Population Growth and Climate Change: A Dynamic Integrated Climate-Economy-Demography Model*

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Abstract

We explore the bidirectional relationship between population growth and climate change: while population determines carbon emissions which drive climate change, climate change impacts the mortality rate and so population growth. Such population-climate feedback effects suggest that demographic policy may represent an alternative to traditional mitigation policies. We explore this possibility by introducing a population policy aiming at imposing a cap on population growth into an extended global integrated assessment model of climate-economy with endogenous fertility choices and temperature-related mortality. We show that the social costs of environmental policies, as reflected by both the social cost of carbon and social welfare, substantially increase by accounting for endogenous population change, but demographic policy allows to significantly reduce such costs. This clearly suggests that population growth does matter and so population policy may represent an effective mitigation tool to complement standard climate policies.

Keywords: Climate Change, Population Growth, Population Policy
JEL Codes: J10, O40, Q50

1 Introduction

Since Malthus (1798), economists have extensively debated on the role of human population dynamics in determining economic growth and environmental outcomes. A clear understanding of their mutual relations still remains elusive, however. Since population growth determines the size of the labor force, it positively contributes to production. However, since it also gives rise to a dilution of resources in per capita terms, it may have negative consequences on economic activities (see Bloom et al., 2003, for a survey of the population and economic growth relationship). Through the interactions between production and pollutant emissions, population growth may be beneficial or harmful for the environment (see Panayotou, 2000, for a survey of the population and environment relation). Given the recent trends in population growth and the predictions about its evolution over the next decades (UN, 2017), understanding the extent to which demographic changes may affect the prospects of sustainable development is a priority for both academics and policymakers. This has been recognized since the first discussions on sustainable development, as emphasized in the 1992 Rio Declaration: *"to achieve sustainable development and a higher quality of life for all people, States*

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should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies" (UN, 1992). However, despite the importance of such an issue, very little has been done thus far in order to quantify the possible impact of population change on sustainable development. This is the goal of our paper which wishes to shed some light on this delicate problem. In particular, focusing on climate change allows us to assess the two-ways relation between economic activities and environmental outcomes, explicitly accounting for the role that population growth and eventual demographic policies may play in this context.

Issues related to climate change are traditionally analyzed through integrated assessment models (IAMs). In the simplest climatic framework, emissions generated by production activities cumulate in the atmosphere affecting the temperature level, which in turn determines the amount of output the economy is effectively able to produce. Several IAMs have been developed and extended over the last decades (see Nordhaus, 2013, for a recent survey), but even if it is now clear that population growth plays a role as important as that played by the discount factor in determining the optimality of climate change policy (Budolfson et al., 2019), only few attempts to discuss how population growth mutually interacts with the economic and climatic sectors have been made. Indeed, in traditional IAMs population dynamics is taken as exogenously given and its effects on climate change are analyzed through a scenario-based approach (for a discussion of this method and some recent developments, see Kriegler et al., 2012; and Riahi et al., 2017).[1] This allows to understand how different demographic patterns, accordingly to the different variants of the UN projections (UN, 2017), will affect the economy and climate (see, among others, Cian et al., 2016; Cuaresma, 2017, Lutz, 2017; Scovronick et al., 2017; Bongaarts and O'Neill, 2018; Budolfson et al., 2019). However, such an approach does not take into account the fact that population growth, exactly as technology and other economic variables, may respond to the changes in the economic and climatic conditions (Lanz et al., 2017; Scovronick et al., 2017; Bongaarts and O'Neill, 2018). In order to account for such endogenous mutual economy-climate-demography feedback it is essential to extend the existing IAMs in order to endogeneize population change.[2] This is exactly the goal of this paper which wishes to stress that taking demographic patterns as exogenously given in IAMs risks to drive to a large extent their results, potentially undermining the entire assessment of the costs of climate change and alternative policies. Our paper wishes thus to make a first attempt in quantifying the extent to which allowing for endogenous population change might matter in the analysis of climate change.

We analyze the simplest IAM (the DICE; see Nordhaus, 2017) and allow for population growth to interact non-trivially with both the economic and climatic sectors. Because of the simplicity with which both the economic and climate systems are modeled, DICE cannot account for several essential aspects of the economy-climate bidirectional relation (i.e., endogenous technological progress, social inequalities, tipping points in climate dynamics, uncertainty), and thus over the years it has been extended along multiple directions to overcome the shortcomings related to such limitations (Nordhaus, 2013). Nevertheless, DICE is still considered an important benchmark framework to assess the desirability of alternative mitigation strategies and to quantify the social costs of climate policy. It seems natural thus to start our analysis by

[1]Several IAMs take into account the effects of exogenous population growth on climate change, including DICE (Nordhaus, 2017), REMIND (Leimbach et al, 2010), DEMETER-1 (Gerlagh, 2006), IMAGE (Sthfest et al., 2014), ANEMI-2 (Akhtar et al., 2013), FUND (Anthoff and Tol, 2014) and SSPs (Kriegler et al., 2012) models. Most of them allow for unidirectional effects from population growth to climate via the production and emission channel, while limited are the frameworks allowing for feedback effects via the health channel (see ANEMI-2 and FUND). Differently from these IAMs, we analyze how population growth is optimally determined via economic (i.e., fertility) and climatic (i.e., mortality) factors.

[2]Moreover, in the median variant scenario the UN projections (UN, 2017) predict that human population growth will gradually decrease over time in order for the world population size to stabilize at a level of about 11.5 billions of people by the end of the century. This is based on the assumption that also in developing countries a demographic transition will take place generating a substantial reduction in fertility rates. However, nowadays in most developing countries fertility rates are still much higher than in developed economies, and this fact along with the wide uncertainty concerning future fertility patterns (UN, 2017; UNFPA, 2012), represent serious challenges for the scenario-based approach in the analysis of the costs of climate change.

focusing on whether and how DICE conclusions might change in an extended framework with endogenous population growth. Specifically, in our extended DICE setup population growth is the result of agents' optimal decisions regarding their fertility rates (i.e., how many children to have). Fertility is determined by balancing the utility gained from having children and the cost of raising them. Since Becker's seminal works (Becker, 1960; Becker and Barro, 1988), optimal fertility decisions have been analyzed extensively in macroeconomic theory in a setting similar to ours (Palivos and Yip, 1993; Marsiglio, 2014) but to the best of our knowledge they have never been related to climate change. Moreover, in our framework the mortality rate is positively affected by climate change: the temperature level determines health conditions and thus contributes to reduce the pace of demographic changes. This is consistent with several works suggesting that increases in the temperature level will be detrimental for health causing increases in morbidity and mortality (IPCC, 2007; Huang et al., 2011; Carleton and Hsiang, 2016; Hsiang et al., 2017; Carleton et al., 2019); to the best of our knowledge temperature-induced mortality has been only seldom included in the analysis of climate change (Akhtar et al., 2013; Anthoff and Tol, 2014; Ikefuji et al., 2014; Bressler, 2020). Extending the analysis of climate change to allow for such a twofold endogenous nature of population growth might have important effects on quantifying the social cost of carbon and on exploring the role of demographic policy as an alternative mitigation tool.

The social cost of carbon summarizes the cost of mitigation policies by measuring the marginal welfare effect of an additional ton of carbon dioxide emissions in terms of consumption (Nordhaus, 2017). Since, according to the traditional total utilitarian criterion typically employed in IAMs,[3] welfare is defined as the discounted sum of the product between per capita utility and population size along with the fact that fertility affects utility while mortality affects the population size, accounting for endogenous population changes allows us to quantify their additional direct and indirect welfare effects. This is likely to have a large effect on the estimates of the social cost of carbon, allowing for a better quantification of the costs of climate change and alternative mitigation policies. Mitigation policies explored thus far in IAMs include optimal emission abatement, imposing a ceiling on temperature and other economic or environmental policies, while demographic policy has never been specifically considered. However, since population policy can affect the fertility rate and thus impact the population size it is likely to have large (direct and indirect) welfare effects, suggesting that it might be an important tool to reduce the social costs associated with climate change (UNFPA, 2009; de la Croix and Gosseries, 2012; Marsiglio, 2017). Indeed, population policy in the form of family planning programs aiming to assist women in achieving their reproductive goals through a variety of arrangements (i.e., promoting access to effective contraception methods, improving women's educational opportunities, or favoring their empowerment) have proved successful in reducing demographic growth by avoiding unplanned pregnancies along with being one of the most cost-effective development strategies to reduce poverty and improve health and environmental outcomes (May, 2002; Bongaarts and O'Neill, 2018). Therefore, exploring whether population policy may be an effective mitigation tool to complement standard climate policies is our main goal in this paper.

This paper proceeds as follows. Section 2 briefly presents our model which is basically a DICE model extended to allow for endogenous population change. Agents by choosing their fertility rate along with consumption and investment, which impact the emissions and thus temperature which in turn affects mortality, determine the net growth rate of population. Section 3 describes our calibration strategy and the scenarios considered, which include also a demographic policy aiming to impose a ceiling on demographic growth. Section 4 presents our simulation results where we focus on the evolution of key economic, environmental and demographic variables, including per capita output, emissions, temperature, fertility and mortality rates.

[3] With the exception of Lutz (2017) and Scovronick et al. (2017) who assess climate change policies under both the total and average utilitarian criteria, to the best of our knowledge all IAMs are built upon total utilitarianism. As we shall discuss with more depth in section 6 total utilitarianism may give rise to ethical issues in a context of a growing population, thus all the results derived from such a framework need to taken with caution. However, as we shall show in our robustness analysis most of our qualitative conclusions hold true also under average utilitarianism.

