Essays on Climate Change Economics and Population Dynamics

Author

Veronica Lupi

Supervisor

Marzio D. Galeotti

Co-Supervisors

Simone Marsiglio

Francesco Bosello

Lombardy Advanced School of Economic Research - L.A.S.E.R.

Universities of Milan, Pavia, Bergamo and Brescia

Academic Year 2016/17

Acknowledgments

I wish to thank my Supervisor, Professor Marzio Galeotti, for his guidance, support and his scientific advice. He has always pushed me to put all my effort in this research. Our long talks have been extremely important during these years. I wish to thank my co-Supervisor, Professor Francesco Bosello: he was extremely helpful, especially at the beginning of my research. Last but not least, a special mention goes to my co-Supervisor Professor Simone Marsiglio. Despite the distance, he has always been there for me. His support and his pragmatism have been fundamental. A special thanks goes my friend Sam: you have been an awesome colleague. I wish to thank Professor Reyer Gerlagh: I will never forget the time spent under his supervision in Tilburg.

I would also thank the Doctoral School director, Professor Alessandro Missale and all the members of staff at University of Milan. Thanks to my parents: the PhD was my own choice, but you supported me and let me free to follow my dreams.

Finally, I wish to thank all my colleagues (special friends at this point). In particular Lucy, Annarita and Fatma for our long discussions and lunches together. Andre and Jacopo, my special office mates. Thanks to Danilo: you are always the best. Finally Dany: I feel lucky to have a person like you in my life. Thanks to all my friends that encouraged me. You are in my heart, especially some of you.

Contents

Acknowledgments

1 Introduction. Demography and Environment in the Previous Literature **1**

1.1 Population and Climate Change in the Current Debate 2

1.2 Population in Integrated Assessment Models (IAMs) 3

1.3 Endogenous Fertility Literature and Mortality 7

1.4 This Work 9

Bibliography **15**

2 Population Growth and Climate Change: a Dynamic Integrated model of Climate, Economy and Demography (DICED) **16**

2.1 Introduction 18

2.2 Population Dynamics and Climate-Change Risk 21

2.3 The Model 28

2.3.1 Calibration and Scenarios 32

2.4 Results 33

2.5 Sensitivity Analysis 41

2.6 Conclusions 42

Bibliography **45**

Appendices **46**

2.A The Equations of the DICED Model 46

3 Endogenous Fertility and Climate Change Policies **51**

3.1 Introduction 53

3.2 Stylized Facts 56

3.3 Fertility, Education and Climate Change 61

3.4 An Endogenous Fertility Model 62

3.4.1 Demographics 62

3.4.2 Production technology 63

3.4.3 Preferences 64

3.4.4 Climate change 67

3.5 Calibration 69

3.5.1 Balanced Growth Path 69

3.5.2 Calibration 70

3.6 Scenarios and Policies 74

3.6.1 Social Welfare Functions and Ethics 74

3.6.2 Education Policy 75

3.7 Results 76

3.8 Sensitivity Analysis 88

3.9 Conclusions and directions for future research 92

Bibliography **96**

Appendices **97**

3.A Competitive equilibrium and optimality conditions 97

3.B Balanced growth path 98

3.C Education Policy 100

3.D Summary of model's equations 100

3.D.1 Non-altruistic model 100

CHAPTER 1

Introduction. Demography and Environment in the Previous Literature

The Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2014) suggests that human influence on the climate system is clear and growing, and the impacts are observed across all continents and oceans. The report, in general, highlights that the more human activities disrupt the climate, the greater the risks of severe and irreversible impacts for the ecosystems. We have the opportunity to limit climate change and its risks, with several alternatives that allow to support, at the same time, economic and human development. However, stabilizing temperature increase at below 2 degrees relative to pre-industrial levels will require an urgent and fundamental departure from "business as usual" scenarios which assume that future development trends will follow those of the past and no changes in policies will take place. In such a context we cannot ignore the fact that future population trends play a role.

