle of the century and then decreases. Note the substantial population gap between the SO and SB-CT scenarios by 2100.

Figure 7. Population

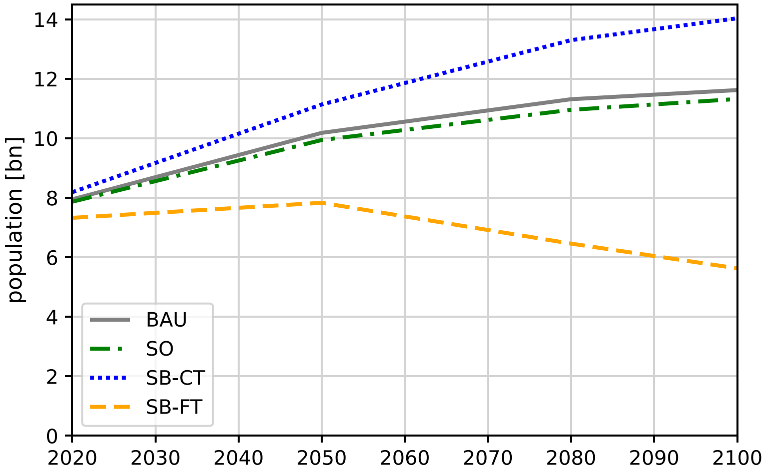


Figure 8. Climate costs of fertility

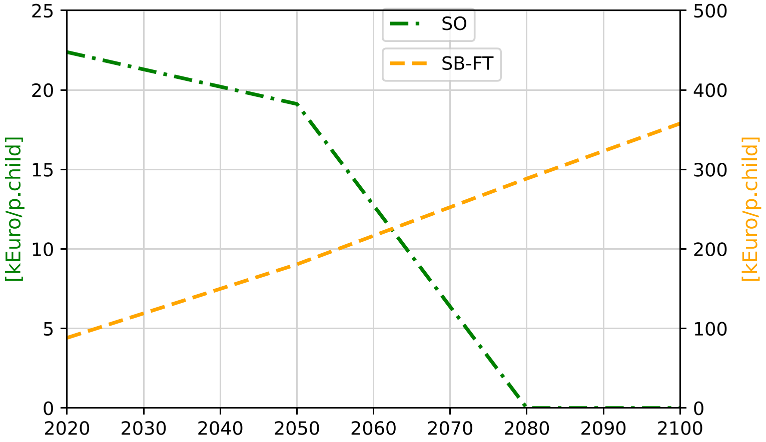
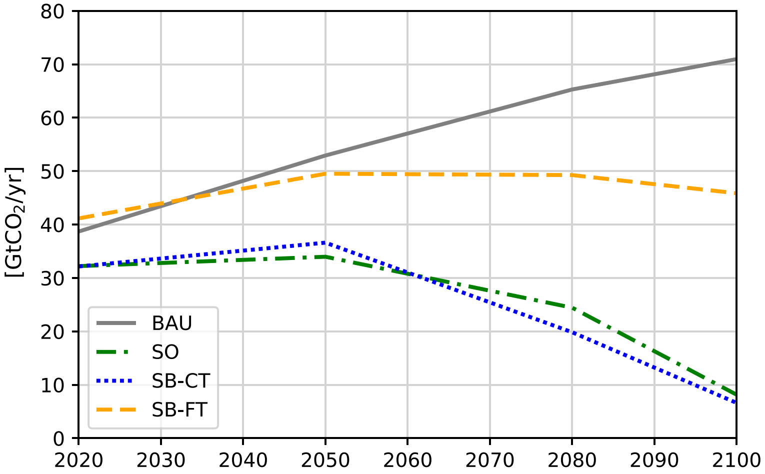


Figure 8 shows the fertility costs in the SO and SB-FT scenarios. The resulting numbers should not literally be interpreted as birth taxes, but as the net present value of change in effective family support, per child, compared with a reference scenario of current family policies that are deemed optimal if no climate concerns are considered. In the SO scenario, the fertility costs start at 22,000 euros per child. To appreciate this figure, note that per capita emissions in 2020 are about 4.6 tCO_2 per year, valued at 80 euros per ton, so that the per