We show how different policies affect such variables and in particular how population policy might be an important mitigation policy since allowing to substantially reduce the social cost of carbon and the welfare cost of climate policy. Section 5 considers how our main results change with the intensity of the population policy, confirming the robustness of our conclusions regarding the viability of demographic policy. Section 6 discusses the main limitations underlying our global (DICE-type) analysis in order to put in perspective our conclusions regarding the implications of introducing endogenous population growth in the assessment of the cost of alternative mitigation policies to address climate change. Section 7 presents concluding remarks and suggests directions for future research. Appendix A describes in full our model's equations and the parameter values employed in our analysis, while appendix B performs robustness analysis showing that our qualitative results hold true even under different values of some key parameters and under different specifications of some functional forms, including the social welfare function.

2 The Model

We extend the simplest IAM in order to account for the mutual links between population growth and climate change. Specifically, we focus on the Dynamic Integrated Climate-Economy (DICE) model[4] (Nordhaus, 2017), and we introduce endogenous population change to allow for population growth to be the result of optimal planning decisions and to both affect and depend upon climate change. By building on a DICE-type setting, we analyze a global model in which there is only one region (i.e., the world), and thus we abstract from migration flows between regions and we focus on the effect of global (world) population on climate change. In most IAMs (also in those exploring the effects of population change on climate change and mitigation policies, as Lutz, 2017; and Scovronick et al., 2017) population growth is assumed to be exogenous and generally, according to the UN projections (UN, 2017), to gradually decrease over time in order to allow human population to stabilize to some exogenous level in the long run. This is a strong simplification of reality where population growth is determined by individuals' fertility decisions, and as such it may respond to both economic incentives and climatic factors. Therefore, relaxing such an assumption of an exogenously growing population allows us to consider demographic policies as an additional tool to reduce the costs associated with climate change.

In the standard DICE model, the exogenous evolution of human population, N_t is described by a logistic-type equation as follows:

$$N_{t+1} = N_t(1 + g_t) \tag{1}$$

where its growth rate g_t exogenously decreases at a constant rate δ_N as follows:

$$g_t = \frac{g_{t-1}}{1 + \delta_N} \tag{2}$$

Such a completely exogenous demographic characterization is the simplest way to allow human population to approach a limit of 11.5 billion people in 2100, as hypothesized by the projections developed by the UN, in the medium variant scenario (UN, 2017). However, this can be accounted for also without imposing any specific constraint to the evolution of human population. Indeed, in our approach we allow human population to be optimally determined and to converge to this exact level in 2100, by simply imposing a terminal condition on the population size. In our setting, the growth rate of human population is endogenously determined as follows: $g_t = n_t - d(T_t)$, where n_t is the optimal fertility rate and $d(T_t)$ is the mortality rate which depends on climate change and in particular on the temperature level, T_t. Therefore, population dynamics is given by:

$$N_{t+1} = N_t[1 + n_t - d(T_t)] \tag{3}$$

[4]Specifically, we rely on the 2013 revised version of DICE, and we update some parameter values borrowing from the 2016 version.

The fertility rate is endogenously determined and we assume that it affects the instantaneous utility function (Barro and Sala–i–Martin, 2004; Palivos and Yip, 1993), which is specified as follows:

$$u(c_t, n_t) = \frac{(c_t n_t^{\kappa})^{1-\zeta} - 1}{1-\zeta}, \tag{4}$$

where $c_t = \frac{C_t}{N_t}$ is per capita consumption, $\zeta > 0$ the marginal elasticity of consumption and $\kappa \in (0, 1)$ the relative weight of fertility in the utility function. The traditional setting in IAMs assumes that $\kappa = 0$, precluding any role for fertility decisions. Introducing fertility in the utility function introduces also an additional control in the social planner's maximization problem, which therefore allows us to understand how population dynamics may be affected by specific policies.

Similar to Voorhees et al. (2011), we model mortality as follows:

$$d(T_t) = d_1 e^{d_2 T_t}, \tag{5}$$

where $d_1 > 0$ and $d_2 > 0$ are exogenous scale parameters. The equation above aims to capture in the simplest possible way the relationship between temperature and mortality, which thus far has been only seldom considered in IAMs (Akhtar et al., 2013; Anthoff and Tol, 2014; Ikefuji et al., 2014; Bressler, 2020). Several papers document the existence of a positive association between temperature and health risk, suggesting how increases in frequency and intensity of heat waves may be detrimental for health, affecting thus mortality[5] (IPCC, 2012; Carleton and Hsiang, 2016; Hsiang et al., 2017). Accounting for such effects of climate change on mortality might help us to quantify more precisely the size of the potential costs induced by climate change.

The introduction of fertility decisions in our setting implies that income can also be used to raise children. Therefore, the closed economy's resources constraint is given by the following expression:

$$Y_t = C_t + I_t + R_t, \tag{6}$$

suggesting that aggregate output, Y_t, can be devoted to either consumption C_t, investment, I_t, or child-rearing activities, R_t. As in Barro and Sala–i–Martin (2005), we assume that the cost of raising children is linear in capital as follows:[6]

$$R_t = \theta n_t K_t, \tag{7}$$

where $\theta > 0$ is a scale parameter and K_t is the aggregate capital stock. The above formulation represents in the simplest possible way the children quantity and childrearing investment trade-off (Becker and Lewis, 1973), since raising children subtracts resources to capital investment. In order to look at this, plug (6) into the following capital dynamic equation: $K_{t+1} = (1 - \delta_K)K_t + I_t$ stating that the next period's capital stock equals the undepreciated current period's capital stock augmented for investment, where $\delta_K > 0$ denotes the capital depreciation rate. Then, by dividing by the population size given by (3), with some straightforward algebra the economy's resource constraint in per capita terms can be expressed as follows:

$$k_{t+1} = \frac{y_t + (1 - \delta_K)k_t - \theta n_t k_t - c_t}{1 + n_t - d(T_t)}, \tag{8}$$

where lower-case letters denote per capita variables. Specifically y_t is output per capita, k_t capital per capita and c_t is consumption per capita. From equation (8), it is clear that an increase in the fertility

[5]This may occur through a variety of channels related to the effects of higher temperature on the living environment, the ozone formation, flooding, disease patterns and food supply (see Bressler, 2020, for an extensive survey of climate-induced mortality).

[6]This assumption states that capital, the main input employed in the production of the unique consumption good, can also be devoted to child-rearing activities, suggesting thus that growing children takes parents' resources away from other alternative uses. Child-rearing activities could alternatively be assumed to depend on parents' time to represent the situation that growing children takes parents' time away from working activities (Marsiglio, 2017), but since in our setting the labor supply is exogenous it is natural to model the cost of raising children as a function of capital.

rate (i.e., increasing the quantity of children) negatively affects the future per capita level of capital by reducing the resources left for investment and by increasing capital dilution; this tends to decrease income and therefore consumption in the following period (i.e., reducing the childrearing investment) affecting thus future fertility decisions. This stresses the existence of a clear trade-off between quantity of children and childrearing investment.

Fertility decisions, by determining the population size and therefore the labor force, play a crucial role in driving climate change. Indeed, since labor is an input in the production function, by affecting output fertility decisions determine the level of pollutant emissions which is an important driver of climate change. Specifically, the net (of abatement and damage) production is determined by a Cobb-Douglas function as follows:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha}, \tag{9}$$

where N_t is total population, $0 < \alpha < 1$ is the capital share of income and A_t the exogenously growing level of technology determining total factor productivity. Industrial emissions, which is an important component of total emissions which in the end determine climate change, are proportional to output; therefore, a larger population size by increasing emissions leads to faster variations in the temperature level, which in turn negatively affects population growth. Because of such a two-ways relation between population growth and climate, demographic policies aiming to modify agents' individual decisions regarding how many children to have can play an important role in reducing climate change.

Apart from the above mentioned peculiarities of our setting, all other elements of the DICE model are entirely preserved. The complete specification of the economic and climatic sectors is reported in appendix A. Therefore, our framework consists of a standard DICE model extended to allow for population dynamics to be affected by agents' optimizing decisions twofold: (i) agents directly determine the fertility rate which determines one component of the net rate of population growth, and (ii) agents indirectly (via their consumption and investment decisions) affect the evolution of temperature which by impacting the mortality rate determines another component of the net rate of population growth. Understanding how these channels work and how specific policies might affect them and in turn contribute to reduce the social costs of climate change is our main concern. As usual in IAMs, we quantify the cost of climate change with the social cost of carbon, which measures the economic cost caused by an additional unit of CO2 emitted in the atmosphere. This provides us with a rough estimate in dollar values of the social cost of emissions. Specifically, we wish to understand the extent to which endogenous population change matters in quantifying such a cost and what role specific demographic policies can play in order to effectively reduce it.

3 Calibration and Scenarios

In order to be able to derive some meaningful comparison, we mainly rely on the same set of parameters and the same scenarios employed in the standard DICE model. Therefore, we only need to calibrate the parameters related to the demographic peculiarities of our setting, that is κ, d_1, d_2, and θ. Consistent with our global modeling approach such parameters need to be calibrated according to world-level estimates. We thus set the relative weight of fertility in the utility function, κ, according to Growiec (2006), Boikos et al. (2013) and Marsiglio (2014). We choose the cost of raising children, θ according to Barro and Sala–i–Martin (2005) and the mortality parameters, d_1 and d_2, are instead calibrated to represent the world mortality rate due to climate change (Voorhees et al., 2011). The value of these parameters are therefore the following: $\kappa = 0.8$, $d_1 = 0.007$, $d_2 = 0.002$ and $\theta = 1.3$. All other parameters are exactly the same as in the standard DICE model and are listed in Table 6 in appendix A.