This thesis analyses the relationship between population dynamics and the environment. In particular, there are two reasons to be concerned with population when dealing with climate change. On the one hand, population's size is one of the main driver of emissions. On the other hand, climate change might affect fertility and mortality rates, as heat waves and jumps in temperature can modify the ability of people to procreate, may induce unexpected death of infants at birth and can worsen the conditions of people already sick, especially among the elderly. The first channel has been widely studied in the economic literature (Meadows et al., 1972) but treating fertility as exogenous, while the second one is relatively new (Barreca et al., 2015; Carleton and Hsiang, 2016). This thesis contributes to the existent literature developing two models to reproduce long-term trends in the economy and climate, including endogenous population dynamics. In the following Section 1.1 we briefly review the main issues arising in the debate; Section 1.2 and Section 1.3 review the previous climate change literature and endogenous fertility literature, respectively. Finally Section 1.4 resumes our contributions.

1.1 Population and Climate Change in the Current Debate

The underlying motivations of this work date back to 1972, when the United Nations Conference on the Human Environment, the first Earth Summit, took place in Stockholm (UN, 1972). The purpose of the conference was to identify a common outlook to inspire and guide people in the preservation and enhancement of the human environment. Actions and proceedings of the conference are collected in a Report and are synthesized in 26 Principles. Specifically, the 16th Principle states: *"Demographic policies which are without prejudice to basic human rights and*

which are deemed appropriate by Governments concerned should be applied in those regions where the rate of population growth or excessive population concentrations are likely to have adverse effects on the environment of the human environment and impede development". Population growth is recognized as one important driver affecting the preservation of the environment and demographic policies are suggested as a mean to deal with it. In 1982 the Earth Summit was held in Nairobi (Kenya). The Principles stated in Stockholm (1972) were reaffirmed and the Conference commended the efforts of the Governments in adopting them. It recognized the need of intensifying the efforts at the global, regional and national levels to protect the environment. Ten years after, in 1992, the United Nations Conference on Environment and Development took place in Rio, with the goal of establishing an equitable global partnership through the creation of new levels of cooperation among States. The outcome of the conference was a Declaration made of 27 Principles which, some years later, in 1997, led (some of) the member countries to sign the Kyoto Protocol. Among these Principles, the 8th one reiterates: *"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).

Since Rio in 1992 onwards, the preservation of the environment and sustainable development became increasingly relevant and turned to be the main goals of the next Earth Summits in 2002 in Johannesburg (South Africa) and in 2012 in Rio. The last United Nations Climate Change Conference was held in Paris in 2015 and the Paris agreement was ratified by all countries after one year. However, starting from the Earth Summit in Johannesburg (2002), population growth and the discussion about demographic policies vanished from the policy debate, despite such policies were a central theme in the previous meetings. Probably, experiences like the One-Child policy in China made Governments afraid to propose interventions affecting personal choices of people. In our view, demographic policies should still be part of the debate on climate change, without forgetting that the freedom (not) to procreate is an inviolable right, so that population policies should be carefully designed.

1.2 Population in Integrated Assessment Models (IAMs)

Traditionally, climate policies are tested with simulation methods which reproduce long-term trends. The type of models used in this stream of literature are called Integrated Assessment

Models (IAMs). As the name itself suggests, these models integrate economic, policy, and aspects of climate change. IAMs are used to produce different scenarios: starting from a baseline, meaning that current policies as in 2018 are extended indefinitely, they calculate the impacts of alternative assumptions on some key variables such as output, emissions and temperature change. Then, several policies can be tested and costs and benefits of alternative strategies are compared. Here below, we provide a short survey of the main (global) IAMs in the literature to see whether and how population is considered.

