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Family Planning and Climate Change

Abstract

The historical increase in emissions is for one-fourth attributable to the growth of emissions per person, whereas three-fourths are due to population growth. This striking evidence is not represented in the majority of climate-economic studies, which mostly neglect the environmental consequences of individuals' reproductive decisions. In this paper, we study the interactions between climate change and population dynamics. We develop an analytical model of endogenous fertility and embed it in a calibrated climate-economy model. Our results present family planning as an integral part of climate policies and quantify the costs of neglecting the interaction.

JEL-Codes: J110, J130, H230, Q540, Q560.

Keywords: fertility, climate change, population, carbon tax, fertility tax, climate-economy models.

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1 Introduction

The International Energy Agency estimates world emissions from fossil fuels to have reached 32.5 $GtCO_2$ in 2017, up from 20.5 $GtCO_2$ in 1990, the reference year of the Kyoto Protocol. Over the same time span, the world population increased from 5.3 to 7.5 billion people (IEA, 2017). If we decompose the 58.5 per cent cumulative growth in total emissions into population growth and growth of per capita emissions, we find that population contributed with 41.5 percentage points and per capita emissions with only 11.9 percentage points. These few numbers make clear one fact: through the growth of his/her consumption of goods and services, and the associated production activities, a living individual has contributed to the increase in emissions by one fourth of the total, whereas three fourths are due to the additional people who have arrived to populate the world.

This striking evidence notwithstanding, the majority of climate-economic studies focuses on emissions through the lens of energy externalities in production and consumption activities, and on policies to correct these. Population dynamics in those models is typically taken to follow exogenous trends. Though population growth is a crucial component of projections of future emissions and population is expected to rise to around 9.8 billion by 2050, climate economists have mostly neglected the environmental consequences of individuals' reproductive decisions.

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 emissions generated by the additional individual, which reduce environmental resources available to the next generations.

Of course, a newborn child also contributes to production when grown up. Through her embedded human capital, she 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 resources and time. Our model draws from the literature on optimal fertility, education decisions, and economic growth. Studies in this area generally neglect the environmental externality generated by fertility decisions, and only recently a few papers have addressed the issue. This is the first paper that connects endogenous family planning, economic growth, and climate-economy interactions. We calibrate the model to provide quantitative support to the "climate population externality" and the interaction between emission reductions and family planning policies.

Our results underscore the importance of family planning policies. 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, similar to the plans developed under the Kyoto Protocol. Yet, the relevance of population dynamics was initially recognized in 1972 during the first Earth Summit.[1] In more recent times, Principle 8 of the 1992 Rio Declaration 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” (UN, 1992).

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 assess the population externality. Yet, the interactions between optimal climate policies and demographic policies are subtler, as the present paper shows. In this study, we use the model to ask three broad questions. First, to what extent can (or should) family planning contribute to climate policy? Does efficient climate policy require a substantial reduction in family size? Second, to what extent should climate policy be adjusted if family planning policies cannot decentralize the social optimum? For example, would the absence of family planning policies lead to a reduction in (second-best) carbon taxes, as a higher carbon tax reduces income, which in turn increases family size, thereby increasing future emissions? Third, if a planner cannot implement optimal climate policies such as carbon taxes, to what extent does the absence of such climate policies raises the pressure for family planning policies to substitute for direct climate policies?

The remainder of the paper is organized as follows. In Section 2 we review a few stylized facts and the relevant literature. Section 3 presents the model. Section 4 discusses its calibration whereas scenario results are presented in Section 5. Conclusions and future research directions close the paper.

2 Stylized Facts and Related Literature

The main broad options to achieve a reduction in CO_2 emissions are to reduce the carbon intensity of production and consumption activities, the income level per capita, or the size of the population. Figure 1 shows that total CO_2 emissions almost tripled from 1960 to 2014. Using the Kaya decomposition, the carbon intensity of the economy is shown to have steadily decreased, but the increase in both income per capita and population have more than offset the efficiency gains.[2]

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[1] Actions and proceedings of the Stockholm conference are collected in a Report and are synthesized in 26 Principles; the 16th 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 environment of the human environment and impede development” (UN, 1972).

[2] See Ehrich and Holdren (1971). The Kaya identity decomposes an environmental impact (e.g., total CO_2 emissions) into carbon intensity, income per capita and population.

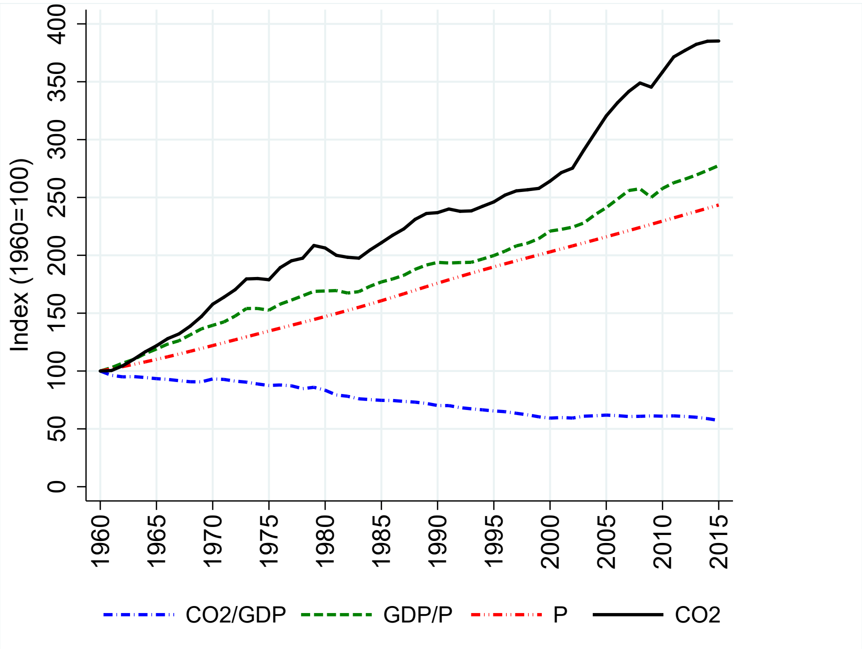

Figure 1: World Emissions (1960-2014) and Kaya decomposition (1960-2014). *Sources:Carbon Dioxide Information Analysis Center(2015), United Nations Population Division and the World Bank.*

While historically the industrialized countries contributed most to emissions, future emissions growth is expected to be mainly driven by lower and middle-income countries that will see a sharp income growth and are currently characterized by significant population growth.

The global population still grows at about 80 million people per year (RS, 2012), despite a declining fertility. 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 retain a more local perspective. However, family planning choices impose external costs to society as a whole. 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 parent's 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 of 58.6 tons CO_2-equivalent for individuals living in developed countries.

In this paper we identify fertility choices as a congestion externality. Individual households do not take into account that the available per capita resources decline with the size of the next generation. Our analysis is based on a standard model of endogenous fertility and education (Becker and Barro, 1988). 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 generate and the amount of education they can provide to each one of them. This is the trade-off between quantity and quality of children highlighted in the seminal paper by Becker et al. (1973) and also documented in Figure 2.

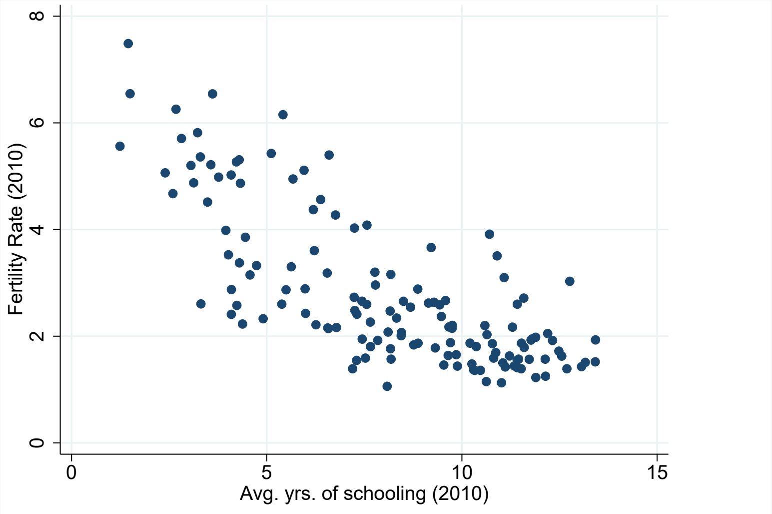

Figure 2: Fertility Rates and Schooling, by World Countries. *Sources: United Nations Population Division and Barro and Lee database.*

Considering all households, by increasing human capital, aggregate education impacts productivity, so that family planning has an effect on economic growth (Becker et al., 1990; Galor, 2005). 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 relationship between inequality and growth. Figures 3 and 4 show the correlation between fertility and income on the one hand and between education and income on the other.