We consider four scenarios, three of which mimic those traditionally employed in DICE while one is introduced in order to account for demographic policy. Specifically, we focus on a business as usual, an optimal benefit-cost comparison, a cost-effective temperature and the cost-effective demography scenario.

Each of them is briefly described below.

(a) Business as usual (BAU): this scenario assumes no changes in the climate policy with respect to the 2015 levels. It is the baseline showing the consequences of inaction.

(b) Optimal benefit-cost comparison (BC): this scenario determines the share of emissions to abate in order to maximize social welfare, accounting for the impacts of climate change on output and therefore consumption. It identifies the optimal climate policy balancing the present value of abatement costs and the present value of benefits associated with climate change mitigation. It provides an efficiency benchmark against which other policies can be measured.

(c) Cost-effective temperature (CE-Temp): this scenario imposes a constraint on the global temperature level, requiring temperature not to exceed 2.5°C with respect to the average temperature in the pre-industrial era. This scenario represents a lenient version of the recent Paris agreement in December 2015, in which governments of several countries have agreed on the long-term goal of keeping the increase in global temperature below 2°C. In order for this goal to be effectively achieved, the co-operation of all major emitters around the world (i.e. USA and China) and the involvement of the developing countries is a necessary condition. Several researchers are skeptic about the effective ability to achieve such a goal, and as Nordhaus (2016) highlights, it will be challenging to achieve the target even if drastic climatic policies are introduced since today.[7] This scenario allows us to quantify the efforts and the costs needed to effectively reach a more realistic temperature target of 2.5°C.

(d) Cost-effective demography (CE-Demo): this scenario imposes a limit on the level of human population, required not to exceed 9 billions of people by the end of the century. This scenario is consistent with the low variant of the UN population projections, but differently from other IAMs we do not assume that such a demographic stabilization will occur automatically but might need to be implemented with specific policies.[8] Since climate-agreements are signed on voluntary basis and countries have common but differentiated responsibilities depending on their socio-economic conditions, the effective success of such agreements is highly uncertain. We thus believe that relying on the de-carbonization of the production plans and on climate policies alone might not be enough and thus we explore how alternative policies, in the form of demographic policies, might contribute to combat climate change.

Note that population change is endogenous in all the scenarios due to the endogenous determination of fertility and the temperature-induced mortality, while population growth is constrained only in the last one. Therefore, even if the first three scenarios resemble those considered in a traditional DICE setup, in our framework they are characterized by endogenous population dynamics and thus they may lead to conclusions substantially different from those derived in DICE.

The results of our scenario analysis are presented in the next section, where we mainly focus on some key variables, and in particular on per capita GDP net of damages and abatement costs, per capita consumption, industrial emissions, temperature level, emission control rate, population size, fertility and mortality rates.

[7] Climate change researchers believe that the global temperature increase will likely exceed 3°C by 2100, and since some environmental feedback effects are likely to be underestimated in current projection methods it may even reach 5°C (Hausfather and Peters, 2020). Therefore, even strict adherence to the Paris accord by major emitters would not be enough to reach the 2°C target, and probably even substantial enhancements in individual and global mitigation efforts would not allow to meet the target (Rogelj et al., 2016). In order to take into account such concerns and not to deviate too much from the analysis generally performed in a similar DICE setup to allow for comparability between results, in our cost-effective temperature scenario we have set the temperature target of 2.5°C.

[8] Population policies in the form of family planning or women empowerment have been proved successful in reducing fertility rates and favoring economic development in developing countries (May, 2002; Bongaarts and O'Neill, 2018). However, socioeconomic factors, religious and cultural traits, along with social norm determine the eventual support or opposition received by population policy at household and social level, affecting thus their potential effectiveness (Bongaarts and O'Neill, 2018). Since ours is a global world-level analysis we cannot account for such eventual differences which might emerge across countries, thus we do not discuss the implementation issues associated with demographic policy but we simply investigate whether it may an effective mitigation instrument.

4 Results

Our model starts in 2015 and each period lasts five years. Table 1 presents the results of our scenario analysis until 2050 in the standard DICE and in our endogenous-population-extended DICE models, respectively. As a matter of expositional simplicity in what follows we shall refer to our extended model as the "DICED" ("Dynamic Integrated Climate-Economy-Demography") model. From a quick comparison of the two models it is straightforward to note that DICE and DICED have the same initial level of income and consumption per capita, of industrial emissions and temperature. Starting from 2020 their predictions change: this is the result of endogenizing population in DICED, where the fertility rate determines the evolution of population differently from DICE, even though in the long run the population converges to the same level. This strongly affects the medium and long run outcomes: by 2050 in DICED the BAU scenario predicts lower industrial emissions (-23%), lower net output (-11.5%) and consumption per capita (-14.1%) than in DICE. Similar conclusions extend also to the optimal and the temperature scenarios.

Table 1 allows us also to compare the effects of the different scenarios in DICED and to derive the following conclusions. The demography scenario guarantees the highest per capita output (+4.4%) and consumption (+5%) by 2050. The temperature scenario is the most effective in reducing industrial emissions, which reach zero in 2050, suggesting a complete shift from fossil fuel-based to renewable production, an option which nowadays still seems quite unrealistic. In terms of temperature, the demography and the optimal scenario provide almost the same results, which suggests that a demographic policy may play an important role in mitigating climate change and, at the same time, increasing output per capita.

		DICE					**DICED**				
Variable	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2050**	**2015**	**2020**	**2025**	**2030**	**2050**
Net GDP per capita	Baseline	14.2	15.9	17.8	19.9	29.9	14.2	15.0	16.3	17.9	26.9
(thousands USD)	Optimal	14.2	15.9	17.8	19.9	29.9	14.2	15.0	16.3	17.9	26.9
	Temperature	14.0	15.7	17.4	19.3	28.6	14.2	14.7	15.9	17.4	25.7
	Demography						14.2	15.3	16.8	18.6	28.1
Consumption per capita	Baseline	10.5	11.8	13.3	14.9	22.6	10.6	11.1	12.0	13.2	19.8
(thousands USD)	Optimal	10.5	11.8	13.3	14.9	22.6	10.6	11.1	12.0	13.2	19.7
	Temperature	10.4	11.7	13.0	14.4	21.5	10.6	10.9	11.7	12.7	18.8
	Demography						10.6	11.4	12.5	13.8	20.8
Industrial Emissions	Baseline	35.7	39.4	42.9	46.3	58.8	35.7	35.9	37.2	39.0	47.8
(GtCO2 per year)	Optimal	35.7	33.1	35.1	36.8	39.1	35.7	29.7	30.0	30.6	31.6
	Temperature	20.1	19.1	17.0	13.6	0	35.7	15.4	13.1	10.2	0
	Demography						35.7	30.6	31.1	31.6	32.5
Temperature	Baseline	0.9	1.0	1.2	1.4	2.1	0.85	1.0	1.2	1.4	2.1
°C	Optimal	0.9	1.0	1.2	1.4	2.0	0.85	1.0	1.2	1.3	2.0
	Temperature	0.9	1.0	1.2	1.3	1.7	0.85	1.0	1.2	1.3	1.7
	Demography						0.85	1.0	1.2	1.3	2.0

Table 1: Main results from the DICE and DICED models.

Note that the peculiarities of our framework, and in particular the optimally determined fertility rate, makes our model's results not easily comparable with those provided by the standard DICE. For example, under a scenario-based approach aimed to analyze the effects of exogenous population growth, it is possible to restore the demographic parameter values employed in DICE and therefore to directly quantify the extent to which a different (exogenous) population pattern may alter the predictions and the results. In our setting this cannot be done since the endogenous fertility rate cannot be set in any way to replicate the demographic growth pattern in DICE, as this is a function of the other endogenous variables and so it does depend on all the model's parameters in a highly nonlinear way. For this reason, in the following, we will compare the results arising from different scenario within DICED limiting a comparison between our results with those from DICE to the social cost of carbon, which represents a summary measure of the costs of climate change and can be easily compared between the two models.