We are not the first one modeling the relationship between economy, climate and demography. IAMs, in general, reproduce long-term trends, including demographic trends too. The DE-carbonisation Model with Endogenous Technologies for Emission Reductions (DEMETER-1) by Gerlagh (2006) is a global level growth model with learning-by-doing for fossil fuels and non-carbon energy. It analyses the possibility of de-carbonization through carbon capture and sequestration (CCS). Population growth is considered as an exogenous driver and standard population projections are reproduced. The Regional Model of Investments and Development (REMIND) by Leimbach et al. (2010) is designed in a multi-regional structure. The version called REMIND-G represents the whole world as the only region. The demographic component reproduces an exogenous population law. So again, demography is part of the model but it plays no role in terms of policy prescriptions. The most known IAM is the Dynamic Integrated model of Climate and the Economy (DICE) by Nordhaus and Sztorc (2013) which considers population dynamics as exogenous and following a logistic type equations in which the growth of population in the first period is given and then declines approaching a certain limit. Population dynamics mimics the medium-variant scenario of the UN (2015). We will describe the DICE model with more details in the second chapter of this thesis, as we extend this model in order to include endogenous fertility choices.

Recently some IAMs model demography in a more sophisticated way. The ANEMI-2[1] by Akhtar et al. (2013) is an Integrated System Dynamics Model for Analyzing Behavior of the Social-Energy-Economic-Climatic-System also at global level. This model has a population component based on WORLD3 [2] population model. The population component of ANEMI-2 includes a four-level population model, meaning that population is divided into four age groups (0 to 14 yr; 15 to 44yr; 45 to 64yr; and 65 to 65 plus). Fertility and mortality rates are modeled

[1] ANEMI is an ancient Greek term for the four winds, heralds of the four seasons; here ANEMI links physical system such as the climate and hydrological- and carbon cycles with the socio-economic systems that change them: the economy, land-use, population change, and water use and quality.

[2] the WORLD3 model is described in Meadows et al. (1972).

too and feedback effects are taken into account in a continuous dynamic interactions among the human population, climate and global resources. Though the ANEMI-2 population module is quite detailed, the optimizing choice of agents with respect to fertility is not taken into account; fertility and mortality rates are exogenously determined. The Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al., 2014) is an ecological-environmental model that simulates the environmental consequences of human activities worldwide. It represents interactions between society, biosphere and climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors. Regarding population, IMAGE assumes exogenous levels of total population per region, household size and urbanization rate. Finally, in the climate Framework for Uncertainty, Negotiation and Distribution (FUND) by Anthoff and Tol (2014), which is a policy optimization model, scenarios of economic growth are perturbed by the effects of climatic change through its impact on health: population decreases with climate-change related deaths, such as cardiovascular associated with heat stress, malaria and others. Climate-induced migration between the regions of the world induces changes in population sizes. Immigrants are assumed to assimilate immediately and completely with the respective host population. The representation of the population module is quite detailed, but all demographic variables in the model are directly or indirectly determined by exogenous scenarios.

Through years, researchers developed new scenarios integrating future changes in climate and society. Recently, several papers (Kriegler et al., 2012; O'Neill et al., 2017; Riahivan et al., 2017) describe a new set of projections simulating alternatives of societal development known as the "shared socioeconomic pathways" (SSPs). [3] IAMs can take into account these SSPs in their scenarios, in order to better understand which variables affect climate change the most. The idea of SSPs is to agree on global pathways which describe the evolution of our society allowing for a certain degree of uncertainty. Depending on how our society will evolve, the challenges in terms of mitigation and adaptations would be higher or lower.[4] The SSPs narratives collect five qualitative descriptions of future changes in demographics, human development, economy

[3]The creation of SSPs derives from many meetings which result in guidelines to build these narratives. For example the IPCC Special Report on Emissions Scenarios (Nakicenovic et al., 2000), the Millennium Ecosystem Assessment (Carpenter et al., 2005) and the UNEP Global Environmental Outlook (GEO) scenarios UNEP (2002, 2007)

[4]The United Nations Framework Convention on Climate Change (UNFCCC) highlights two alternatives to deal with climate change: mitigation and adaptation. Mitigation comprises all human activities aimed at reducing emissions to contain climate change. Adaptation, instead, refers to any transformation that takes place in natural or human system in response to the (expected) impacts of climate change.

and life style, policies and institutions, technology and environment and natural resources. In particular, future demographic trends are derived from age, sex and education projections as described in KC and Lutz (2017).