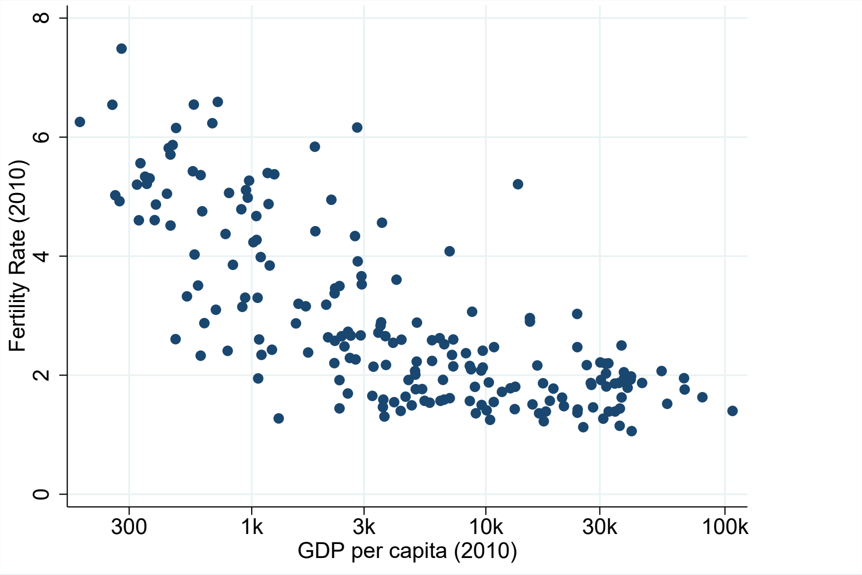

Figure 3: Fertility Rates and Income, by World Countries. *Sources: WDI database, World Bank for GDP per capita (constant 2010 EUR); United Nation Population Division database for Fertility Rates (child per female).*

Figure 4: Schooling and Income, by World Countries. *Sources:WDI database, World Bank for GDP per capita (constant 2010 EUR); Barro and Lee database for average hours of education.*

The trade-off between fertility and education does not only play out between families, but also leave their 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 et al., 1990; Becker and Barro, 1988; de la Croix and Doepke, 2003). The trade-off also means that women who are better educated tend to have fewer children (UN, 2017). From a policy perspective, Shi and Zhang (2009) study two types of population policies to reduce fertility and promote growth. In an endogenous growth model with quantity-quality trade-off, they consider birth limits and birth taxes as a way to correct a human capital externality. They show that the most desirable policy is to tax births and use the tax revenue to subsidize education, thus providing support for China's recent move from strict birth limits to birth taxes and education subsidies. Relatedly and in line with the previous findings, Xue and Yip (2017) examine the effects of the One Child Policy (OCP) in China in a Galor and Weil (2000) model with a population constraint and show that parents are willing to increase the investment in the education of their children immediately after the OCP intervention. A permanent OCP is found to depress long-run growth and welfare, thus rationalizing the decision of the Chinese government to abandon the OCP.

The above considerations on fertility versus education and the related policies aim at the consequences for economic growth and ways to promote it. We introduce climate change and climate policies in the picture. In the scientific debate on the threat to the global economy posed by climate change excessive population growth is often considered to be a significant problem, aggravating pollution problems. It has been suggested that one of the most important policies in this respect is to curb population growth. There is however, a nearly universal aversion to viewing childbearing in purely economic terms. This makes population control controversial. Climate policies, therefore, require a careful inclusion of demographic policies. Various philosophers and economists have considered the idea of 'optimal population' (Zimmermann, 1989). To many, the free choice (not) to procreate is an inviolable right (Dillard, 2007). When we consider population policies, in this paper, we have in mind voluntary programs, such as those that promote women's social status, health and education. There is evidence that such interventions 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).

A handful of papers have studied environmental externalities associated with fertility decisions. When a public good externality (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. Schou (2002) studies endogenous fertility decisions in a long-run growth model with production-related environmental externalities. It is shown that a government setting out to regulate these externalities must also take into account the effects of its policies on fertility. In some cases – but not all – a birth tax may be needed to implement the optimal solution.

When choosing the number of their offspring, parents do not take into account the environmental damage to which their children will contribute in the future. Endogenous fertility choice thus creates an externality which has been referred to as population externality. 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 depending on a number of factors. Based on this conclusion the authors argue in favour of fertility-related policies, although their model cannot study such policies. In a balanced growth setting, Bohn and Stuart (2015) quantitatively assess the size of this population externality with a view to the associated policy prescriptions. In their exercise, the government imposes a constant cap on emissions, implying that there is a fixed common property externality. Each newborn leads to a situation where more people share the same total amount of available emissions, and living standards decrease. Also these authors find that the population externality can be large implying that the tax or subsidy policy that is optimal for currently living individuals can be large.

In this paper, we use a simplified version of the fertility and growth model by de la Croix and Doepke (2003) where parents make choices concerning the quantity and quality of children and integrate into that framework climate change dynamics and its effects on the economy. Compared to Harford (1998), our model allows for education and human capital as crucial elements of family decisions and contains a representation of the environmental externality in line with that of integrated assessment models of climate change. Unlike O'Neill and Wexler (2000), our model does not rely on exogenous emissions and population scenarios and involves a micro-foundation of household behavior, where fertility choice is part of a households rational decision. Finally, we extend Bohn and Stuart (2015) by developing and studying an analytical model outside steady state, where we bring the climate calibration up to the level common among analytical integrated assessment models (Golosov et al., 2014; Gerlagh and Liski, 2017; Dietz et al., 2017). As a case in point, we do not impose an exogenous emission cap, but instead, consider the case of endogenous abatement levels based on dynamic efficiency considerations. This more general set up is essential for one of the more remarkable findings: in the absence of family control, higher population levels lead to second-best cumulative emissions *below* the social optimum.

Before turning to the description of the model in the next section, we note that this paper shares a limitation common to the aforementioned studies. 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, as adults children enlarge the tax base and may help pay for public pensions to the elderly, 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. On the other hand, children may receive transfers from the working age population 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 like public lands, publicly owned mineral or fishing rights, and parks. 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. We, therefore, study here only one underlying externality arising from the climate damage associated with childbearing. As our quantitative estimates show, this is a very important external effect.

3 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 incorporate this framework in a climate module that enables us to investigate the interrelationship between fertility decisions and climate change. As in standard growth models, lower-case variables are expressed in intensive form. Production variables are normalized per unit of labor supply L_t. Thus $y_t = Y_t/L_t$ is output per labour input, $e_t = E_t/L_t$ is emissions per labour input, and $h_t = H_t/L_t$ is human capital intensity. Household variables, though, are normalized per size of the parent population N_t. We assume that only parents work, whereas children are inactive. Thus, $l_t = L_t/N_t$ is the employment rate, $c_t = C_t/N_t$ is consumption per parent, and $s_t = S_t/N_t$ is education expenditures per parent.

3.1 Demographics

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 $M = 30$. Within a period parents are of age 15-45, the range that corresponds to the fertility period of a woman. Generations overlap as, at each point in time, adults, old, and children are alive. Total population, P_t, is given by:

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

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 $\epsilon = \frac{1}{2}$, as babies are born uniformly over the period.[3] The life expectancy in years is given by $(1 + \frac{1}{2} + \nu_{t-1})M$, yet it does not play any role in our analysis.[4] Given fertility measured as child per parent, f_t, the next generation's size is:

$$N_{t+1} = f_t N_t \tag{2}$$

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[3] Which is the expected value of a uniform distribution.

[4] See Gerlagh et al. (2017) for an extensive analysis of the implications of increasing life expectancy on optimal climate policies.

3.2 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. As their 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 abstract from savings for future consumption when old, while we focus on the costs of rearing and educating children. Let u_t be per parent utility which is increasing in consumption, family size, and utility of children. Parents maximize u_t with recursive utility given by:

$$u_t(h_t) = \ln(c_t) + \gamma \ln(f_t) + \beta u_{t+1}(h_{t+1}) \tag{3}$$

where c_t is per parent consumption and f_t is the fertility level chosen by parents. We assume that parents can only increase the welfare of their children by increasing bequests of human capital, h_{t+1}, and in turn, parent's utilities depend on the amount of human capital they received.[5] The parameter $\gamma > 0$ weighs the utility derived from family size, while β is the (altruistic) weight associated with children's (average) utility.[6]

Through altruism, each generation positively weighs future consumption and fertility, so that we can rewrite (3) as:

$$u_t(h_t) = \sum_{i=0}^{\infty} \beta^i (ln(c_{t+i}) + \gamma ln(f_{t+i})) \tag{4}$$

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. Parents can transmit wealth to children only by providing them with education:[7]

$$h_{t+1} = (\chi + s_t)^{\eta} \tag{5}$$

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.[8]

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

[6] While models with exogenous population tend to define welfare in aggregate terms, models with endogenous fertility more often describe altruism through offspring's average utility, e.g. Shi and Zhang (2009); de la Croix and Doepke (2003). The model in de la Croix and Doepke (2003) can be considered the special case of our model with $\gamma = \beta$. See also the discussion in footnote 14, and Appendix C.