Figure 9. Emissions

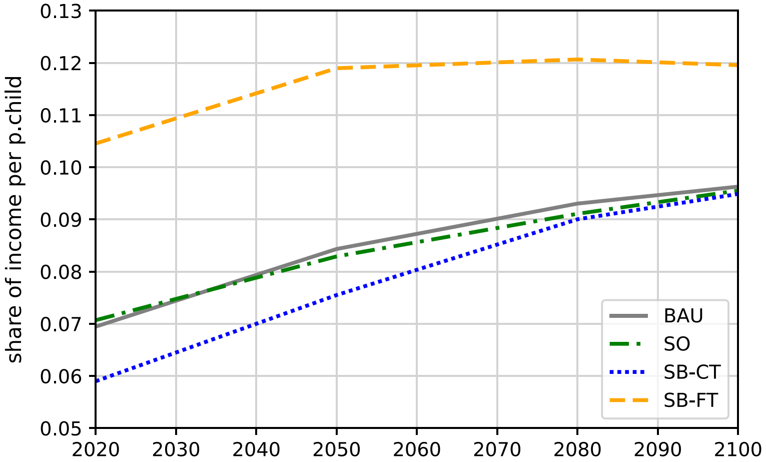


capita climate externality is valued at about 370 euros per capita per year. In the SO scenario, the economy fully decarbonizes after 2110; we find a period of emissions somewhat below a hundred years. This fits the resulting fertility costs by 2020, as 22,000 euros is somewhat below 370 euros per year multiplied by 100 years. Fertility costs drop after 2050 anticipating the decarbonization of the economy. In the SB-FT scenario instead, emissions per capita continue to rise throughout and after the 21st century, and fertility costs rise, reflecting the setting in which family planning is the only instrument available to abate emissions.

In Figure 9, in the BAU scenario, emissions increase over the whole period as the carbon tax and the fertility costs are set to zero. As expected, in the SB-FT run, fertility costs reduce the level of emissions compared with the BAU scenario. However, the boost in productivity induced by total factor productivity (TFP) and increased schooling investment, prevent emissions from declining rapidly. Conversely, in both the SO and SB-CT scenarios, emissions decrease after 2050 when carbon prices rise sufficiently, and eventually reach zero after 2100. Note that our model features an endogenous environmental Kuznets curve.

Figure 10 further explores the interaction between climate policies and education. The figure shows investment in education per child. We find the same mechanism as in Casey and Galor (2017) and Xue and Yip (2017), who observe that a population constraint increases parents' willingness to invest in the education of their children. The intuition is that lower fertility levels direct parents' resources to be used for increasing human capital of fewer

Figure 10. Investment in education as a share of income



children. This effect is clear when looking at both the SO and SB-FT scenarios, where family planning policies are adopted as a separate policy instrument for climate policies. Thus, in the SB-FT case, which is the most severe in terms of fertility policies, the investment in education per child reaches 12 percent of income and then stabilizes after 2050. Conversely, in the SB-CT scenario, investments in education per child are initially lower compared with both the BAU and the SO cases, due to the rebound effect of carbon prices on fertility. Differences between these three scenarios disappear by the end of the century.

We now compare emissions and fertility externalities. Figures 11 and 12 give quantitative substance to the concept of family planning as “the ultimate externality” (Harford, 1998). Figure 11 shows the welfare loss associated with emissions. The outcome is obtained by multiplying emissions by their shadow price (e.g., the social cost of carbon as net present value of future damages caused by one extra unit of emissions) and dividing the result by gross output. We repeat this procedure in all the scenarios (and for the BAU and SB-FT scenarios where carbon prices are zero but the social costs of carbon are positive). When we multiply the social cost of carbon by emissions, we find an annual emissions externality in the order of magnitude of about 3–4 percent of income. In Figure 12, we adopt the same procedure for the shadow price of fertility multiplied by the fertility level, then divided by gross output. Comparing both indicators for all scenarios, we notice that without carbon taxes, the fertility externality is much larger than the emission externality. We can estimate the size of the birth externality by a back-of-the-envelope

Figure 11. Welfare loss associated with emissions as a share of income

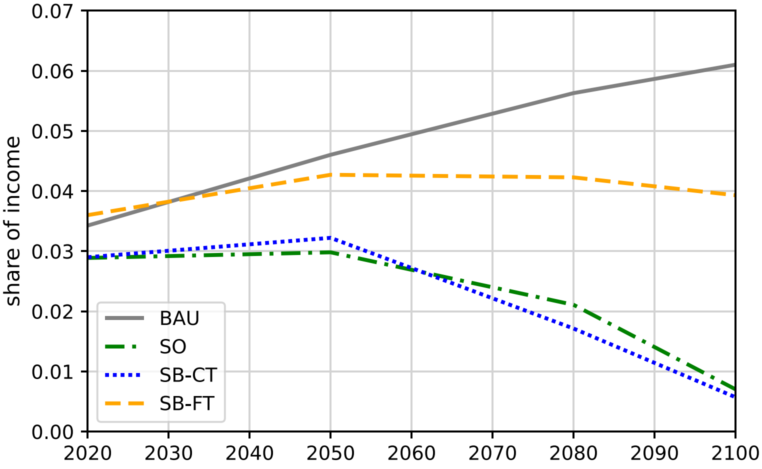
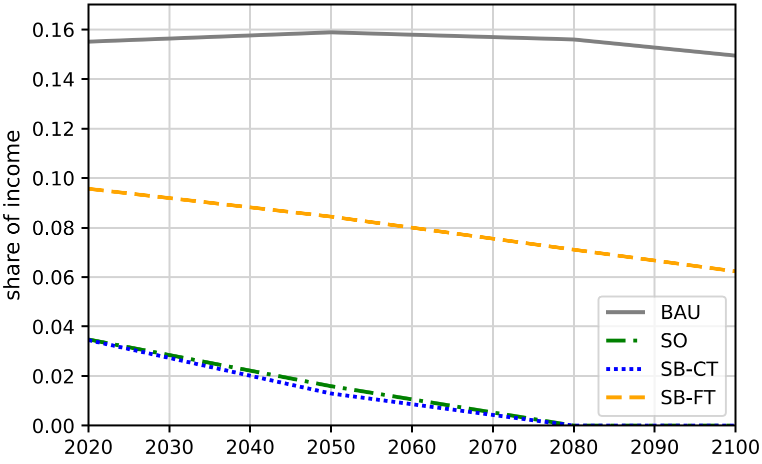