The evolution of our key variables is presented in Figures 1 and 2, which focus on the main economic-

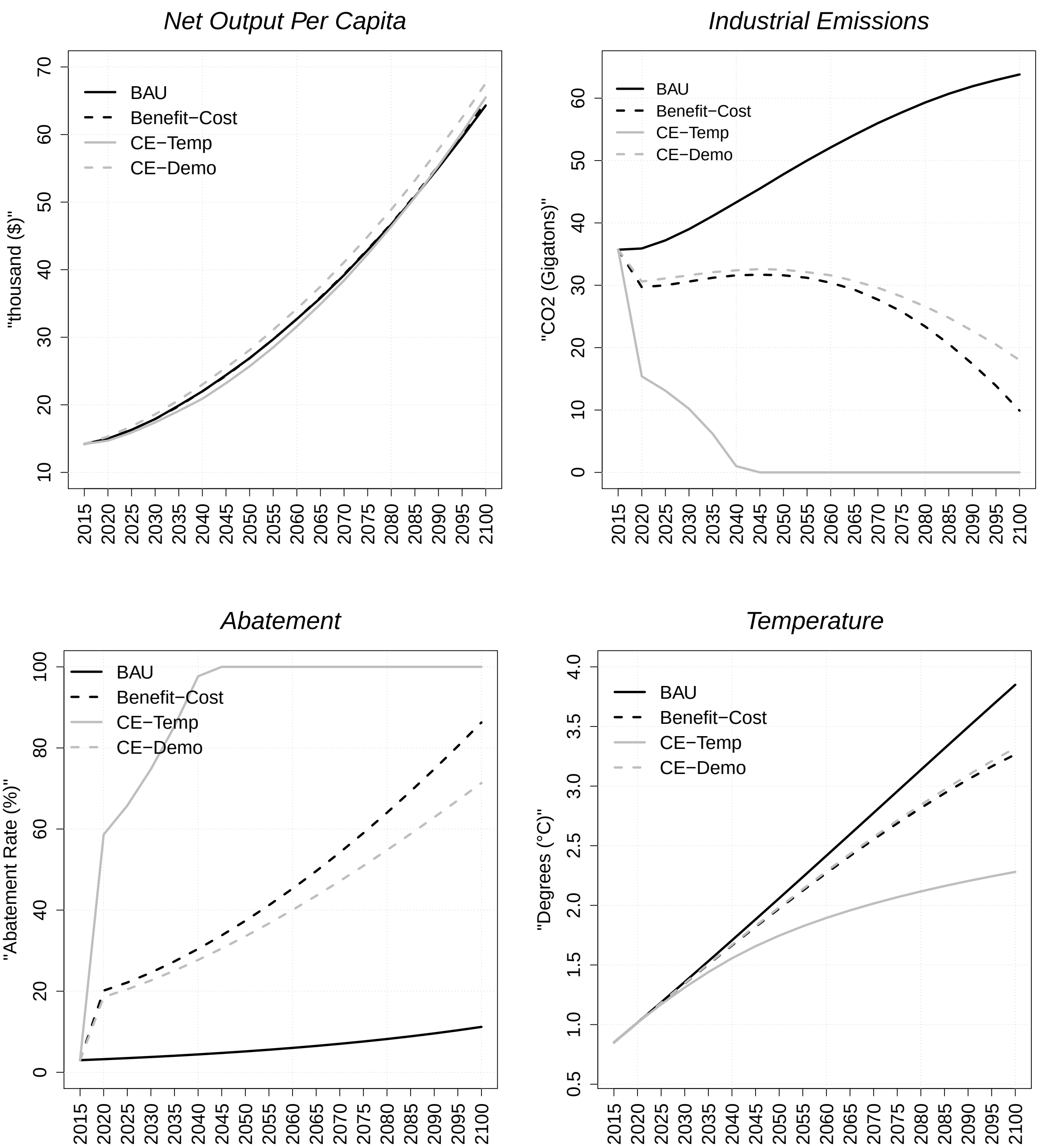

Figure 1: Evolution of economic and environmental variables.

environmental and demographic variables respectively. The solid black curve represents the baseline scenario, the dashed black curve the optimal scenario, the solid gray curve the temperature scenario and the dashed-gray curve the demography scenario. In the BAU scenario we can note that technological progress allows to achieve a substantial increase in output per capita over time, even if such an increase in economic performance comes at the cost of a deterioration in environmental performance. Emissions monotonically rise over time, and their cumulated effects in the atmosphere determine the temperature level, which increases above 3.5°C by the end of the century suggesting that without policy changes the temperature goal imposed by the Paris agreement will clearly not be achieved (Figure 1). Such a temperature increase leads to a gradual increase in the mortality rate, which combined with the decreasing fertility rate determines a drop in population growth, allowing the population size to stabilize at the end of the century (Figure 2). In the optimal scenario the emission control rate increases dramatically reaching 80% by 2100; this allows to reduce

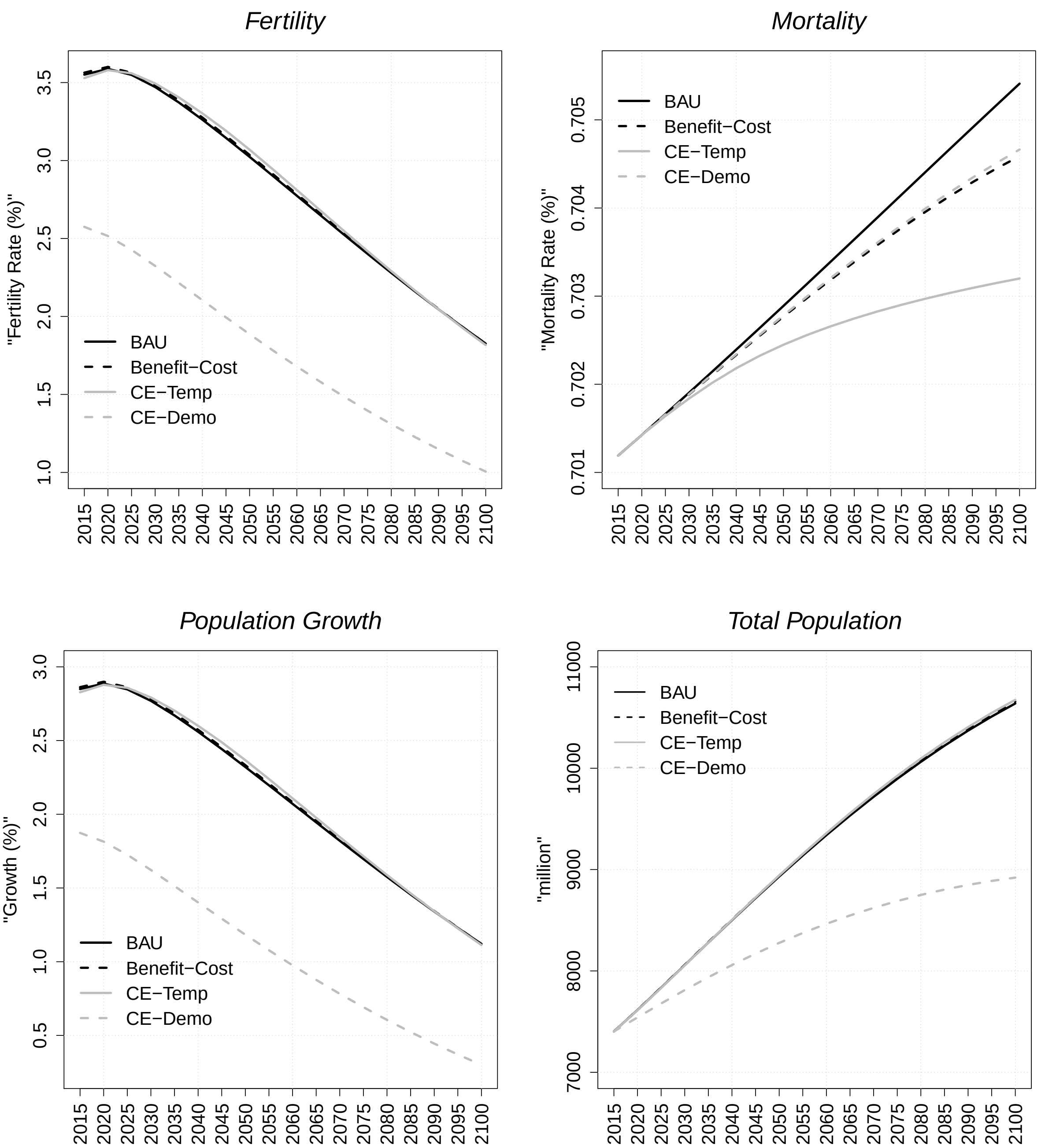

Figure 2: Evolution of demographic variables.

substantially emissions, leading to a lower temperature and so mortality with respect to the BAU. In the temperature scenario the emission control rate reaches 100% in 2040 implying that emissions are completely null from that date onwards. The substantial drop in the temperature level leads to a significant reduction in the mortality rate. In these three (BAU, optimal, temperature) scenarios the variations in income per capita and fertility rates are almost negligible. In the demography scenario a ceiling on fertility is imposed (this can be thought of as the result of specific demographic policies, aiming for example to incentivize women's education at the cost of fertility). Apart from leading to a substantial drop in the fertility rate, the demographic policy generates also an important increase in output per capita with respect to the other three scenarios; this is clearly due to the smaller dilution effect which allows aggregate output to be split across fewer people. The emission control rate is lower than in the optimal scenario and as such emissions are higher; despite this, the temperature level and the mortality rate mimic well those associated with the optimal scenario. This is due to the role of the control on fertility, which represents an alternative instrument to mitigate climate change allowing to achieve similar temperature patterns with lower emissions control. Such an instrument appears quite effective, since allowing to achieve the same temperature level as in the optimal scenario but a higher level of income per capita, suggesting that demographic policy may be a viable tool to attain a win-win outcome favoring both economic and environmental performance (measured by income per capita and temperature level, respectively). Moreover, as we shall clarify in a while, the cost of a such a demographic policy is lower than that associated with other policies, indicating that demographic policy is an effective tool to mitigate the effects induced by climate change.