[7] There are no financial bequests as in Eckstein and Wolpin (1985) and Becker and Barro (1988).

[8] In studies that focus on between-family differences, the parameter χ can also be considered as compulsory

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:

$$l_t = 1 - \phi f_t \tag{6}$$

where ϕ is the time needed to raise a child.

Finally, we assume that the government can subsidy children or levy a 'fertility tax' ξ_t per child for family planning policies. The household budget constraint becomes:

$$c_t + s_t f_t + \xi_t f_t = w_t h_t l_t + T_t \tag{7}$$

where income consists of labour income $w_t h_t l_t$ and transfers T_t. It is spent on consumption, education s_t and taxes, the latter two multiplied by the number of children f_t.

Parents maximize their utility (3) subject to labour supply (6), the budget constraint (7) and human capital production (5).[9] The first-order conditions for fertility f_t and schooling s_t, are given by the following expressions:

$$(s_t + \xi_t + \phi w_t h_t) f_t = \gamma c_t \tag{8}$$

$$f_t(\chi + s_t) = \eta\beta \frac{w_{t+1} h_{t+1} l_{t+1}}{c_{t+1}} c_t \tag{9}$$

On the left-hand side of (8) we have total expenditures on education $s_t f_t$, the fertility tax and the reduction in labour income due to children. These expenditures are, on the right-hand side, proportional to consumption expenditures, scaled by the preference parameter γ, as is typical for the log-utility parametric form. In (9) we have on the left-hand side total expenditures on education. They also increase proportionally with consumption, on the right-hand side, scaled with the elasticity of education in human capital η, times the ratio between next generation's discounted income out of human capital and consumption.

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 wages, such as climate policies, will affect future fertility choices, the share of schooling in expenditures, and thereby also present fertility and schooling choices. Nevertheless, this model also captures the quality-quantity children's trade-off highlighted by Becker et al. (1973) and our simulations will show this feature to have substantial consequences for efficient policy choices. Note however that in our model education affects fertility through income, $w_t h_t l_t$, as seen in (9). There is no direct effect of education on variables such as family size preferences, anti-conception knowledge, and delayed start of motherhood. While following standard practice, our model

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education provided for free.

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

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.

3.3 Production

The model describes both environmental and population externalities, so that we can analyze the interactions between demographic and climate policies. 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:

$$Q_t = \omega_t h_t L_t \tag{11}$$

where aggregate human capital (or effective labour supply), $H_t = h_t L_t$, is expressed in quality-adjusted or efficiency units (Lucas, 1988); $L_t = l_t N_t$ is labor supply, and ω_t is the level of technology which evolves over time with an exogenous constant growth rate $\widehat{\omega}$:[10]

$$\omega_{t+1}/\omega_t = \widehat{\omega}. \tag{12}$$

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 laborer emissions, e_t, are then given by:

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

where $q_t = Q_t/L_t$ is per laborer gross output. 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.[11] Firms maximize profits in a competitive market:

$$\Pi_t = Y_t - w_t h_t L_t - \tau_t e_t L_t \tag{15}$$

subject to (10) and (11), where w_t is the wage rate expressed in per quality workers and τ_t a tax on emissions. The first order conditions give the abatement intensity μ_t, then emissions

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[10] There is no physical capital accumulation.

[11] 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.

through (13), and wages w_t:[12]

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

$$w_t = \frac{y_t - \tau_t e_t}{h_t} \tag{17}$$

3.4 Climate damages

Climate damages d_t, are assumed to depend on cumulative emissions:

$$d_t = 1 - exp(-\delta CE_t) \tag{18}$$

$$CE_{t+1} = CE_t + M e_t L_t \tag{19}$$

where CE_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.

The effect of cumulative emissions on damages per period (18) reflects the parametric form of Golosov et al. (2014), yet deviates importantly in the sense that it assumes that emissions lead to immediate and lasting temperature changes.[13]

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 impact emissions and the economy.

3.5 Competitive Equilibrium

The economy produces one homogeneous good that can be used both for consumption and education. The price of this final good in normalized to one. Thus:

$$N_t c_t + N_t s_t f_t = Y_t \tag{20}$$

Given the description of households and firms behavior, we can now define the equilibrium of this model economy. Given technology ω_t, initial values of population N_1 and human capital h_1, a competitive equilibrium consists of sequences for parents' sizes and human capital, (N_t, h_t), consumption, schooling, fertility and labour decisions (c_t, f_t, s_t, l_t), firms' emissions and output decisions (e_t, y_t), supported by wages, carbon and fertility taxes (w_t, τ_t, ξ_t), such that:

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

[13] This is a peculiar consequence of the depreciation of atmospheric CO_2 and slow temperature adjustment, that almost exactly cancel each other out. Relative to Nordhaus and Sztorc (2013), we do not have to model the link between GHG concentrations and temperature, thus considerably simplifying the climate module (Dietz et al., 2017).

a. households maximize utility subject to their budget constraint;

b. firms maximize profits;

c. markets clear.

3.6 Welfare

The competitive equilibrium takes carbon and fertility taxes as given, and the equilibrium conditions then define wage, output, consumption, labour, fertility and schooling choices. Households and firms do not consider the externalities they generate. We now consider a planner who maximizes the utility of the first generation u_1, expressed by (4). The main analytical result is summarized by the following preposition.[14]

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:*

$$\tau_t = \delta M N_t c_t \sum_{i=1}^{\infty} \beta^i \frac{l_{t+i} y_{t+i}}{c_{t+i}} \tag{21}$$

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

$$\xi_t = \frac{\beta \tau_{t+1} e_{t+1} l_{t+1} c_t}{f_t c_{t+1}} + \frac{\beta \xi_{t+1} c_t f_{t+1}}{f_t c_{t+1}} \tag{22}$$

The planner returns lump-sum carbon tax and fertility tax revenues to current households:

$$T_t = \tau_t e_t + \xi_t f_t \tag{23}$$

ensuring that the current value of output equals the income of the current adult generation equal to its expenditures, as given by (7)*.*[15]

The carbon tax formula resembles the one in Golosov et al. (2014) in the following precise sense: if savings are approximately constant, $c_t \approx (1 - g) y_t l_t$ for some education investment

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[14] Scovronik et al. (2016) explore the consequences for mitigation policy of assuming different future populations and social objectives. To that end they simulate the DICE model by Nordhaus and Sztorc (2013) under different U.N. population projections and for total utilitarian as opposed to average utilitarian social welfare functions to assess the impact on the social cost of carbon. Note that they use an ethical approach of welfare aggregation. In a descriptive approach, model parameters are re-calibrated when switching from average to aggregate utility such that outcomes do not differ between the two. See Gerlagh et al. (2017) for further discussions on calibration procedures. 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, in Appendix C we see that aggregate income is maximal in scenarios with high fertility and low in scenarios with low fertility, reversing the ordering of average income. Using average utility does not lead to preferences for very low populations, as congestion externalities disappear long before population becomes very small.

[15] In Appendix A.3 we provide the full welfare program with all constraints and optimality conditions and we prove the above prepositions.

ratio g, then the carbon tax reduces to:[16]

$$\tau_t \approx \frac{\beta\delta}{1-\beta} Y_t \tag{24}$$

so that also here the carbon tax is approximately proportional to net output. The fertility tax ξ_t measures the decrease in welfare per increase in the size of the children N_{t+1}. We see that one unit of children decreases average welfare because the children contribute to emissions that are negatively valued, $\tau_{t+1}e_{t+1}l_{t+1}$. These are discounted because of time preferences β, and are scaled by the relative size of present aggregate consumption versus future aggregate consumption, $c_t/f_t c_{t+1}$. The last term on the right-hand side defines the recursive negative effects as grandchildren also contribute to the damages caused by the population, etcetera. That is, ξ_t measures the net present value of future emissions caused by each child and its descendants.