Figure 12. Welfare loss associated with births as a share of income



computation, providing a first quantitative estimate of the damages associated with current population growth. Every year, about 140 million children are born. If efficient carbon policies are implemented, the externality costs associated with these births amounts to about 3 trillion euros per year. If no effective climate policies are implemented, then the externality costs amount to 12 trillion euros per year.

6.2. Robustness assessment

The above results are calculated using the calibrated model parameters from Table 1. Here we assess the robustness of our findings; we present results for a series of 1,000 alternative parameter sets. We let the capital−income share α vary between 0.2 and 0.4. The annual pure rate of time preference ranges from 0.5 to 2 percent; β covers the interval $[0.55, 0.86]$.[30] Time for education per child varies between $\phi = 0.15$ and 0.25. Climate damages vary between $\delta = 0.0042$ and 0.0142. The autonomous emission intensity decline is set between 1 and 2 percent per year, $\widehat{\sigma} \in [0.55, 0.74]$. The costs of fully decarbonizing the economy θ_1 range from 5 to 15 percent of output in the first period, and its decline is between 1 and 2 percent per year, $\widehat{\theta}_1 \in [0.55, 0.74]$. These are the direct parameter choices. The other parameters $\gamma, \eta, \widehat{A}$ are based on targeted long-run macro moments. We target BAU fertility in 2020 between 1.15 and 1.25, long-term fertility between $f_\infty = 0.9$ and 1.05, and long-term education expenditure shares between $j_\infty = 0.15$ and 0.25. We target income growth between 1 and 3 percent per capita per year.

We run 1,000 scenario sets. Randomization is such that, for each parameter and target, the 1,000 draws cover the interval uniformly, and the distribution is independent between the parameters and targets. The graphs report p10, p25, p50, p75, and p90 percentiles with the median emphasized, for each variable, for each point in time.[31] Table 2 reports the dependence of the main outcome variables on parameter values through linear OLS. By construction, the parameters fully determine outcomes; thus, R^2 is a measure of the non-linearity of outcomes with respect to the parameters. The standard error of the coefficients is, on average, 0.035, sufficiently small to identify the

Table 2. Monte Carlo outcomes statistics

	Carbon tax SO 2020	Birth externality SO 2020	Fertility SO/BAU 2020	Population SO/BAU 2110	Carbon tax CT/SO 2020	Population CT/BAU 2110
Mean	71	17.4	0.97	0.97	0.83	1.17
SD	42	10.7	0.04	0.08	0.12	0.07
Min	14	0.0	0.55	0.31	0.33	1.03
p10	28	7.5	0.92	0.88	0.68	1.08
p50	60	14.8	0.98	0.98	0.83	1.16
p90	133	30.3	1.01	1.04	0.97	1.26
Max	224	125.9	1.05	1.11	1.00	1.46

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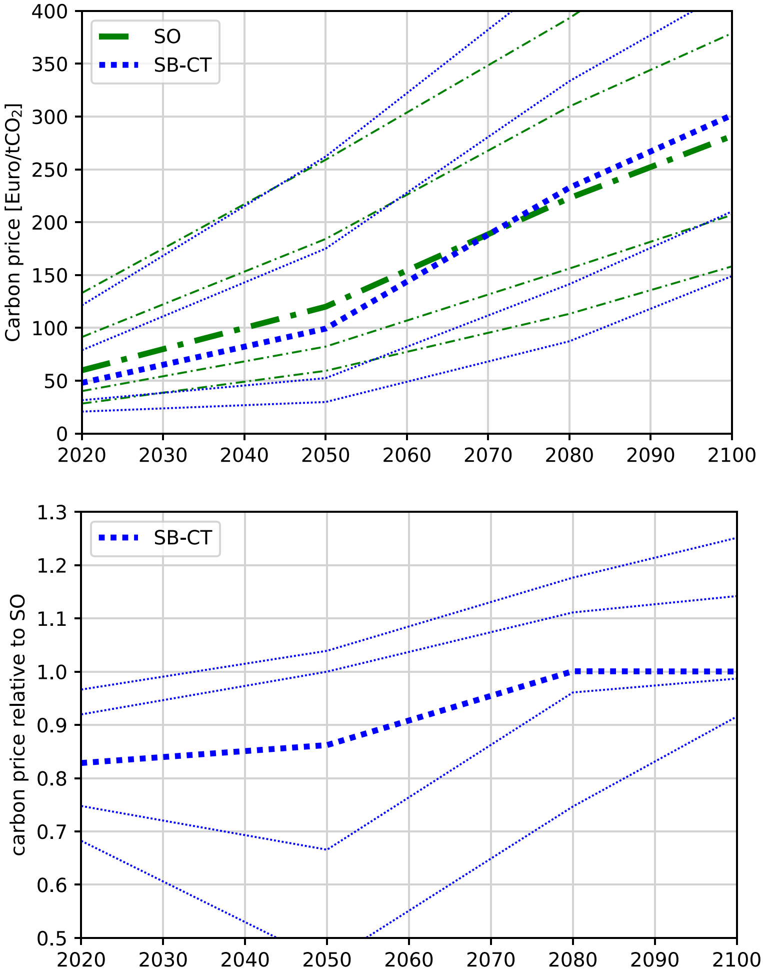
[30] $(0.98)^{30} = 0.55$, $(0.995)^{30} = 0.86$.