Finally, Table 2 presents the social cost of carbon (SCC) computed from the DICE and our DICED models. We can note that in the BAU scenario the SCC in 2015 is about $31.2\$/tCO2$ in DICE, while in DICED it is substantially higher and precisely equal to $39\$/t$. Similar qualitative differences apply also in other scenarios: in the optimal scenario the SCC is $30.7\$/t$ in DICE and $37.9\$/t$ in DICED, while in the temperature scenario it is $155\$/t$ in DICE and $204\$/t$ in DICED. Note that this type of result is driven by the introduction of endogenous population change and in particular by the role played by endogenous fertility choices: since fertility enters the welfare function, such fertility effects are quantified in the assessment of the SCC. Indeed, since the SCC quantifies the marginal welfare effects of mitigation policy, the introduction of fertility in the utility function increases such welfare effects, as mitigation policy impacts welfare both directly (via the utility channel) and indirectly (via the population size channel) through its effects on fertility. It is interesting to note the effects of demographic policy which helps to substantially reduce (by around 16% with respect to the BAU) the social cost of carbon. Indeed, in the demography scenario the SCC is $32.6\$/t$. This suggests that relying on demographic policy can be an effective means to combat climate change at lower social costs. Such a conclusion is consistent with other studies (UNFPA, 2009; de la Croix and Gosseries, 2012; Marsiglio, 2017) which stress that non-coercive population policies, in the form of family planning, access to effective contraceptive measures and education, represent a successful means to favor economic development (May, 2002; Bongaarts and O'Neill, 2018), and thus they may be also effectively used as alternative or complementary means to traditional mitigation policies.[9]

Variable	Scenario	2015	2020	2025	2030	2050
SCC, DICE	Baseline	31.2	37.3	44.0	51.6	90.5
(USD)	Optimal	30.7	36.7	43.5	51.2	91.0
	Temperature	155.4	194.2	241.5	298.8	658.4
SCC, DICED	Baseline	39.0	42.5	48.1	55.3	96.9
(USD)	Optimal	37.9	41.3	46.8	54.0	95.3
	Temperature	204.3	228.1	267.5	320.1	693.7
	Demography	32.6	36.3	41.3	47.3	80.2

Table 2: Social cost of carbon in the DICE and DICED models.

Since the SCC assesses only the marginal impacts of policy changes, we may wonder whether it can effectively be used to compare the policy effects under two substantially different frameworks, like those presented in the DICE and DICED models. An alternative measure in this context is represented by social welfare which, by quantifying the discounted sum of utilities, takes into account the impact of alternative policies on all variables over the entire time horizon. Welfare is the preferred variable in the macroeconomic literature to assess the desirability of different policy options (Acemoglu, 2008) and it has also been used in IAMs to complement the SCC (Scovronick et al., 2017). Remember that the welfare function in DICED directly includes fertility since it enters the utility function while in DICE the utility function depends only upon per-capita consumption, thus a policy affecting demography may give rise to large welfare effects in

[9]Note that the type of demographic policies we are referring to include only non-coercive methods to reduce fertility rates. Due to their ethical implications and questionable effects of the sex-ratio in the medium and long rum, our analysis and our conclusions do not extend also to coercive and institutionalized forms of population policy, such as the one-child policy introduced in China in 1979, later substituted by a two-child policy in 2015 (Zeng and Hesketh, 2016).

DICED. We now reassess the implications of alternative scenarios by focusing on their welfare effects, and the results of this analysis are reported in Table 3. In both DICE and DICED, we consider the BAU scenario as the benchmark and we measure how such a welfare level changes across the different scenarios.

Variable	**Baseline**	**Optimal**	**Temperature**	**Demography**
Welfare, DICE	100	102.7	101	
Welfare, DICED	100	102.15	85	88

Table 3: Welfare effects in the DICE and DICED models.

Table 3 shows that in DICE welfare increases both under the optimal (by 2.7%) and the temperature (by 1.0%) scenarios, and intuitively the optimal scenario provides the highest welfare increase. This seems to suggest that imposing a cap on the temperature level will be beneficial for the economy as a whole. This kind of result is biased by the absence of demographic considerations, since by focusing on DICED we can observe that the figures are substantially different. Indeed, in DICED the optimal scenario is still welfare improving (by 2.15%) while both the temperature and the demography scenarios are welfare deteriorating since reducing it by 15% and 12%, respectively. By comparing our welfare estimates between DICE and DICED, we can conclude that, by taking into account the endogenous patterns of population growth, the beneficial effects of the optimal policy are reduced and the temperature policy requires an important sacrifice for the entire economy, justifying somehow policymakers' concerns towards mitigation policies. Considering that in the real world the optimal scenario cannot realistically be achieved and that the necessity to combat climate change is nowadays undeniable, it may be useful to restrict our focus on the alternative mitigation scenarios. By comparing our welfare estimates between the temperature and demography scenarios, our results suggest that the population policy may be a viable option since allowing to achieve desirable outcomes (see Table 1) and at the same time to reduce the costs of mitigation (see Table 3). Our welfare analysis reinforces our previous conclusions that population policy may be a viable tool to contrast climate change and lower the social cost of mitigation.

5 Population Policy Intensity

It may be argued that our results regarding the effectiveness of population policy as a viable mitigation tool depend on the level of policy intensity. Indeed, in our specification of the demography scenario we have assumed that the population policy leads the population size to stabilize in 2100 at a level of 9 billions of people (consistent with the low variant of the UN population projections) by imposing a constraint on the population terminal value. However, different types of population policy may be more or less effective leading to lower or higher terminal population values respectively, thus it may be interesting to understand whether our conclusions are affected by the stringency of the population policy. In order to do so, we now consider three alternative frameworks in which the population policy is stringent (leading to a terminal value of 8.5 billions people), mild (terminal value of 9 billions people), and lenient (terminal value of 9.5 billions people).

Table 4 shows the evolution of our main economic, environmental and demographic variables (production, consumption, emissions and temperature, fertility rate, population) and on the SCC in the cases in which the population policy is lenient (top part), mild (mid part) and stringent (bottom part). We can observe that the dynamic evolution of the variables is qualitatively similar to that presented in our benchmark model, and that the effects of different population policy intensities are intuitive. A more severe population policy leads to higher population size at the end of the century and thus it requires a higher demographic growth rate, which is possible only with an increase in the fertility rate; as the population grows larger, output and consumption per capita decrease while emissions and temperature increase, leading overall to an increase in the SCC. Independently of the stringency of the population policy, the SCC in the demography scenario is

Lenient population policy					
Variable	**2015**	**2020**	**2025**	**2030**	**2050**
Net GDP per capita	14.52	15.31	16.61	18.28	27.44
Consumption per capita	10.90	11.36	12.26	13.46	20.16
Industrial Emissions	33.81	28.38	28.65	29.16	30.35
Temperature	0.85	1.01	1.18	1.34	1.95
Fertility Rate	0.031	0.031	0.031	0.030	0.025
Population	6838.0	7004.3	7175.3	7346.7	7994.3
SCC	34.07	36.78	41.40	47.42	82.21
Mild population policy					
Variable	**2015**	**2020**	**2025**	**2030**	**2050**
Net GDP per capita	14.52	15.38	16.74	18.44	27.72
Consumption per capita	10.90	11.42	12.37	13.60	20.40
Industrial Emissions	33.81	28.58	28.87	29.36	30.50
Temperature	0.85	1.01	1.18	1.34	1.96
Fertility Rate	0,029	0.029	0,028	0,027	0,023
Population	6838.00	6989.45	7143.41	7296.02	7858.87
SCC	32,96	35.76	40,28	46,08	79,15
Stringent population policy					
Variable	**2015**	**2020**	**2025**	**2030**	**2050**
Net GDP per capita	14.52	15.48	16.89	18.64	28.04
Consumption per capita	10.90	11.50	12.50	13.76	20.67
Industrial Emissions	33.81	28.81	29.12	29.61	30.67
Temperature	0.85	1.01	1.18	1.34	1.96
Fertility Rate	0.027	0.026	0.025	0.024	0.020
Population	6838.0	6971.7	7105.6	7236.6	7705.0
SCC	31.68	34.56	38.96	44.52	75.56

Table 4: Evolution of the main variables in the demography scenario under different intensities of the population policy.

lower than in the other (BAU, optimal and temperature) scenarios confirming that demographic policy can be an effective means to fight climate change at lower social costs (see Table 2).

In order to compare not only the marginal but also the total effects of different intensities of the population policy, we compute the social welfare associated with our demography scenario in Table 5. We can observe that from a quantitative point of view different degrees of policy stringency lead to similar welfare values and that welfare increases with the leniency of the policy. This result is due to the fact that according to the total utilitarian approach per capita utility is multiplied by the population level in the definition of welfare and since the marginal utility is decreasing while the marginal effect on welfare of the population size is constant, social welfare tends to respond more strongly to variations in the population size than in the level of consumption and fertility (Marsiglio, 2014); as a consequence, a more lenient policy leading to a larger population size yields a higher welfare. Independently of the stringency of the population policy, in the demography scenario welfare is lower than in the BAU and optimal scenarios while it is higher than in temperature scenario (see Table 3). This confirms that, in the comparison between the most realistically implementable mitigation efforts (i.e., the temperature and demography), population policy represents a viable option allowing to achieve desirable outcomes and to reduce the costs of mitigation. Overall, our analysis of the implications of different population policy intensities confirms entirely our main conclusions regarding the viability of demographic policy as an effective mitigation tool to complement standard climate policies.

Variable	**Lenient policy**	**Mild policy**	**Severe policy**
Welfare	91	88	85

Table 5: Welfare effects in the demography scenario under different intensities of the population policy.