The proposition highlights that household's education decisions need no correction, but that in addition to carbon taxes, family planning also needs a correction to achieve the social optimum. The question is how second-best carbon taxes respond if family planning cannot be adapted to climate policy goals and, on the other way, how family planning policy must correct for missing carbon taxes. To answer this question, we calibrate the model and run four scenarios. The 'Business as Usual' (BAU) scenario sets both carbon and fertility taxes to zero and solves the laissez-fair competitive equilibrium. The 'Social Optimum' (SO) implements the policies as described in the proposition above. The 'Second-Best Carbon-Taxes' (SB-CT) scenario sets the fertility tax to zero, and adjusts the carbon tax to maximize welfare. Finally, the 'Second-Best Fertility-Taxes' (SB-FT) scenario abstracts from carbon taxes but selects the fertility tax that maximizes welfare. The precise definitions of the scenarios are provided in Appendix B.

4 Calibration

Calibration entails determining the starting values of a few key variables for our policy simulations as well as the values of the relevant parameters.

4.1 Demographics

The first year of our model, $t = 1$, is labelled '2020' and each period lasts 30 years. We begin by calibrating the initial number of parents, N_1. Using equation (1), we start the first period

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[16] In the standard OLG model (Diamond, 1965), the young save part of their income in order to finance consumption when they retire. We do not model the behavior of agents when old. In our context, instead, parents, i.e. the young, save part of their income in terms of current consumption to invest in their children education.

with 7 billion people. Life expectancy in 2010 was 72 years, from which we conclude that $\nu_0 = 27/30 = 0.9$.[17] Fertility of the previous generation, around 1990, was close to 1.7, so that $N_1 = 1.7N_0$. Fertility f_1 in 2020 is around 1.2. Using (1) and (2) we obtain:

$$N_1 = \frac{P_1}{1 + \nu_0/f_0 + \epsilon f_1} = \frac{7}{1 + 0.9/1.7 + 0.5 \cdot 1.2} = 3.28. \tag{25}$$

4.2 Long-run parameters

Parameter ϕ represents the time-cost of children. In the literature, the value chosen for ϕ is between 15% and 30% (Haveman and Wolfe, 1995; de la Croix and Doepke, 2003). We set $\phi = 0.2$, implying that a couple spends about 20% of its time raising two children. Based on a 2% pure discount rate per year, we exogenously set the altruism preference parameter equal to $\beta = 0.74$.

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.

For calibration purposes, we 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:

$$\omega_t = \omega_0 \widehat{\omega}^t, \tag{26}$$

In the long-run emissions are zero and damages are a constant fraction of output.[18] 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 $y_t = q_t$, $\tau_t = e_t = 0$, $w_t h_t = y_t$ and $\chi << s_t$. While fertility is constant, consumption and schooling expenditures increase proportionally with output $\widehat{s} = \widehat{c} = \widehat{y}$. In turn, output increases proportionally with human capital times technology $\widehat{\omega}\widehat{h} = \widehat{y}$. The long-run human capital build-up (5) reads as $s_t = h_{t+1}^{1/\eta}$, which gives in growth factors $\widehat{h} = \widehat{s}^\eta$. Combining all these linkages, we obtain $\widehat{\omega}\widehat{y}^\eta = \widehat{y}$, resulting in the long-run growth dependence on technology:

$$\widehat{y} = \widehat{\omega}^{1/(1-\eta)} \tag{27}$$

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

There is no need for a fertility tax or income transfers in the long run, $\xi_t = T_t = 0$. Then, we can rewrite equation (7) and specify the income shares for consumption and educational

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[17] Setting $(1 + \frac{1}{2} + v_0)M = (1 + \frac{1}{2} + v_0)30 = 72$ and solving for v_0 yields the value 0.9.

[18] 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. This can be seen from (21), but it is most clear in (24). In response to rising carbon taxes, abatement (16) increases to 100%, and emissions (13) become zero in finite time. Then, given our assumption of damages dependent on cumulative emissions (18), d_t will become a constant value.

expenses:

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

To find the second part, that is the share of education expenditures in income, $i = \frac{s_t f_t}{y_t l_t}$, we divide equation (9) by $y_t l_t$, resulting in $i = \eta\beta$. Substituting this into equation (8), together with equation (28), we derive the balanced growth equivalents for fertility levels and schooling expenditures:

$$f = \frac{\gamma - (1+\gamma)\eta\beta}{\phi(1+\gamma)(1-\eta\beta)} \tag{29}$$

$$i = \eta\beta \tag{30}$$

We can invert these equations to calibrate the model to long-run targets. Given parameters β, ϕ, and long-run values for i and f, we can compute:

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

$$\eta = i/\beta \tag{32}$$

The three parameters $(\gamma, \eta, \widehat{\omega})$ are calibrated on long-run targeted moments: fertility, schooling expenditures, income growth, while parameter χ is calibrated to reproduce first-period fertility f_1.

4.3 Climate

The pre-industrial level of GHG concentrations in the atmosphere was 280 *ppmv* of carbon (IPCC, 2014), which corresponds to 2.17 $TtCO_2$. Doubling this value may lead to irreversible climate events due to the subsequent increase in temperature. The IPCC (2014) states that about 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% will stay in the atmosphere for many thousands of years depending on the amount of carbon emitted. New evidence is more pessimistic, however. Archer et al. (2009) suggest that between 20% to 35% of CO_2 remains in the atmosphere for centuries. To calibrate δ, we assume that about 30% 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 projected that a doubling of atmospheric concentrations would yield damages equal to few percentage points of GDP. In his paper, Tol (2009) collects the most recent impact estimates of climate change on GDP. Depending on temperature increase, we may have a loss in GDP between 1%-5%. We impose the central value. Thus, doubling concentration levels in the atmosphere, by emitting 7.23 $TtCO_2$, reduces world output by 3%. We can then calibrate δ by solving (18), i.e. given $\exp(-\delta CE) = 1 - d$ we get:

$$\delta = -\frac{\ln(1-d)}{CE} = -\frac{\ln(0.97)}{7.23} = 0.0042. \tag{33}$$

Following Nordhaus and Sztorc (2013), we assume that in 2020 100% of abatement costs equals 7% of aggregate GDP and that the abatement function (14) is quadratic, so that $\theta_2 = 2$. This in turn implies $\theta_1 = 0.07$.

4.4 Starting values

We determined N_1 as described in Section 4.1. World cumulative emissions between 1750 and 2005 (the first year in the first period) amount to about 355 GtC, corresponding to 1.3 $TtCO_2$ (Tera tonnes) (IPCC, 2014). In 2015, world GDP was about 75 trillion euro per year (constant 2010 prices), increasing at about 3% per year, so that we target $Y_1 = 0.075$. Since $\phi = 0.2$ and $f_1 = 1.2$ from Sections 4.1 and 4.2 labour supply is $l_1 = 1 - \phi f_1 = 0.76$. Combine (10), (11) and (18) and assume $\mu_1 = 0$ to get:

$$Y_1 = exp(-\delta CE_1)\omega_1 h_1 L_1 = exp(-\delta CE_1)\omega_1 h_1 l_1 N_1 \tag{34}$$

This yields:

$$\omega_1 h_1 = \frac{\exp(\delta CE_1)Y_1}{l_1 N_1} = \frac{1.0062 \cdot 0.075}{3.28 \cdot 0.76} = 0.0305 \tag{35}$$

We note that the equilibrium first-period income does not depend on ω_1 or h_1 separately; firm's and household's choices only depend on overall labour productivity as captured by the product of the two terms. However, the second period output depends on $\omega_2 = \omega_1 \widehat{\omega}$, which allows us to identify the two terms separately. Thus, we calibrate $h_1 = 0.18$ and $\omega_1 = 0.1695$, and find that this pair leads to a smooth decline in per capita income growth.

Total world industrial emissions from fossil fuels, E_t, in 2015 were equal to 36 $GtCO_2$ (gigatonnes): assuming a 5% growth up to 2020 we have $E_1 = 0.038$ $TtCO_2$. Without abatement emissions per unit of output from (13) are $\sigma_1 = e_1/q_1$. From (11) we have $\sigma_1 = e_1/(\omega_1 h_1)$. Using (35) we get:

$$\sigma_1 = \frac{E_1}{\exp(\delta CE_1)Y_1} = \frac{0.038}{1.0062 \cdot 0.075} = 0.504 \tag{36}$$

We assume emission intensity decreases by 0.5% per year. Table 1 below summarizes the calibration outcome.[19]

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[19] The value for $\eta = 0.369$ is in the range of estimates of returns on education (de la Croix and Doepke, 2003).