[31] Thus, the p10, p25, etc., lines do not represent one parameter vector but several parameter configurations.

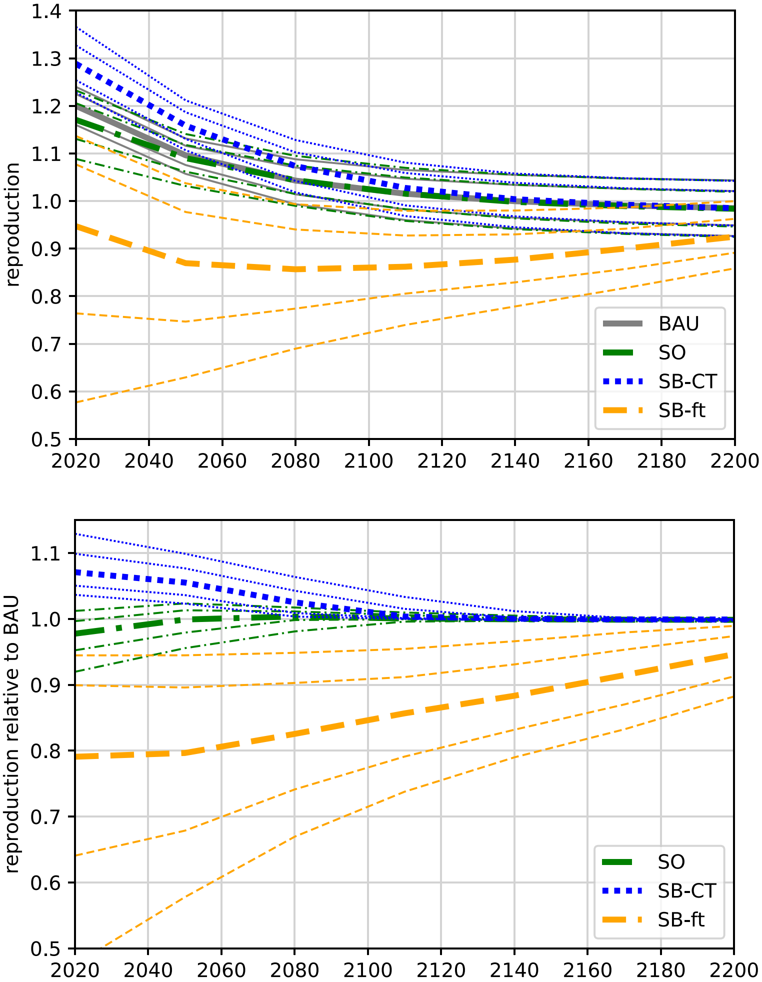
Figure 13. Carbon taxes: (top panel) in social optimum and second-best carbon taxes; (bottom panel) relative to social optimum



parameters that are most important, typically with coefficient values above 0.5. Consistent with the standard error, we report coefficients in two digits.

As noted previously, and in equation (25), carbon prices (see Figure 13) are approximately proportional to income and increase with the weight given to the future, β, and with the damages estimate, δ. Indeed, Table 2 confirms these are the relevant parameters. In the second-best scenario, when carbon taxes are not complemented by fertility policies, optimal carbon taxes are consistently lower compared with the first-best scenario, on average about 18