6 Limitations

In order to fully understand the implications of our results it is essential to carefully comment the limitations underlying our analysis. Indeed, by relying on an extended DICE setup, our analytical framework inherits all weaknesses embedded in DICE, but some of them may give rise to further issues when combined with endogenous population growth. Specifically, the absence of a regional dimension precludes the analysis of different population patterns across regions, the reliance upon total utilitarianism as a welfare criterion raises ethical concerns on its predictions, and the simplistic damage function ruling out extreme catastrophic effects highly reduces the assessment of the social costs of mitigation policies.

One important issue is related to the fact that the model aims to describe the global economy which thus aggregates all regions of the world. Even if this is generally considered a simplifying assumption allowing to focus on the broad-scale effects of climate change, it may be problematic in a framework with endogenous population change since it tries to characterize the evolution of the world population size. Therefore, in our model calibration in which we have imposed a terminal condition on the population size to ensure its stabilization in 2100 consistent with a demographic transition argument, we cannot account for the uncertainty associated with the true occurrence of a demographic transition at world level and for the eventual differences in the pace and phase of the demographic transition experienced at regional level (Budolfson et al., 2019). Indeed, the demographic transition at world level is driven by the assumption that fertility rates will continue to decline in developing high-fertility countries, however it is debated whether the fertility rates in developed low-fertility countries will keep remaining that low or rather it will start increasing (UN, 2019). In this latter scenario the increase in fertility in industrialized countries may partly compensate the reduction in developing countries dampening the size and the speed of the global demographic transition. Accounting for such different patterns in demographic trends across the globe would necessarily require to rely on a regional (RICE-type) model, thus the conclusions from our extended DICE need to be taken with caution and considered as a simplified benchmark to assess the consequences of endogenous population growth on climate change and mitigation policy options.

Another issue is related to the welfare function which as traditionally assumed in macroeconomic theory is based on a classical or total utilitarian criterion, in which social welfare is defined as the (discounted) sum of the total instantaneous utilities, given by the product between the utility of the average individual and the population size. Even if this is considered as a standard assumption, it is quite problematic in a context of endogenous population growth as it implies that social welfare is higher in a setting with an infinitely large population enjoying barely worth living standards than in a setting with a small population enjoying high standards of living. This outcome is deemed as a "repugnant conclusion" (Parfit, 1984) which should be naturally ruled out by a proper definition of welfare and several proposals to define alternative welfare criteria have been advanced in literature (Blackorby et al., 2005). In order to favor some degree of comparability with DICE, we have relied on total utilitarianism in our analysis but it is important to understand that under different welfare criteria (like the average utilitarianism or the critical-value utilitarianism) the effects of different policy options may radically change and in particular the desirability of the policies giving rise to a larger population size or to high a temperature level may substantially decrease (Lutz, 2017; Scovronick et al., 2017).

A further issue is related to the simplicity of the damage function which does not account for the possibility that the effects of climate change on economic production capabilities may be disruptive if the average temperature level exceeds certain threshold levels (Weitzman, 2012; Dietz and Stern, 2015). The existence of such an eventual possibility may introduce some extra complications in our setting with endogenous population growth since the temperature level increases mortality reducing (through the population size channel) production and so the resources available for emissions abatement; therefore, if a certain climate tipping point is achieved it will become particularly difficult to reverse the climate dynamics. This suggests that accounting for a more severe damage function than that actually considered in our framework will increase the social cost of inaction, which in turn will increase the severity of the prescribed optimal mitigation policy. The issue might be even more relevant if considered jointly with the regional aspect earlier mentioned, since accounting for a severe damage function with heterogeneous effects across regions to represent the situation that poorer people are more vulnerable to climate change than the rest of the population will tend to increase social inequality impacting thus the overall assessment of the costs of climate change and mitigation policies (Dennig et al., 2015; Budolfson et al., 2017).

Such limitations embedded in our DICED model should suggest caution in interpreting our results. Since the analytical framework mimicking DICE's is based on a series of oversimplifying assumptions, our conclusions cannot be considered definitive but rather they should represent the starting point of a deeper analysis aiming to assess the true consequences of endogenous population dynamics on climate change and to initiate a discourse on the effective viability of population policy as an alternative mitigation tool to those traditionally discussed in extant literature.

7 Conclusions

Population growth and climate change are mutually related: on the one hand, by determining the size of the labor force population growth determines the economic production and therefore the level of emissions, which in turn contribute to climate change; on the other hand, climate change affects health conditions and as such affects the mortality rate, which in turn determines the population growth rate. Despite the existence of such important channels, in the extant IAMs literature population growth is taken as exogenously given (Lutz, 2017; Scovronick et al., 2017), and no IAM has thus far analyzed the extent to which endogenous population change matters in quantifying the costs associated with climate change. In order to do so, we extend the simplest IAM (i.e., the DICE) by endogeneizing population change in a setting where agents optimally determine their fertility rates; this allows us also to analyze the role that demographic policy may play in mitigating climate change. Specifically, we consider a demographic policy aiming to impose a ceiling to the population growth rate in order ensure that by the end of the century the population size will achieve a level consistent with what predicted by the low variant of the UN population projections. We show that: (i) accounting for endogenous population change substantially increases the estimates of the social costs of environmental policies (measured by both the social cost of carbon and social welfare), and (ii) relying on demographic policy largely reduces the costs associated with climate change (precisely by about 16% in 2015). This clearly suggests that population change does matter in the assessment of climate change and related policies, and that demographic policy may be an effective mitigation tool to promote sustainable development.

To the best of our knowledge no other work has ever tried to do something comparable to ours, and thus we have tried to present our arguments in the simplest possible framework. This however has precluded us to take into account other relevant issues, including the assessment of regional costs, the evaluation of migration and the analysis of population policy design. Indeed, in a regional setting it might be possible to quantify who might be the winners and losers from climate change and how different policies might be used to ensure a certain degree of equity across regions; it might also be possible to account for regional migration, which is another essential determinant of demographic growth complicating further the nature of the population growth and climate change relation. Moreover, our discussion of population policy has been particularly simplistic since in an infinitely-lived agent framework it is not possible to understand how such a policy should be effectively designed, but considering short-lived agents evolving in overlapping generations may permit us to analyze how alternative programs, like education or family planning, may provide individuals with the incentive required to modify their fertility choices. Furthermore, our analysis implicitly assumes that population growth will decrease over time to allow the population size to stabilize by the end of the century, and thus we do not take into account the possibility that fertility might increase in response to climate change; if climate change increases inequality within and between countries, especially in developing countries where income levels are low, households may be tempted to increase their size by raising more children as an insurance strategy (against increased mortality or reduced agricultural productivity). Extending the analysis along these directions is on top of our future research agenda.

A The DICED Model

The social planner maximizes social welfare, W, which is the product between per capita utility and population size, N_t, discounted by the rate of time preference, ρ:

$$\max_{c_t, n_t} W = \sum^{T} u(c_t, n_t) N_t (1+\rho)^{-t} \tag{10}$$

In equation (10) per capita utility depends on per capita consumption c_t and fertility n_t and it is specified as follows:

$$u(c_t, n_t) = \frac{c_t^{1-\zeta} n_t^{\kappa(1-\zeta)} - 1}{1-\zeta} \tag{11}$$

where ζ is the marginal elasticity of consumption and κ the relative weight of fertility with respect to consumption. per capita consumption is the ratio between the aggregate consumption, C_t and the population size, N_t:

$$c_t = \frac{C_t}{N_t}. \tag{12}$$

Population, N_t, and labor perfectly coincide since there is no unemployment. Demographic dynamics is therefore captured by the following equation:

$$N_t = N_{t-1}[1 + n_t - d(T_t)] \tag{13}$$

where the growth rate of population, $g_{Nt} = n_t - d(T_t)$, is given by the difference between fertility and mortality, $d(T_t)$. Mortality depends on the temperature level as follows:

$$d(T_t) = d_1 e^{d_2 T_t}, \tag{14}$$

where d_1 and d_2 are scale parameters.

The output net of damages and abatement is denoted with Q_t and is equal to:

$$Q_t = \frac{[1 - \Lambda_t] Y_t}{1 + \Omega_t}, \tag{15}$$

where Ω_t represents the damage function linking the effects of climate change on the production process, Λ_t is the abatement cost and Y_t is gross output. Gross output is produced according to a constant returns to scale capital Cobb-Douglas production function combining capital, K_t and labor, N_t as follows:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha} \tag{16}$$

where A_t denotes the total factor productivity, which grows at an exogenous rate g_t^A as follows:

$$A_t = A_{t-1}(1 + g_t^A) \tag{17}$$

where δ_A determines the decline in the growth rate of the total factor productivity:

$$g_t^A = \frac{g_{t-1}^A}{(1+\delta_A)} \tag{18}$$

The economy is closed and its resource constraint is given by:

$$Y_t = C_t + I_t + R_t, \tag{19}$$

where I_t is investment and R_t child-rearing activity. Child-rearing activities are proportional to the stock capital K_t as follows:

$$R_t = \theta n_t K_t, \tag{20}$$

where θ is a scale parameter. The law of motion of capital depends on investment and capital depreciation as follows:

$$K_{t+1} = (1 - \delta_K)K_t + I_t \tag{21}$$

where δ_K is the constant depreciation rate.

Total emissions, E_t are given by the sum of land-use ELU_t and industrial EI_t emissions as follows:

$$E_t = EI_t + ELU_t \tag{22}$$

where land-use emissions are exogenous and modelled as:

$$ELU_t = ELU_{t-1}(1 - \delta_L). \tag{23}$$

where δ_L is the constant declining rate of land use emissions.