Par	Description	Value	Target
long-run parameters			
ϕ	Opportunity cost of children	0.2	literature
β	Altruism	0.74	discount rate ($2\%/yr$)
γ	Fertility preferences	0.548	long-run fertility ($f_\infty = 0.95$)
η	Elasticity of human capital to education	0.273	share of education ($s/y = 0.2$)
χ	Compulsory school	0.00113	fertility in 2010 ($f_1 = 1.2$)
$\widehat{w}$	TFP growth	1.383	long-run economic growth ($y_{t+1}/y_t = 1.56$)
δ	Exponent in damage equation	0.0042	long-run climate damages
dynamic parameters			
ω_1	Productivity	0.1695	world GDP (75 tn euro)
σ_1	Emission Intensity	0.504	first-period emissions (36 GtCO$_2$).
θ_1	Abatement Coefficient	0.07	mitigation costs
θ_2	Abatement Exponent	2	literature
starting values			
N_1	Number of Parents [bn]	3.28	population 2010 (7 bn)
h_1	Human capital	0.18	smooth economic growth
E_1	Emissions [TtCO$_2$]	0.038	world emissions
CE_1	Cumulative emissions [TtCO$_2$]	1.48	historic emissions

Table 1: Parameters and Starting Values

5 Scenarios and 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 deliberate policies affecting either climate or family planning. The next scenario is the *Social Optimum* (SO), where welfare is maximized, and the policy maker implements the optimum through carbon and fertility taxes. The third scenario is the *Second-Best with Carbon-Taxes* (SB-CT), where the policy maker cannot steer family planning. That is, we set fertility taxes 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 tax adjusts to maximizes welfare.[20]

Figure 5 shows the optimal carbon tax. Only the Social Optimum and the Second-Best with Carbon Taxes cases are depicted, as the carbon tax is zero in the other two scenarios. In the SO and the SB-CT runs the carbon tax starts, respectively, at 30 euro/tCO$_2$ and 20 euro/tCO$_2$. In the next periods, it tends to rise approximately with income.[21] The tax is relatively low compared to other recent estimates, because we assume modest damages (parameter δ) and we have a substantial discount rate.

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[20] The precise definitions of the scenarios are provided in Appendix B.

[21] See C for further clarifications about the mechanism behind that result.

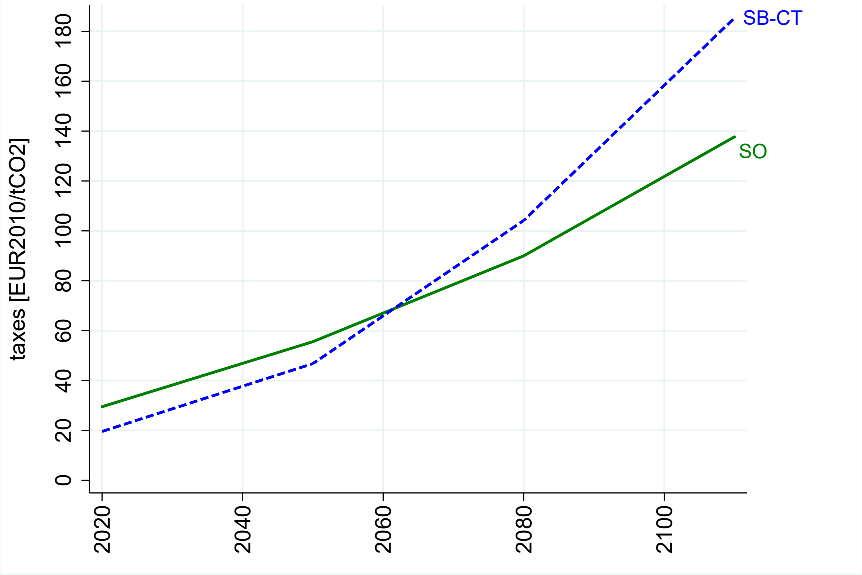

Figure 5: Carbon Taxes.

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: (1) 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; (2) carbon taxes tend to scale with income (Golosov et al., 2014; van den Bijgaart et al., 2016). In the SB-CT scenario fertility is higher, the future population is larger, income is higher (as seen in the next chart), and thus the carbon tax is higher. We see that the second mechanism outweighs the first one from the end of the 21st century onwards. This naturally introduces the following two charts.

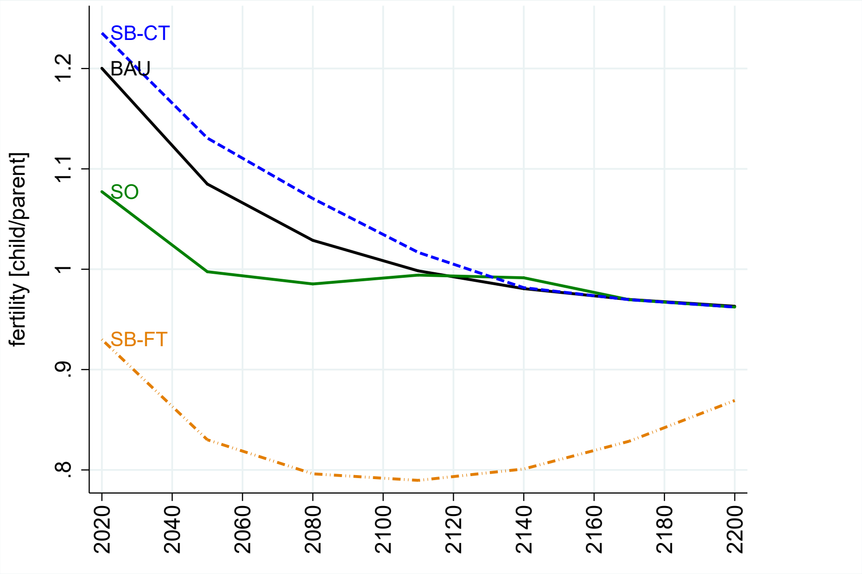

Figure 6: Fertility.

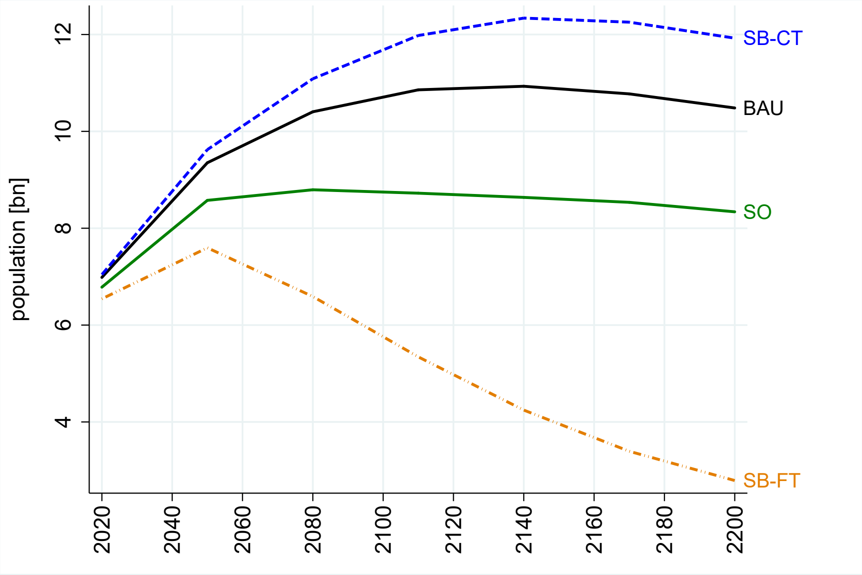

Figure 7: Population.

Figure 6 and Figure 7 show, respectively, fertility and population. Here we see that the social optimum indeed reduces fertility, while carbon policies tend to increase fertility due to lower income in the SB-CT scenario. The SB-FT scenario, instead, very strongly reduces fertility. 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, respectively, at above-10 billion and 12 billion. In the SO run, instead, the population remains below 9 billion. The SB-FT run reduces fertility so much that population level peaks by the mid of the century and then decreases. Note that the difference between the SO and the SB-CT scenario is almost 4 billion people by 2200.

Figure 8 shows the fertility tax. In the Social Optimum the fertility tax starts at 30 thousand of euro per child and peaks at 50 thousand of euro per child. Then it decreases and eventually is set zero as it is replaced by carbon taxes. In the SB-FT scenario, fertility taxes are initially low, but then increase sharply as family planning is the only instrument available to abate emissions.