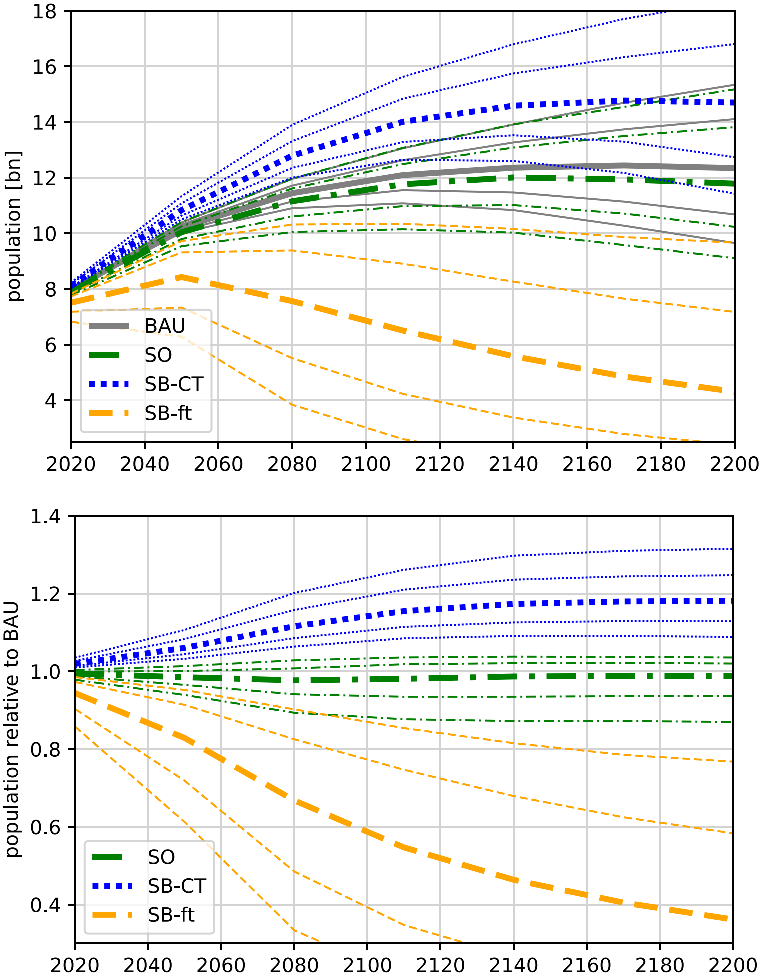
Figure 14. Fertility: (top panel) all scenarios; (bottom panel) relative to BAU



percent in 2020. Over time, carbon taxes in the two scenarios swap positions because income scales with population, which is consistently higher in the SB-CT scenario. This feature can be seen in Figures 14 and 15.

The patterns for fertility and population that we found for the main analysis are robust to changes in parameters. Over all scenario sets, the SO scenario reduces fertility in 2020 by, on average, 3 percent, and population in 2110 by 4 percent, compared with BAU, but a second-best scenario without fertility policies increases population by 17 percent at the end of the century. Table 2

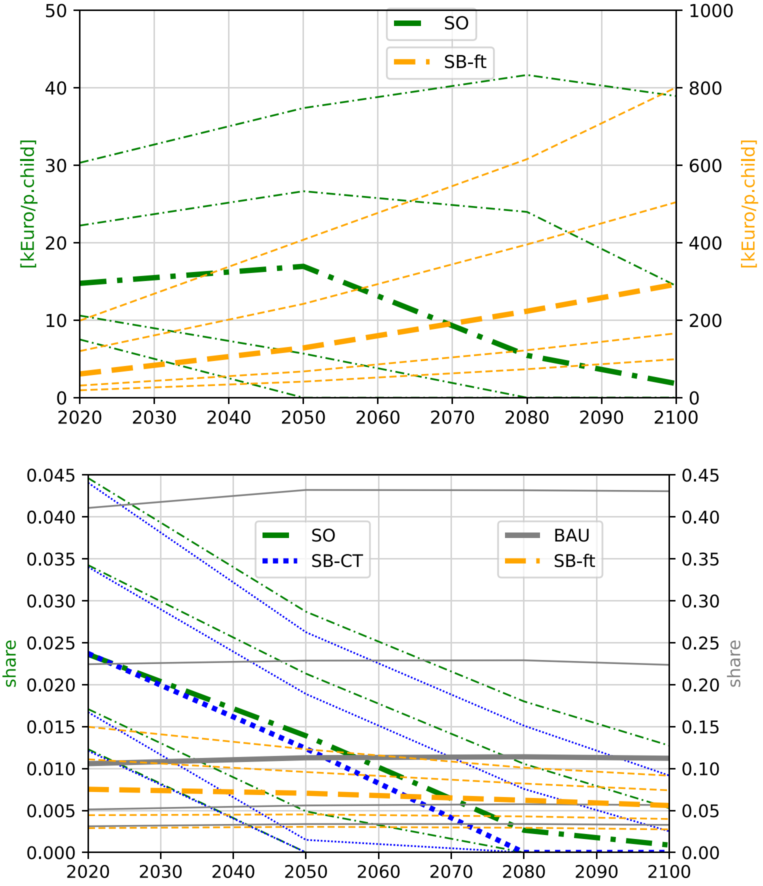
Figure 15. Population: (top panel) all scenarios; (bottom panel) relative to BAU



shows that the gap increases with the income loss associated with reducing emissions θ_1 relative to the time costs of raising children ϕ.