Figure 1.2.1: Shared Socioeconomic Pathways (SSPs). Source: O'Neill et al. (2017)

.

Figure 1.2.1 shows the main SSPs, which are five. Each of them corresponds to a certain level of adaptation and mitigation, reported on the "x" and "y" axis. For example, SSP1 is depicted at the bottom left of Figure 1.2.1. In SSP 1, the combination of low population growth due to education improvements, development of green technologies, a favorable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand, results in low challenges to mitigation. Moreover, the improvements in human well-being, along with strong and flexible global, regional, and national institutions imply low challenges to adaptation. On the other end, there is SSP3 in which high fertility rates in developing countries, growing fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply high challenges to mitigation. The limited progress on human development, slow income growth, and lack of effective institutions implies high challenges to adaptation. For a complete description of each SSPs refer to O'Neill et al. (2017).

As already said, researchers can use these SSPs narratives in their IAMs to reproduce the current state of the world and to make projections. SSPs can be modified in order to take into account other aspects of the society to better understand the drivers of challenges in mitigation and adaptation.

The importance of demographic factors is highlighted in several works in this stream of lit-

erature. Cuaresma (2013) uses population projections by age, sex and educational attainment to obtain reliable gross domestic product projections which are fundamental in the quantitative assessment of climate change effects. Cian et al. (2016) state that the influence of socio-economic scenarios, including population scenarios, are fundamental to project the evolution of technological change. We are in particular interested in how these narratives reproduce population dynamics: fertility rates, education choices and mortality rates are modeled exogenously, meaning that they are not the result of an optimization process. Nevertheless, a policy on population is not considered and, in such a context, uncertainty surrounding population can only be tested just through the means of sensitivity analysis on key parameters.

We highlight that taking demographic patterns as given may drive to a large extent the results of IAMs, potentially undermining the assessment of climate change costs. The existent IAMs cannot address, at the moment, how a demographic policy would affect population dynamics - and then climate change - when individuals take decisions following a maximization behavior on how many kids to have or how much to invest in their education.

1.3 Endogenous Fertility Literature and Mortality

In this section we review the literature on endogenous fertility and we discuss about the morality-temperature relationship. In order to model fertility and, then, educational choices, we refer to the endogenous fertility growth literature. Since Becker's seminal works (Beker, 1960), optimal fertility decisions have been extensively analyzed in growth theory, but they have never been included in the assessment of climate change using IAMa. Becker and Barro (1988) study fertility choices in an intergenerational model in which altruistic parents derive utility from their offspring and children utility. Moreover, children are themselves altruistic towards their (future) children, which induces in parents a form of "dynastic utility", as their "happiness" depends also on grandchildren utility, and so on.

Latest works on this topics refer to the Unified Growth Theory (UGT) literature (Galor, 2005), where endogenous fertility is a crucial element to reproduce the demographic transition, i.e. the demographic shift from high to low birth and death rates, which characterizes the transition from stagnation to growth in the developing process (and is a condition for it). In these kind of models, parents obtain satisfaction not only from having children, but also from investing in their education. The investment in children's education affect human capital growth

which is recognized as a driver of economic growth also in climate change scenarios (Cuaresma, 2013). The choice between one additional child and the possibility to invest in his education is modeled by the classic trade-off between quantity and quality of children, explained in the seminal paper by Becker et al. (1973). This trade-off is a key element to account for the joint demographic transition and economic take-off, through human capital accumulation, that characterizes successful economies. Only recently this literature started including some concerns about the environment, like pollution. Panayotou (2000) surveys the papers analyzing the relationship between population and environment. Moreover, an even more recent work by (de la Corix and Gosseries, 2012) analyses the effect of endogenous fertility on pollution. Compared to our dynamic setting, these are theoretical growth models whose analysis concentrate in the steady state. Though useful to gain some intuitions, our setting is more complex and complete and give us the possibility to analyze with more details the linkages of interest.