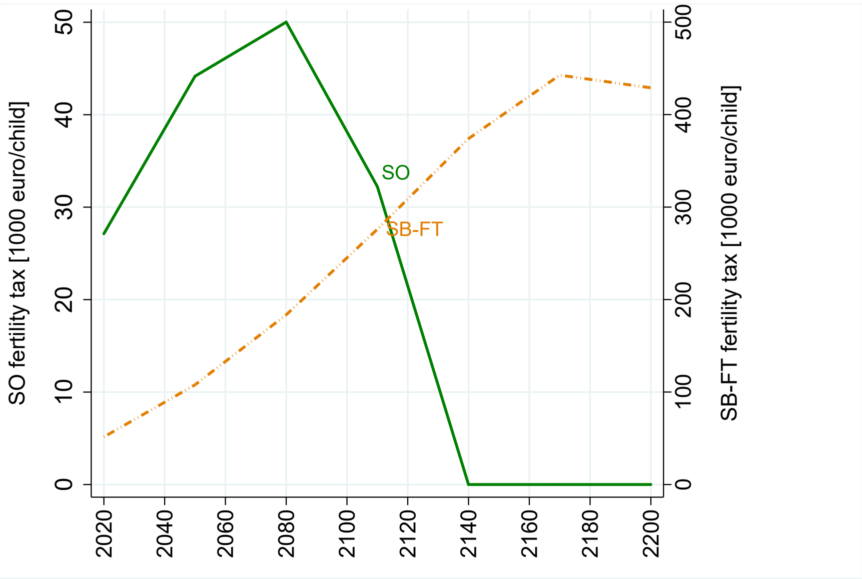

Figure 8: Fertility Tax.

The next chart shows the effectiveness of each policy in mitigating climate change.

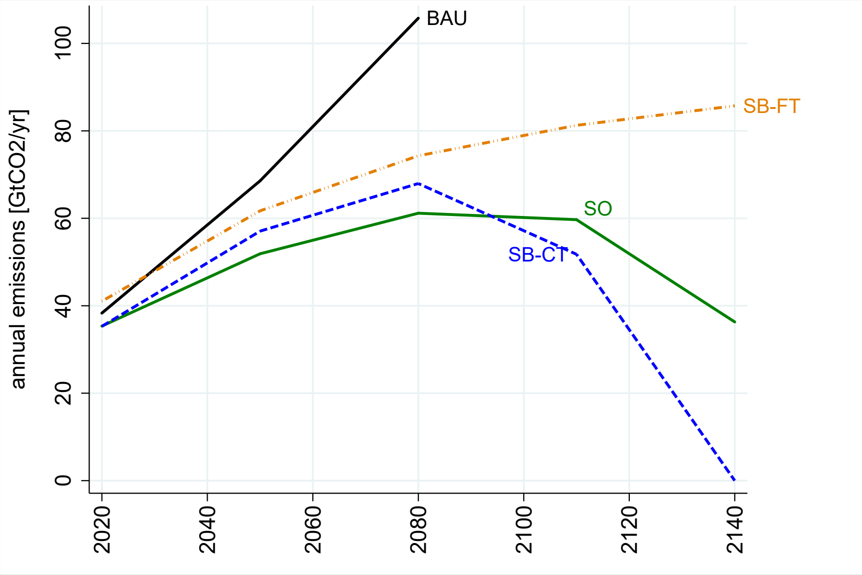

Figure 9: Emissions.

In Figure 9, in the BAU scenario emissions increase along the whole period as the carbon tax and the fertility tax are set to zero. Not surprisingly, in the SB-FT run fertility taxes reduce the level of emission compared to the BAU scenario. However, the boost in productivity induced by increased schooling prevents emissions to decline. Conversely, in both the SO and the SB-CT scenarios, emissions decline after 2080 and eventually reach zero. The outstanding feature is that cumulative emissions are lower in the SB-CT as compared to the SO: the explanation is that in the SB-CT scenario population increases significantly, and so it speeds up emissions through higher production, but it also induces a higher carbon tax reducing emissions after some time.[22] The following chart further clarifies the mechanisms behind our model, reporting a key economic variable.

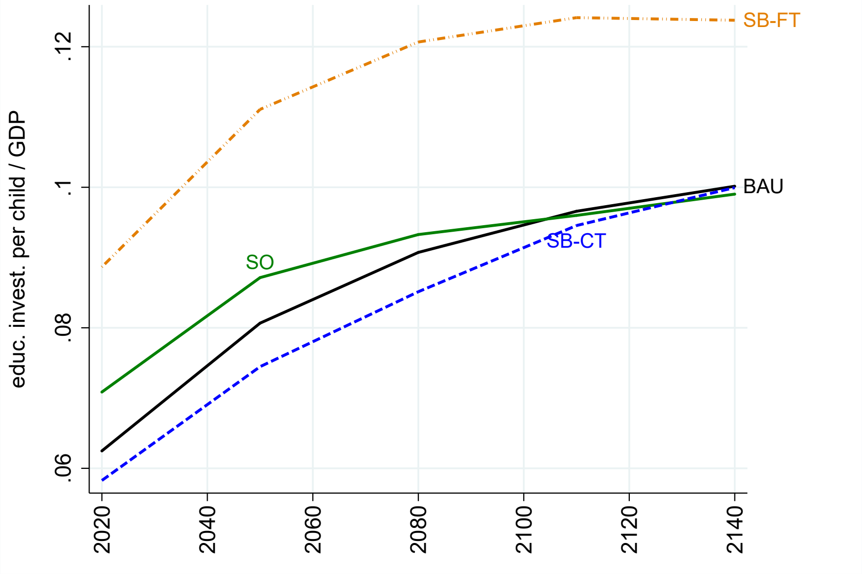

Figure 10: Investment in education as a share of income.

Figure 10 shows investment in education per child.[23] We find the same mechanism as in Xue and Yip (2017) who test the effect of one-child policy in China in a Unified Growth model: if the population is constrained, parents are willing to invest more in the education of their children. This is clear looking at both the SO and the SB-FT scenarios where family planning policies are adopted as a separate instrument for climate policies. In the SB-FT case investment in education reaches 12% of income and then stabilize. Fertility taxes lower the optimal fertility level, and parents' resources are spent in increasing the human capital of their few children. For the same reason, in the SO scenario investment in education are initially higher compared to both the BAU and the SB-CT scenarios where no fertility tax is imposed. Differences disappear by the end of the century and investment in education converges to 10 % of income.

We now compare emissions and fertility externalities. The next figures give quantitative substance to the concept of family planning as 'the ultimate externality' (Harford, 1998).

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[22] That is, our model features the Environmental Kuznets Curve.

[23] For a family with two children, multiply the number by 2 to find the share of education expenditures in income.

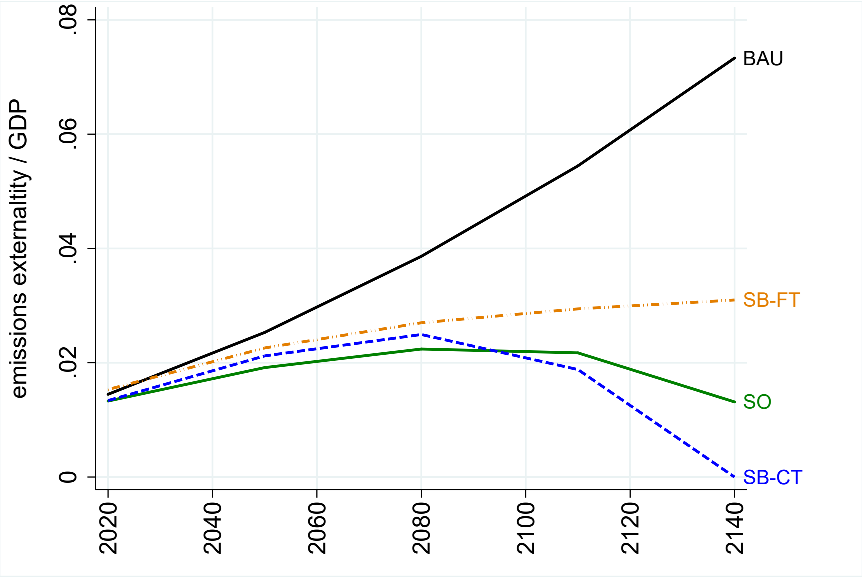

Figure 11: Welfare loss associated with emissions as a share of income.