Figure 16 reproduces Figures 8 and 10. The externality per child in 2020 in the SO scenario shows a wide variation between 10,000 and 50,000 euros (top panel); when we multiply that number with fertility rates (bottom panel), we find the externality caused by births, in the order of some percentage of GDP. The birth externality becomes very large absent carbon taxes.

Figure 16. Fertility costs and externalities: (top panel) costs per child; (bottom panel) welfare costs associated with births relative to GDP

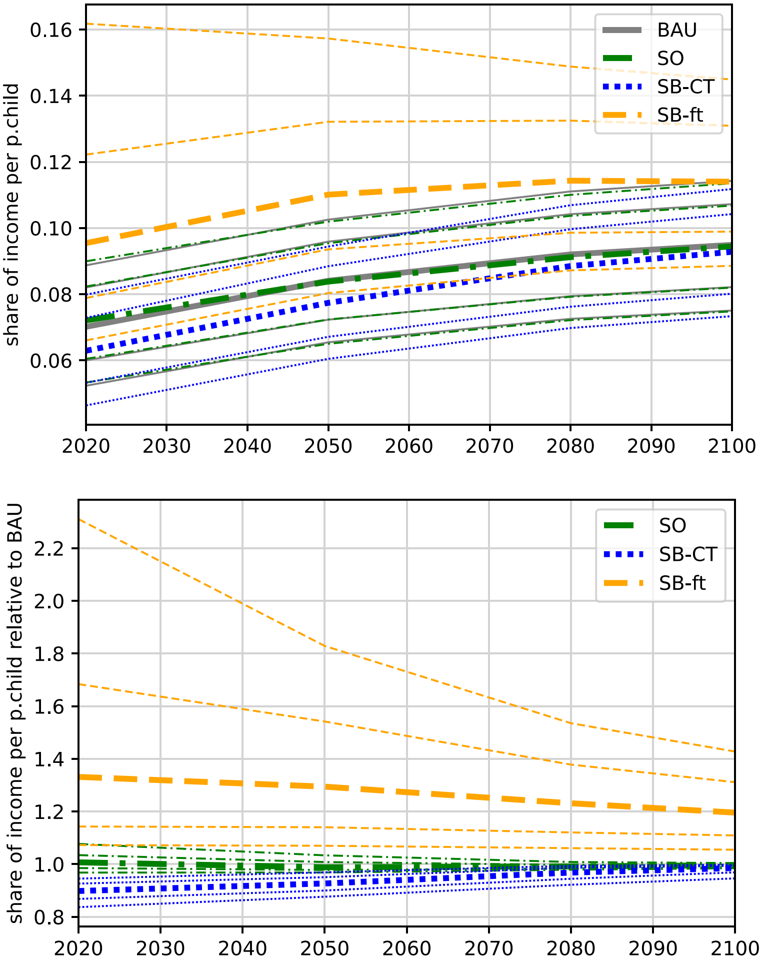


Education expenditures per child are approximately inversely related to fertility. Figure 17 mirrors Figure 14.

Finally, Figure 18 clarifies the mechanism discussed when presenting Figure 5. Because of higher fertility in the SB-CT scenario compared with the SO, aggregate income rises faster (top panel) while human capital and average income is low (Figures 17 and 18, bottom panels). As the carbon tax approximately scales with aggregate income, its level in the SB-CT scenario overtakes that in the SO scenario (Figures 5 and 13, bottom panels).

Though scenarios with lower population have higher per capita income, welfare based on average income does not rank low-fertility scenarios above high-fertility scenarios. Children also directly and positively enter utility,