An exhaustive discussion of population dynamics should consider also mortality trends. Globally, life expectancy at birth is projected to rise from 71 years in 2010-2015 to 77 years in 2045-2050; in Africa is expected to rise to 71 years in 2045-2050 UN (2017). Nevertheless, there are some factors that may induce higher mortality rates. In particular, we are interested in the effect of climate change on mortality, through temperature dynamics. There is a new empirical literature studying the social and economic impacts of climate change (Carleton and Hsiang, 2016; Hsiang et al., 2017) on gross domestic product and health. Some epidemiological studies (Hajat et al., 2010; Medina-Ramon et al., 2006) find an ambiguous correlation between deaths and increase in temperature. The nature of this relationship varies depending on the geographical location and on the socio-economic status of population (Braga et al., 2002; Hajat et al., 2010; Yu et al., 2010). Huang et al. (2011) offer an extensive review about projecting future heat-related mortality under climate-change scenarios. They find that, on the basis of the climate-change scenario considered, it is possible to identify different patterns of mortality.

Though the link between temperature and mortality is still ambiguous, the scientific community agree on the fact that and an indiscriminate temperature increase could be harmful to humans (IPCC, 2014).

1.4 This Work

A green technological progress and a more sustainable production path are necessary conditions to limit environmental damages. Nevertheless, demographic factors have an important role in shaping the future environment. Nowadays, the world is split into two macro areas: on the one hand, developed countries which face low fertility rates, aging population with high levels of per-capita consumption and emissions; on the other hand, developing countries, which show high fertility rates and lower per-capita emission compared to the industrialized areas of the world. This poses the problem of how to design an efficient and fair global mitigation policy. The problem is twofold: climate change has an impact on the whole population through disasters such as droughts, sea-level rise, hurricanes; moreover global warming, resulting in higher temperatures, worsens the living conditions of people, causing death in extreme cases. On the other hand, a changing population level and growth affects environment too as a larger population entails higher emission levels. A further step is considering whether climate change strengthens the case for population policies. We investigate which type of demographic policy could be suitable as a tool to reach win-win outcomes, meaning lower emissions levels, without penalizing economic growth.

Few empirical works underline how demographic policies and climate change may be related: increasing access to family planning and sexual and reproductive health and rights (education and welfare), enlarge individual choices and opportunities. Moreover, this may help in achieving sustainable development (UNFPA, 2012), may offset some impacts of climate change, i.e. food security (Lutz, 2010) and it is a cost-effective way to mitigate human induced climate change (PNAS, 2012). The inclusion of endogenous fertility adds completeness to the modeling effort, as in reality people choose how many children to have. A recent contribution by Casey and Galor (2016) shows that policies directed towards population may be beneficial for both the economy, in terms of income gains, and the environment, in terms of lower emissions. Gerlagh et al. (2017), instead, add population aging in an integrated assessment model of the economy and climate change. They show that the optimal carbon price, i.e. carbon tax[5], is upwardly influenced by the population structure.

In the second chapter of this work, we include endogenous fertility. We model also the temperature-mortality relationship assuming that, potentially, climate change will be detrimen-

[5]The carbon price is defined as *"the additional decrease in GDP when decreasing emissions by an additional unit of CO2"* (Nordhaus and Sztorc, 2013).

tal for health causing increases in mortality in future projections (IPCC, 2007; Carleton and Hsiang, 2016). In the third chapter, we consider also education choices, modeling the quality-quantity trade-off as in de la Croix and Doepke (2003).