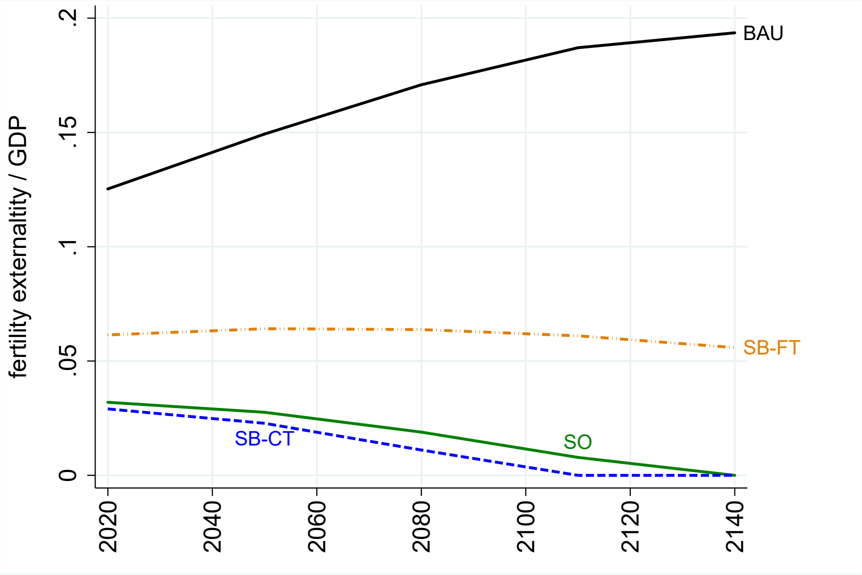

Figure 12: Welfare loss associated with births as a share of income.

Figure 11 shows the outcome if we multiply emissions by their shadow-price, and divide by gross output. We do the same for all scenarios (also for BAU and SB-FT where carbon prices are zero). In Figure 12, we repeat the procedure for the shadow price of fertility multiplied by the fertility level, divided by gross output. When we compare both indicators for all scenarios, we see that the fertility externality is much larger than the emissions externality. We can gauge the size of the birth externality by some back-of-the-envelope calculations. The fertility tax figure provides 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 5 trillion euro per year. If no effective climate policies are implemented, the externality costs amount to 10 trillion euro per year. That is much larger than the carbon tax times emissions.

6 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 ones.

We 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 scenarios results suggest that family planning aiming at smaller families should be addressed as a separate policy instrument against climate change. In particular, we found that: (i) family planning contributes to abate emissions and a reduction of population growth is an important element of efficient climate policy. The fertility tax increases the cost of having many children while stimulating parents to invest more in the education of their offsprings; (ii) without a family planning policy, carbon taxes should be reduced as they otherwise (unintentionally) increase family size through the quality-quantity trade-off ; (iii) in 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. The 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 new born increases the pressure on resources of our finite 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 followed a common economic approach and calculated the birth externality costs, which could be interpreted as a Pigouvian birth tax. A proposal for a birth tax is not easily imaginable; instead an alternative policy to increase women's education can receive more support. Yet, our model has insufficient detail for describing the relevant mechanisms to robustly analyze such policy, and we consider our study as an important first step that characterizes the magnitude of the challenge.

The model presented in this paper addresses two stock environmental externalities: climate damages originate from both the emissions generated firms' production activities and the emissions generated by net additions to current population. This is a simple consequence of the fact that cumulated emissions depend on the population size. We derive optimal carbon tax and fertility taxes designed to cope with the two externalities just mentioned.

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 taxing fertility decisions. Several countries show a declining labor force coupled with aging, some even declining population. This raises concerns about the sustainability of pension systems, accumulation of human capital, innovation potential and productivity of the economy. Yet, the environmental impact of newborns does not disappear even in those countries. Perhaps, an alternative policy instrument aiming at the same goal, is more appropriate. Support for education, especially at the lower end, 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 fertility, and higher education investments. We have presented simulation results concerning a social optimum scenario where both optimal carbon and fertility taxes are implemented and second best scenarios where only on tax at time is implemented. This has enabled us to provide evidence on the size of the 'population externality', among other things. Our approach, also bears on climate policy scenarios, including constrained scenarios such as temperature concentrations stabilization and Paris agreement. This is another natural extension of our work which we plan to pursue in the near future.

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A Model Derivations

A.1 Households

Parents maximize (4) subject to (5), (6), (7). The Lagrangian is:

$$\begin{aligned}\mathcal{L} = \sum_{t=0}^{\infty} \beta^i \{ & ln(c_{t+i}) + \gamma ln(f_{t+i}) \\ & + p_{t+i}[w_{t+i}h_{t+i}l_{t+i} + T_{t+i} - c_{t+i} - s_{t+i}f_{t+i} - \xi_{t+i}f_{t+i}] \\ & + \psi_{t+i}[(\chi + s_{t+i})^{\eta} - h_{t+i+1}] + \zeta_{t+i}[(1 - \phi f_{t+i}) - l_{t+i}]\}\end{aligned}$$

The firs order conditions for $(c_t, f_t, l_t, s_t, h_{t+1})$ are:

$$\frac{1}{c_t} = p_t \tag{37}$$

$$\frac{\gamma}{f_t} = p_t(s_t + \xi_t) + \phi\zeta_t \tag{38}$$

$$p_t w_t h_t = \zeta_t \tag{39}$$

$$p_t f_t = \eta\psi_t(\chi + s_t)^{\eta-1} \tag{40}$$

$$\psi_t = \beta p_{t+1} w_{t+1} l_{t+1} \tag{41}$$

After some manipulations we obtain (8),(9) in the main text.

A.2 Production

The firm maximises profits (15) in competitive markets, subject to (10), (11), (13), (14). The first order condition with respect to L_t yields:

$$y_t - w_t h_t - \tau_t e_t = 0 \tag{42}$$

Solving for the wage rate we obtain (17) in the main text. Then, substituting the constraints into the definition of profits and differentiating with respect to μ_t yields:

$$(1 - d_t)\theta_1\theta_2\mu_t^{\theta_2 - 1} = \tau_t\sigma_t \tag{43}$$

Solving for μ_t we obtain (16).

A.3 Social Optimum

In this appendix, we derive the optimal fertility tax, (22) used in (8), and the optimal carbon tax (21) used in (16). We also show the first order condition for the household's education expenditures to be consistent with the social optimum. The social optimum maximizes welfare (4), subject to the constraints (2), (5), (6), (20), (10), (11), (13), (14), (18), (19). We can simplify the optimization problem by combining some of these constraints. The Lagrangian is:

$$\begin{aligned}\mathcal{L} = \sum_{t=0}^{\infty} & \beta^i \{ (ln(c_{t+i}) + \gamma ln(f_{t+i})) \\ & + \lambda^N_{t+i}[N_{t+i+1} - f_{t+i}N_{t+i}] + \lambda^l_{t+i}[l_{t+i} - (1 - \phi f_{t+i})] \\ & + \lambda^c_{t+i}[exp(-\delta CE_{t+i})(1 - \theta_1 \mu^{\theta_2}_{t+i})q_{t+i}l_{t+i} - c_{t+i} - s_{t+i}f_{t+i}] \\ & + \lambda^q_{t+i}[q_{t+1} - \omega_{t+1}(s_{t-1+i})^{\eta}] \\ & + \lambda^{CE}_{t+i}[CE_{t+i+1} - CE_{t+i} - MN_{t+i}l_{t+i}(1 - \mu_{t+i})\sigma_{t+i}q_{t+i}]\}\end{aligned} \tag{44}$$

Let us compute the time t firs order conditions with respect to $(c_t, f_t, s_t, \mu_t, l_t, q_t)$:

$$\frac{1}{c_t} - \lambda^c_t = 0 \tag{45}$$

$$\frac{\gamma}{f_t} - \lambda^N_t N_t + \lambda^l_t \phi - \lambda^c_t s_t = 0 \tag{46}$$

$$-\lambda^c_t f_t - \eta\beta\lambda^q_{t+1}(\chi + s_t)^{\eta-1}\omega_{t+1} = 0 \tag{47}$$

$$-\theta_1\theta_2\mu_t^{\theta_2-1}\lambda^c_t(1 - d_t)q_t l_t + \lambda^{CE}_t M N_t l_t \sigma_t q_t = 0 \tag{48}$$

$$\lambda^l_t + \lambda^c_t(1 - d_t)(1 - a_t)q_t - \lambda^{CE}_t M N_t(1 - \mu_t)\sigma_t q_t = 0 \tag{49}$$

$$\lambda^c_t(1 - d_t)(1 - a_t)l_t + \lambda^q_t - \lambda^{CE}_t M N_t(1 - \mu_t)\sigma_t = 0 \tag{50}$$

and with respect to the stocks of parents and cumulative emissions (N_{t+1}, CE_{t+1}):

$$\lambda^N_t - \beta\lambda^N_{t+1}f_{t+1} - \beta\lambda^{CE}_{t+1}Ml_{t+1}e_{t+1} = 0 \tag{51}$$

$$\lambda^{CE}_t - \delta\beta\lambda^c_{t+1}l_{t+1}(1 - d_t)(1 - a_t)q_{t+1} - \beta\lambda^{CE}_{t+1} = 0 \tag{52}$$