Industrial emissions EI_t, instead, are a by-product of gross production and determined as follows:

$$EI_t = \sigma_t(1 - \mu_t)Y_t \tag{24}$$

where μ_t is the optimal emission-control rate and σ_t is the exogenous level of carbon intensity which evolves as:

$$\sigma_t = \sigma_{t-1} e^{g_{\sigma t}} \tag{25}$$

where $g_{\sigma t}$ is the growth rate of σ_t which reads as:

$$g_{\sigma t} = g_{\sigma t-1}(1 + \delta_\sigma) \tag{26}$$

where δ_σ is the exogenous rate of energy efficiency.

Equations (27) - (29) reflect the evolution of carbon concentration in the atmosphere, MAT_t, shallow ocean concentration, MUP_t, and lower oceans concentration, MLO_t:

$$MAT_t = E_t + \phi_{11} MAT_{t-1} - \phi_{12} MAT_{t-1} + \phi_{21} MUP_{t-1} \tag{27}$$
$$MUP_t = \phi_{22} MUP_{t-1} + \phi_{12} MAT_{t-1} + \phi_{32} MLO_{t-1} \tag{28}$$
$$MLO_t = \phi_{33} MLO_{t-1} + \phi_{23} MUP_{t-1} \tag{29}$$

where ϕ_{ij} is the transfer rate from reservoir i to reservoir j.

Accumulation of emissions in the atmosphere leads to global warming, through changes in radiative forcing. Specifically, the increase in radiative forcing, F_t, since 1900 in watts per square meter (W/m^2) is given by:

$$F_t = \eta \left\{ log_2 \left[\frac{MAT_t}{MAT_t^{PI}} \right] \right\} + O_t \tag{30}$$

where O_t is the forcing of other GHGs (CFCs, CH4, N2O,...) and MAT_t^{PI} is the pre-industrial level of atmospheric concentrations of CO2 (equal to 596.4 GtC, about 280 parts per million). Changes in radiative forcing are linked to temperature, T_t, as follows:

$$T_t = T_{t-1} + c_1 F_t - \frac{\lambda_1}{\lambda_2} T_{t-1} - c_2(T_{t-1} - TLO_{t-1}) \tag{31}$$
$$TLO_t = TLO_{t-1} + c_3(T_{t-1} - TLO_{t-1}) \tag{32}$$

where c_1, c_2 and c_3 are the climate coefficients for the upper level, the transfer from upper to lower stratum, and for the lower level, respectively. The parameter λ_1 represents the forcing of equilibrium doubling CO2 and λ_2 the equilibrium temperature impact. TLO_t is the increase of temperature in the deep oceans.

The relationship between global-temperature increase and income loss is described by the following damage function, Ω_t:

$$\Omega_t = \psi_1 TAT_t^{\psi_2} A_t K_t^{\alpha} N_t^{1-\alpha} \tag{33}$$

where TAT_t is the increase of temperature in the atmosphere.

Finally, the cost of emissions abatement, Λ_t, in terms of income loss is given by:

$$\Lambda_t = (\epsilon_1 \mu_t^{\epsilon_2}) K_t^{\alpha} N_t^{1-\alpha} \tag{34}$$

The DICE model calculates the social cost of carbon which represents the economic cost caused by an additional unit of CO2 emitted in the atmosphere. The cost is the monetized damage on the discounted intergenerational utility of consumption. The SCC is a signal, a measure in dollars that estimates the (social) cost of emissions (see Tol, 2011 for a literature review on the SCC). Mathematically, the SCC is the shadow price of carbon emissions along a reference path of output or emissions. Following Nordhaus (2017) we take a discrete approximation to compute the SCC:

$$SCC_t = -\frac{dW/dE}{dW/dC} \tag{35}$$

where the numerator is the marginal impact of emissions at time t on welfare, while the denominator is the marginal welfare value of a unit of aggregate consumption in period t. The ratio calculates the economic impact of a unit of emissions in terms of t-period consumption as a numeraire.

The complete list of parameters and their specific values used in the simulations is reported in Table 6.

B Robustness Analysis

In this section we analyze the extent to which our results are robust to variations in some parameter values and some functional forms. Specifically, we consider how different values for the weight of fertility in the utility function and for the rearing cost of children, along with different functional forms for the utility function and the child-rearing cost function and different specifications of the welfare function, impact our qualitative conclusions, focusing on some key variables and in particular the social cost of carbon (SCC) which concisely sums up our results.

B.1 Sensitivity to Parameter Values

First of all, we analyze the extent to which uncertainty about some parameter impacts our main results, summarized by emissions and the SSC. Emission is the variable connecting economy, environment and demography. The social cost of carbon, instead, is the main outcome of IAMs. Specifically, we perform a sensitivity analysis on the weight of fertility with respect to consumption, κ, and on the rearing cost of children, θ. We decrease (increase) these parameters by 5% and 20%, separately. Overall, our sensitivity analysis suggests that our main results are not significantly affected by perturbations in these parameters.[10]

[10] Even if our sensitivity analysis confirms our main conclusions, this does not allow us to state whether this will still be true if we were to expand the parameter range. Indeed, since the model is extremely nonlinear, there may be nonlinearities also in the dependence of our results on the parameter values, opening for the possibility of different conclusions. Moreover, due to the high degree of uncertainty that surrounds several other parameters (both in the model's economic and climatic sectors) our results may be highly dependent on the specific parameter values employed in our numerical simulations (Weitzman, 2012). Nevertheless, since we wish to understand the implications of endogeneizing population growth and we are taking DICE as a benchmark, it seems natural to focus on the (marginal) effects of the main parameters driving our extended endogenous population setup.

Parameter	Value	Definition
θ	1.35	Cost of children
κ	0.8	Preference for children
d_1	0.007	Mortality coefficient
d_2	0.002	Mortality exponent
ζ	1.45	Elasticity of consumption
ρ	0.015	initial rate of social time pref(year)
α	0.300	Capital elasticity in production function
δ_K	0.100	Depreciation rate on capital per year
δ_A	0.005	Rate of technology per year
δ_L	0.115	Decline rate of land emissions (per period)
δ_σ	-0.001	Rate of energy efficiency
ϕ_{11}	0.810712	Carbon cycle transition matrix
ϕ_{12}	0.189288	Carbon cycle transition matrix
ϕ_{21}	0.097213	Carbon cycle transition matrix
ϕ_{22}	0.852787	Carbon cycle transition matrix
ϕ_{23}	0.05	Carbon cycle transition matrix
ϕ_{32}	0.003119	Carbon cycle transition matrix
ϕ_{33}	0.996881	Carbon cycle transition matrix
η	3.6813	Forcings of equilibrium CO2 doubling (Wm-2)
λ_1	3.6813	Forcings of equilibrium CO2 doubling
λ_2	3.1	Equilibrium temperature impact
$c1$	0.1005	Climate-equation coefficient for upper level
$c2$	0.088	Transfer coeffic upper to lower stratum
$c3$	0.025	Transfer coeffic for lower level
ψ_1	0.0028388	Damage quadratic term
ψ_2	2.00	Damage exponent
ϵ_1	0.074	Abatement quadratic term
ϵ_2	2.00	Abatement exponent

Table 6: Complete list of parameters and their values.

Table 7 shows the results of varying κ on emissions and on the SCC. The variation is expressed in percentage terms with respect to the baseline values. A decrease in κ leads to a decrease in emissions and to a lower SCC, compared to the baseline case. An increase in κ leads exactly to the opposite effect. Note that the quantitative effects of an increase or decrease in the parameter are very similar.

κ	Variable	2015	2020	2025	2030	2050
-5%	Emissions	0	-0.052	-0.06	-0.04	-0.13
	SCC	-0.4	-0.5	-0.6	-0.6	-0.6
$+5\%$	Emissions	0	0.005	0.006	0.004	0.012
	SCC	0.05	0.06	0.062	0.064	0.065
-20%	Emissions	0	-0.07	-0.08	-0.05	-0.19
	SCC	-0.2	-0.4	-0.5	-0.5	-0.5
$+20\%$	Emissions	0	0.05	0.06	0.04	0.01
	SCC	0.3	0.4	0.4	0.4	0.5

Table 7: Effects of changes in κ (percentage variation with respect to the baseline).

Table 8 shows the effects associated with a change in θ on emissions and on the SCC. A lower value of θ leads to an increase in emissions and a subsequent increase in the SCC. Exactly the opposite occurs when θ increases. Also in this case the quantitative effects of an increase or decrease in the parameter are very similar.

θ	Variable	2015	2020	2025	2030	2050
-5%	Emissions	0	0.34	0.5	0.55	0.6
	SCC	0.05	0.5	0.65	0.71	0.7
$+5\%$	Emissions	0	-0.34	-0.5	-0.54	-0.56
	SCC	-0.05	-0.48	-0.64	-0.70	-0.7
-20%	Emissions	0	1.5	2.18	2.45	2.6
	SCC	0.3	2.21	3	3.24	3.0
$+20\%$	Emissions	0	-1.44	-2.05	-2.28	-2.4
	SCC	-0.34	-2.13	-2.77	-3.0	-2.8

Table 8: Effects of changes in θ (percentage variation with respect to the baseline).

B.2 Robustness to Functional Forms

We now analyze whether the choice of some functional form may have driven our results. In particular, two assumptions may play a critical role in our endogenous population setup: the separability of the utility function and the linearity of the child-rearing cost function. Therefore, we now relax these assumptions and we consider the possibility that the utility function is non-separable and that child-rearing entails a convex cost. Overall, our robustness analysis shows that our qualitative conclusions will still hold true even in such alternative frameworks.