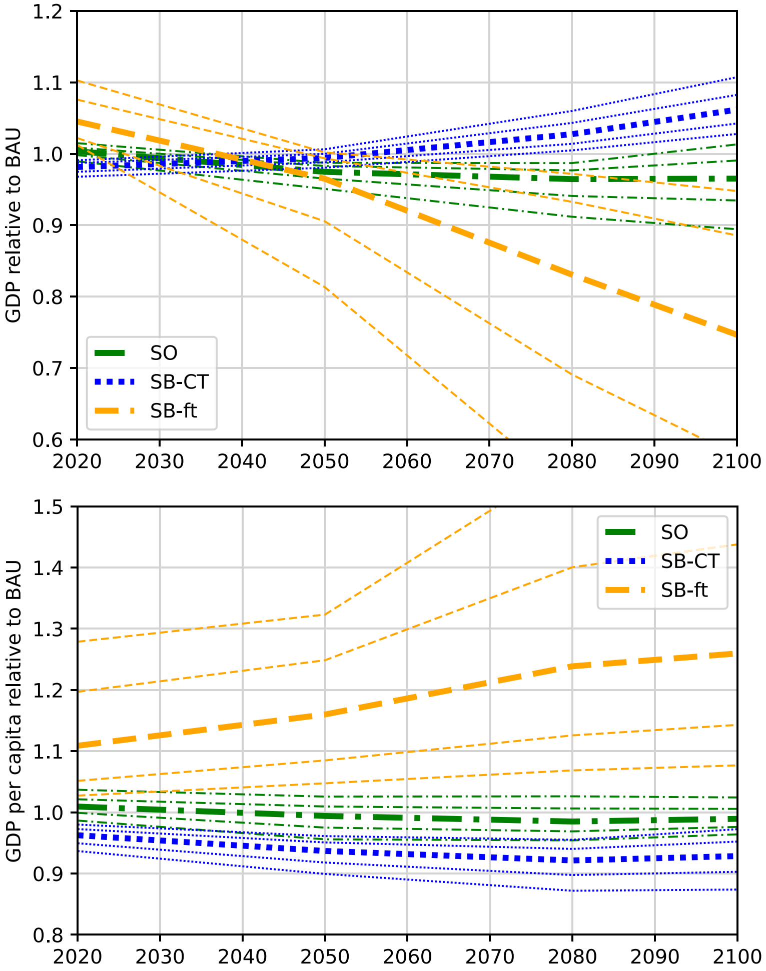
Figure 17. Education share: (top panel) all scenarios; (bottom panel) relative to BAU



which in the SO scenario precisely compensates the income effect of more children. That is, taking average utility balances the direct utility benefits of more children with the costs of lower average income. If we were to model welfare through aggregate utility, however, the model would reproduce the repugnant conclusion (Parfit, 2016) and would tend to rank high population and low per capita income scenarios on top.

Tables 2 and 3 summarize the effects of parameters on outcome variables of interest. The top rows present the outcome variable of interest, the scenario considered, and the year at which the variable is measured. Fertility and population are presented relative to BAU, while the carbon price is presented

Figure 18. Net income relative to BAU: (top panel) aggregate; (bottom panel) per capita



both for the SO, and for the second-best without family policies relative to the first-best. Table 2 presents the variation in main outcome variables; the average value, its standard deviation over the 1,000 scenario sets, and the percentiles. Table 3 presents the outcome dependence on parameter values. We can draw some general lessons from Table 2. The first-best carbon price (first column) is on average 71 euros per ton CO_2, and increases with a higher weight for future welfare (β) and higher damage estimates (δ), re-iterating the common wisdom of the literature (van den Bijgaart et al., 2016). Higher costs of emission reductions (θ_1) decrease the present and future responses

Table 3. Sensitivity of outcomes with respect to parameters

	Carbon tax SO 2020	Birth externality SO 2020	Fertility SO/BAU 2020	Population SO/BAU 2110	Carbon tax CT/SO 2020	Population CT/BAU 2110
α	0.06	−0.05	0.04	0.10	0.10	0.14
β	**0.91**	0.36	−0.12	0.02	0.42	0.15
γ	−0.14	−0.04	0.19	0.14	−0.12	0.14
δ	**0.54**	−0.04	0.27	0.33	0.44	0.14
η	0.12	−0.04	0.16	0.23	0.17	0.05
ϕ	0.04	0.00	**0.27**	**0.28**	0.15	**−0.39**
χ	0.01	−0.04	0.03	0.01	−0.10	0.17
$\widehat{A}$	0.01	−0.09	0.12	0.18	0.05	−0.09
$\widehat{\sigma}$	0.01	−0.09	0.12	0.18	0.01	−0.06
θ_1	0.00	**0.62**	**−0.52**	**−0.47**	**−0.75**	**0.60**
$\widehat{\theta}_1$	0.02	0.32	−0.32	−0.36	−0.18	0.28
R^2	0.89	0.60	0.62	0.65	0.89	0.62

Notes: All coefficients in the table are normalized so that they measure the change in the dependent variable relative to its standard deviation, caused by one standard deviation variation of the parameter. R^2 is a measure of the non-linearity of the relation between parameters and outcomes. The coefficients in bold are referred to in the text.

to carbon prices, and thus increase the birth externality (second column), and increase the importance of population as part of climate policy. Birth rates in the SO scenario (third column) and long-term population levels (fourth column), relative to the BAU scenario, then decline. Fertility and population are less sensitive to family policies if the costs of raising children are large (ϕ); a higher value for this parameter brings fertility and population closer to the BAU scenario (third, fourth and sixth columns). Second-best carbon taxes, if not supported by family policies, are on average 17 percent below first-best (fifth column) and are lowered if emission reductions are costly (θ_1) as such scenarios exhibit a strong rebound effect on fertility (sixth column).

7. Conclusions and directions for future research

Future global population growth matters for human well-being and for the natural environment. In this paper, we have shown the extent to which world population growth could be reduced by implementing family planning policies complementary to climate policies.