Consider now (52) and use (10) in per parents term to get:

$$\lambda^{CE}_t = \beta\lambda^{CE}_{t+1} + \delta\beta\lambda^c_{t+1}l_{t+1}y_{t+1} \tag{53}$$

Use (45) and solve forward to obtain:

$$\lambda_t^{CE} = \delta \sum_{j=0}^{\infty} \beta^j \frac{l_{t+j} y_{t+j}}{c_{t+j}} \tag{54}$$

Then, multiply both sides by MN_t/λ_t^c to obtain the expression for the carbon tax (21) in the main text. Consider now (51). After some manipulations it reads as:

$$\frac{\lambda_t^N N_t}{\lambda_t^c} = \beta \frac{\lambda_{t+1}^N N_{t+1}}{\lambda_{t+1}^c} \frac{f_{t+1}}{f_t} \frac{c_t}{c_{t+1}} + \beta \frac{\lambda_{t+1}^{CE} M N_{t+1}}{\lambda_{t+1}^c} \frac{l_{t+1} e_{t+1}}{f_t} \frac{c_t}{c_{t+1}} \tag{55}$$

Converting the population dual variable λ_t^N in birth tax that is expressed in euro per child we define $\xi_t = \beta \xi_{t+1} \lambda_t^N N_t / \lambda_t^c$ and use (21) to obtain the expression for the fertility tax (22) in the text.

B Scenarios

The quantitative model has finite periods $t = 1, ..., T$. We rewrite the objective (4) recursively as:

$$u_t = \ln(c_t) + \gamma \ln(f_t) + \beta u_{t+1} \text{ for } t = 1, ..., T-1, \tag{56}$$

$$u_T = ln(c_T) + \gamma ln(f_T) + \beta\eta \ln(\chi + s_T) - \frac{\beta\delta}{1-\beta} CE_{T+1}. \tag{57}$$

The value of period-T education beyond the simulation period is proxied by $\beta\eta\ln(\chi + s_T)$. The intuition for this proxy is that, in the long run, individual income is proportional to human capital (5), which has elasticity η with respect to education (7). The last term captures welfare losses beyond the simulation period associated with all emissions during the simulation period, and equals $\beta\delta + \beta^2\delta + ...$ The welfare function representation is provided in Gerlagh and Liski (2017) .

The carbon tax (21) and the fertility tax (22) are also rewritten recursively as:

$$\tau_t = \delta\beta M N_t c_t \frac{l_{t+1} y_{t+1}}{c_{t+1}} + \beta \frac{c_t}{f_t c_{t+1}} \tau_{t+1} \tag{21'}$$

$$\tau_T = \frac{\beta\delta}{1-\beta} Y_T \tag{24'}$$

$$\xi_t = \beta \tau_{t+1} l_{t+1} e_{t+1} + \beta f_{t+1} \xi_{t+1} \tag{22'}$$

$$\xi_T = 0. \tag{58}$$

Note that, by the end of the simulation period, emissions are zero, which implies zero fertility taxes for the last period. Finally, we have to adjust the education first order condition (FOC)

(9) for the final period:

$$f_T(\chi + s_T) = \eta\beta y_T l_T \tag{59}$$

Business as Usual

We calculate the BAU scenario in two ways, to check the consistency of the GAMS source code. The first approach, labeled BAU0, is based on recursive welfare (56-57), population growth (2′), human capital production (5′), labour supply (6′), commodity balance (20′), final good production (10′), gross production before abatement and damages (11′), emissions (13′). We leave out the cumulative emissions definition (19′), and cumulative emissions from the last-period utility (57), so that current emissions do not decrease future output or welfare. We then iterate the solutions, substituting correct damages into the equilibrium, until the solution converges.

Subsequently, we define the 'full' BAU, labeled BAU1, by adding both the cumulative emissions definition (19′), and the FOCs fertility expenditures (8′), schooling expenditures (9′), abatement levels (16′), zero profit condition (17′) and the adjusted expression for education for the final period (59). In this construction, we set carbon and fertility taxes to zero, $\tau_t = \xi_t = 0$, leaving out (21′), (22′), (24′), (58). Both constructed solutions are the same, which ensures that the FOCs have been properly derived.

Social Optimum

We define SO0 through recursive welfare (56-57), population growth (2′), human capital production (5′), labour supply (6′), commodity balance (20′), final good production (10′), gross production before abatement and damages (11′), emissions (13′), cumulative emissions (19′). There is no need for an updating of damages. The solution is immediately correct. This is the solution approach typically used in IAMs such as DICE.

To check our analytical derivations for the FOCs, we define SO1 by adding the FOCs fertility expenditures (8′), schooling expenditures (9′), (59), abatement levels (14′), zero profit condition (17′), carbon taxes (21′), (24′), and fertility taxes (22′), (58).

Second best only carbon taxes

We define SBCT through recursive welfare (56-57), population growth (2′), human capital production (5′), labour supply (6′), commodity balance (20′), final good production (10′), gross production before abatement and damages (11′), emissions (13′), cumulative emissions (19). We add the FOCs fertility expenditures (8′), schooling expenditures (9′), (59), abatement levels (16′), zero profit condition (17′), leaving carbon taxes free to be chosen by the optimization and setting fertility taxes to zero, $\xi_t = 0$, and leaving out (21′), (24′), (22′), (58).

Second best only fertility taxes

We define SBFT through recursive welfare (56-57), population growth (2′), human capital production (5′), labour supply (6′), commodity balance (20′), final good production (10′), gross production before abatement and damages (11′), emissions (13′), cumulative emissions (19′). We add the FOCs fertility expenditures (8′), schooling expenditures (9′), (59), abatement levels (16′), zero profit condition (17′), setting carbon taxes to zero, $\tau_t = 0$, and leaving fertility taxes free and leaving out (21′), (24′), (22′), (58).

C Net Income

Figure C.1 clarifies the mechanism discussed when presenting Figure 5 in the main text. Due to higher fertility in the SB-CT scenario compared to the social optimum, aggregate income is high and average income is low. As the carbon tax approximately scales with aggregate income, its level in the SB-CT scenario overtakes that in the SO scenario.

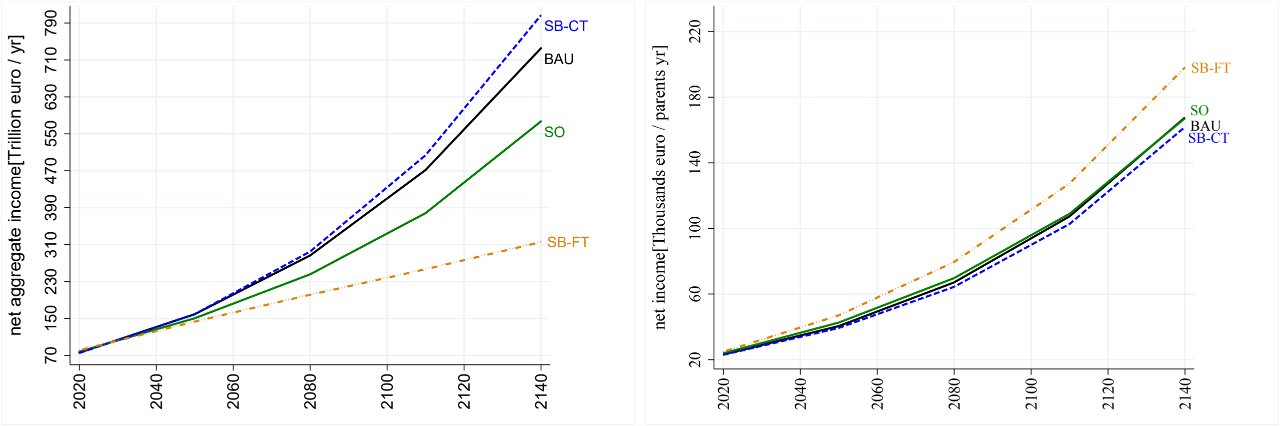

Figure C.1: Net Income: Aggregate (left panel) and Per Capita (right panel).

Figure C.1 also shows that scenarios with higher population have lower per capita income, but higher aggregate income. Welfare based on average income tends to rank low-fertility high per capita income scenarios above high-fertility scenarios with low per capita income. But as children also directly and positively enter utility, the social optimum is not the scenario with lowest fertility. That is, taking average utility balances the direct utility benefits of more children with the costs of lower average income. When we would model welfare through aggregate utility, on the other hand, the model would reproduce the repugnant conclusion (Parfit, 2016) and tend to rank high population low per capita income scenarios on top.