We consider first the utility function. Our assumption that the utility function is nonseparable in c_t and n_t suggests that consumption and fertility are related, and the marginal utility of consumption increases with fertility since children represent a desirable good. However, it may be argued that consumption and fertility are unrelated such that the marginal utility of each factor is independent from the other since parents' preferences for consumption do not depend on the number of children they may have. In order to account for this possibility we now consider a special case of (4) obtained by taking the limit for $\zeta \to 1$, which yields:

$$U(c_t, n_t) = \log c_t + k \log n_t \tag{36}$$

Table 9 presents the effects of this alternative functional form of the utility function on our main variables (production, consumption, emissions and temperature) and on the SCC in the different scenarios. We can observe that the dynamic evolution of the variables is qualitatively similar to that presented in our baseline model (Tables 1 and 2), and so is also the difference between the SCC in DICED under a separable utility function and DICE. This confirms that our previous conclusions straightforwardly extend also in this alternative setting.

We now consider the child-rearing cost function. Our assumption that child-rearing depends linearly on capital suggests that raising children entails the same constant cost in terms of capital, no matter the number of children. However, it may be argued that, since raising children subtracts not only resources but also time to their parents, the cost of growing children increases with the number of children such that the child-rearing cost function may be convex. In order to account for this possibility we now consider the following specification of (7):

$$R_t = \theta n_t^{\omega} K_t, \tag{37}$$

where $\omega \geq 1$ quantifies the elasticity of child-rearing with respect to children. If $\omega = 1$ we are back to the linear case analyzed in our benchmark model, while if $\omega > 1$ we are in the convex case. In the following we shall set $\omega = 2$ to focus on the special case of a quadratic child-rearing cost function. Table 10 presents the effects of this alternative functional form of the child-rearing cost function on our main variables (production, consumption, emissions and temperature) and on the SCC in the different scenarios. Also in this case we can note that the dynamic evolution of the variables is qualitatively similar to that presented in our baseline model (Tables 1 and 2), and the same is true for the difference between the SCC in DICED under a convex child-rearing cost function and DICE. This confirms that our previous conclusions apply also in this alternative setting.

Variable	Scenario	2015	2020	2025	2030	2050
Net GDP per capita	Baseline	14.5	14.7	15.8	17.4	26.5
(thousands USD)	Optimal	14.5	14.7	15.7	17.4	26.5
	Temperature	14.5	14.5	15.3	16.8	25.4
	Demography	14.5	15.3	16.6	18.4	27.9
Consumption per capita	Baseline	10.9	10.8	11.5	12.6	19.4
(thousands USD)	Optimal	10.9	10.7	11.5	12.6	19.3
	Temperature	10.9	10.9	11.2	12.2	18.4
	Demography	10.9	11.2	12.2	13.4	20.4
Industrial Emissions	Baseline	33.8	33.8	34.2	36.3	46.6
(GtCO2 per year)	Optimal	33.8	27.2	27.6	28.4	30.3
	Temperature	33.8	15.0	13.1	10.6	0
	Demography	33.8	28	28.2	28.7	29.5
Temperature (°C)	Baseline	0.9	1.0	1.2	1.3	2.0
	Optimal	0.9	1.0	1.2	1.3	1.9
	Temperature	0.9	1.0	1.2	1.3	1.7
	Demography	0.9	1.0	1.2	1.3	1.9
SCC	Baseline	40.2	42.3	47.9	55.6	100.9
(USD)	Optimal	39.1	41.2	46.7	54.4	100
	Temperature	195.7	211.2	247.8	300	667
	Demography	38.5	41.8	47.4	54.5	94.2

Table 9: Effects of assuming a separable utility function.

Variable	Scenario	2015	2020	2025	2030	2050
Net GDP per capita	Baseline	14.5	16.0	17.7	19.6	29.7
(thousands USD)	Optimal	14.5	15.9	17.7	19.6	29.7
	Temperature	14.5	15.7	17.3	19.1	28.4
	Demography	14.5	16.1	18.8	20.0	30.2
Consumption per capita	Baseline	11	12.8	13.2	14.7	22.2
(thousands USD)	Optimal	10.9	12.0	13.2	14.7	22.2
	Temperature	11	11.8	12.9	14.2	21.2
	Demography	10.9	12.1	13.5	15.0	22.6
Industrial Emissions	Baseline	35.7	39.4	42.9	46.3	58.8
(GtCO2 per year)	Optimal	35.8	30.4	31.8	33.1	34.9
	Temperature	33.8	16.6	14.3	10.9	0
	Demography	33.8	30.3	31.4	32.3	33.4
Temperature (°C)	Baseline	0.9	1.0	1.2	1.4	2.1
	Optimal	0.9	1.0	1.2	1.3	2.0
	Temperature	0.9	1.0	1.2	1.3	1.7
	Demography	0.9	1.0	1.2	1.3	2.0
SCC, DICED	Baseline	32.9	38.9	46.3	55.1	102.8
(USD)	Optimal	32	37.9	45.2	53.8	101.6
	Temperature	171.5	209.7	259.5	322.1	757
	Demography	30.5	35.9	42.2	49.4	86.7

Table 10: Effects of assuming a convex child-rearing cost function.

B.3 Robustness to Welfare Specifications

As discussed in section 6, our analysis is based on a total utilitarian approach in which social welfare is defined as the sum of the total instantaneous utilities (i.e., the product between the utilities of the average individual and the population size), and this raises several concerns in a setting with endogenous population change. One of the most commonly employed alternative approach consists of relying on the average utilitarian criterion which instead defines social welfare as the sum of average instantaneous utilities (i.e., the utilities of the average individual). We thus now analyze whether such an a different specification of the welfare function may modify our results, but also in this case we can prove that our qualitative conclusions straightforwardly extend even in such an alternative setting.

Rather than defining social welfare as in (10), we can rely on a more general formulation which accounts for both total and average utilitarianism as special cases. Specifically, we now assume that social welfare is given by the following expression:

$$W = \sum^{T} u(c_t, n_t) N_t^{\epsilon} (1+\rho)^{-t}, \tag{38}$$

where $\epsilon = \{0, 1\}$ measures the degree of altruism quantifying the weight attached to the size of future generations (Marsiglio, 2014). If $\epsilon = 1$ social welfare is defined according to total utilitarianism and thus we are back to our benchmark model, while if $\epsilon = 0$ it is defined according to average utilitarianism as only the sum of the instantaneous utilities of the average individual (and not the sum of the utilities of all individuals) matter in the determination of social welfare.

Variable	Scenario	2015	2020	2025	2030	2050
Net GDP per capita	Baseline	14.5	14.4	15.4	17.1	27.2
(thousands USD)	Optimal	14.5	14.4	15.4	17.1	27.2
	Temperature	14.5	14.1	15.1	16.7	26.1
	Demography	14.5	14.6	16.1	18.6	29.4
Consumption per capita	Baseline	10.7	10.3	11.1	12.4	19.8
(thousands USD)	Optimal	10.7	10.3	11.1	12.3	19.6
	Temperature	10.7	10.1	10.8	11.9	18.8
	Demography	10.4	9.8	10.1	10.2	22.3
Industrial Emissions	Baseline	33.8	32.6	34.1	36.7	48.2
(GtCO2 per year)	Optimal	33.8	25.8	26.2	26.9	26.3
	Temperature	33.8	14.9	13.2	10.7	0
	Demography	33.8	27.4	29.1	32.7	35.5
Temperature (°C)	Baseline	0.9	1.0	1.2	1.3	2.0
	Optimal	0.9	1.0	1.2	1.3	1.9
	Temperature	0.9	1.0	1.2	1.3	1.7
	Demography	0.9	1.0	1.2	1.3	2.0

Table 11: Effects of assuming a welfare function based on average utilitarianism in DICED.

Table 11 presents the effects of this alternative specification of social welfare in which $\epsilon = 0$ on our main variables (production, consumption, emissions and temperature) in the different scenarios in DICED, while Table 11 the effects on the SCC both in DICE and DICED. The dynamic evolution of the variables is qualitatively similar to that presented in our benchmark model, and the same is true for the difference between the SCC in DICED under an average utilitarian welfare function and DICE (Tables 1 and 2): the SCC substantially increases by accounting for endogenous population change but demographic policy allows to significantly reduce the SCC, suggesting that population policy represents an effective mitigation tool to complement standard climate policies. Clearly, from a quantitative point of view there exist sizable differences between the total and average utilitarianism cases, driven to a large extent by the different evolution of the demographic variables underlying the two settings: under average utilitarianism it is convenient to substantially increase the fertility rate and grow a larger population than under total utilitarianism, yielding some discrepancies also in economic and environmental variables. Overall, these results reinforce further our previous conclusions regarding the desirability of population policy, as they turn out to be independent of the specific utilitarian approach employed in the definition of social welfare.

Variable	Scenario	2015	2020	2025	2030	2050
SCC, DICE	Baseline	22.4	26.9	32.3	39.0	76.4
(USD)	Optimal	22.1	26.4	32.0	38.6	76.8
	Temperature	135.5	171.1	219.2	281.3	742.5
SCC, DICED	Baseline	54.4	55.7	64.0	76.3	151.8
(USD)	Optimal	51.7	53.0	60.9	72.7	145.1
	Temperature	202.7	210.0	246.0	299.8	679.0
	Demography	42.1	41.1	42.8	42.9	66.9

Table 12: Social cost of carbon in the DICE and DICED models under average utilitarianism.

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