We have developed an analytical model of endogenous fertility and embedded it in a calibrated climate–economy model. Endogenous fertility choices generate an externality (i.e., a birth externality), as parents do not consider the contribution of each child to emissions when deciding the size of their family. Given the current global trend of population growth, our scenario results suggest that family planning aimed at smaller families should be addressed as a separate policy instrument against climate change. In particular, we find the following.

(i) Family planning contributes to abate emissions, and a reduction of population growth is an important element of efficient climate policy. Optimal family policy reduces the family size from 2.4 children per family in the baseline scenario to 2.3 children per household, while stimulating parents to invest more in the education of their offsprings. Population peaks at 11.6 billion in the optimal case instead of 14.6 billion in the pure carbon tax policy scenario. These numbers are subject to large uncertainty, but the robust message is that climate concerns justify family policies.

(ii) Without a family planning policy, carbon taxes should be reduced as they (unintentionally) increase family size through the quality–quantity trade-off. Costly emission reductions have the potential to increase population by a few billion in 2100.

(iii) In the absence of efficient climate policies, family control should further be tightened to reduce emissions indirectly.

(iv) We also compute the implied fertility externality. Our results show that its magnitude is substantial, even larger than the emissions externality.

If climate change is seen as a congestion externality, newborns will add to congestion but mortality dampens it. While we believe that the mortality channel is potentially important for regions with heat stress, at the global level the impact is less obvious. IPCC (2014, p. 51) states: “At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (medium confidence). Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors (medium confidence).” It would appear that modeling the impacts of climate change on mortality is more relevant in a regional context rather than in a global model.

This paper has delved into a relevant but ethically sensitive issue: every newborn child increases the pressure on the finite resources of our planet and contributes to increase the stock of harmful carbon emissions. Standard economic arguments suggest a role for public policies in fertility decisions. The case for carbon taxes is, by now, accepted as part of the economist’s toolkit for effective climate policies. We have followed a common economic approach and calculated the birth externality costs. The model presented in this paper addresses two stock environmental externalities: climate damages originate from both the emissions generated by firms' production activities and the emissions generated by net additions to the current population. This is a simple consequence of the fact that cumulated emissions depend on the population size. We have presented simulation results concerning a social optimum scenario, where both optimal carbon taxes and family planning policies are implemented, and second-best scenarios where only one policy variable at time is aimed at. This has enabled us to provide evidence on the size of the population externality, among other things. Overall, we believe that our qualitative results robustly point to the need for carbon taxes and demographic policies, designed to cope with the two externalities.

The demography results we present need not be interpreted as a proposal for smaller families across the board. There are many institutional settings that intentionally and unintentionally affect family planning decisions by households. The societal response and career costs of parental leave, the attitude towards childcare, and many other variables explain diverse outcomes between countries as much as income and educational differences (Morgan, 2003; Dasgupta and Dasgupta, 2017).

Our model economy is global and does not differentiate across world regions. While it is true that world population is increasing fast, in many developed countries it is difficult to debate fertility decisions. Several countries show a declining labor force coupled with aging, some even with declining populations. This raises concerns about the sustainability of pension systems, accumulation of human capital, innovation potential, and productivity of the economy. Countries with low fertility rates might benefit from increased fertility; yet our analysis makes a strong case for benefits of smaller average family size at the global level. The environmental impact of newborns does not disappear in high-income low-fertility countries. At the same time, an acceleration of the demographic transition can be a relevant contribution to climate policy mostly for the poorer parts of the world. Whereas low-income countries also experience, on average, lower per capita emission levels, depressing the birth climate externality, what matters is the externality costs relative to other costs of raising children. As emissions tend to increase less than proportional with income, we conjecture that in a model with rich and poor countries, family planning policies are likely to be binding mostly in the latter group.[32]

A second important remark is that the environmental externality to childbearing considered here is but one of a wide range of impacts, both positive and negative, that the birth of an additional child will have on

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[32] We note that recent evidence suggests that the pace at which developing countries, especially emerging economies, undergo a demographic transition has sped up (Delventhal et al., 2021).

society. Some of these effects have been noted in Section 3. In principle, if the different external costs and benefits to childbearing could be identified and estimated, they would all be part of the design of optimal family policy. In practice, externalities to childbearing are difficult to measure and to allow for in dynamic general equilibrium models. Therefore, here, we study only the externality arising from the climate damage associated with childbearing. As our quantitative estimates show, this is a very important external effect.

We would like to extend the analysis with endogenous innovations, as an increasing population contributes to the stock of knowledge (Bretschger, 2020).[33] Yet, family planning policies can also be directed at support for education, especially at the lower end. It increases human capital, stimulates growth, and also reduces fertility. Indeed, though our model is not fit to directly assess education policies, the results suggest that the social optimum scenario has lower emissions, lower and/or delayed fertility, and higher education investments.

Supporting information

Additional supporting information can be found online in the supporting information section at the end of the article.

Online appendix
Replication files

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[33] The model by Bretschger (2020) has endogenous population size but no quality–quantity trade-off.

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