In particular, the second chapter of this thesis extends the DICE model by Nordhaus and Sztorc (2013) to include endogenous fertility and mortality induced by temperature increase. Such a twofold nature of population growth might have important effect on quantifying the social cost of carbon, i.e. the carbon tax. Since welfare is the discounted sum of the product between per-capita utility and population size along with the fact that fertility affects utility while mortality influences the size of population, accounting for endogenous demography gives us the possibility to quantify their direct and indirect welfare effects. Moreover, we investigate whether a demographic policy which imposes a cap on fertility is beneficial in terms of both emissions and income gains. As expected, accounting for endogenous population increases the estimates of the social costs of environmental policies (measured by the social cost of carbon), and relying on demographic policy directed to stabilize fertility largely reduces the costs associated with climate change (precisely by 16% by 2050). This clearly suggests that population change does matter in the assessment of climate change and related policies, and that demographic policy may be a valid tool to promote environmental sustainability.

In the third chapter, we build an integrated model of economy, climate and demography by including endogenous fertility choice in an overlapping generations framework, modeling also endogenous investment in education. We can capture the quality-quantity trade-off as in de la Croix and Doepke (2003). This is an important difference compared to the second chapter as we can clearly understand the mechanism that induces fertility to decrease. Our model generates a population externality: each child contributes to the future level of emissions, something that parents do not take into account when choosing how many children to have. Policies affecting the level of investment in education of children are desirable in their own right, but also accelerate fertility decline, which may have beneficial effects in the context of climate change. So, instead of imposing a cap on fertility as in chapter 2, we design an education policy aiming at lowering global fertility exploiting the quality-quantity trade-off. We show that the resulting optimal population level is lower compared to the population resulting from a standard climate policy. Population stabilizes around 10 billion of people by 2100 compared to 14 billion of people without demographic intervention. This is an important result in terms of sustainability and preservation of the environment. An optimal carbon price adjusted by optimal fertility

level gives the possibility to contain the increase in temperature below 3 degrees with respect to pre-industrial level by the end of this century. By using both policies, i.e.education and demographic policy, at the same time it is possible to increase the quality of families, boosting economic growth.

We think that demographic policies should be considered in the scientific debate and in future climate agreements. In particular, policies addressing education can be extremely efficient and should be a priority in the context of sustainable development (Lutz, 2014).

Bibliography

Akhtar, M. K., Wibe, J., Simonovic, S. P., and MacGee, J. (2013). Integrated assessment model of society-biosphere-climate-economy-energy system. *Environmental Modelling and Software*, 49:1 – 21.

Anthoff, D. and Tol, R. S. (2014). Fund climate framework for uncertainty, negotiation and distribution. Technical report, Various institutions.

Barreca, A., Deschenes, O., and Guldi, M. (2015). Maybe next month? temperature shocks, climate change, and dynamic adjustments in birth rates. *Working paper. National Bureau of Economic Research.*

Becker, G., Lewis, and Gregg, H. (1973). On the interaction between the quantity and quality of children. *Journal of Political Economy*, 81(issue 2):279–88.

Becker, G. S. and Barro, R. J. (1988). A Reformulation of the Economic Theory of Fertility. *The Quarterly Journal of Economics*, 103(1):1–25.

Beker, G. (1960). An economic analysis of fertility. *Columbia University Press.*

Braga, A., Zanobetti, A., and Schwartz, J. (2002). The effect of weather on respiratory and cardiovascular deaths in 12 u.s. cities. *Environmental Health Perspectives*, 110:859–863.

Carleton, T. A. and Hsiang, S. M. (2016). Social and economic impacts of climate. *Science*, 353(6304).

Carpenter, S., Pingali, P., Bennet, E., and Zurek, M. (2005). *Ecosystems and human well-being: Scenarios. Findings of the scenarios working grgroup the millennium ecosystem assessment.* Island Press, Whashington DC.

Casey, G. and Galor, O. (2016). Population growth and carbon emissions. *NBER working paper.*

Cian, E. D., Sferra, F., and Tavoni, M. (2016). The influence of economic growth, population, and fossil fuel scarcity on energy investments. *Climatic Change*, 136:39–55.

Cuaresma, J. C. (2013). Income projections for climate change research: a framework based on human capital dynamics. *Global Environmental Change*, 42:226–236.

de la Corix, D. and Gosseries, A. (2012). The natalist bias of pollution control. *Journal of environmental economics and management*, 63(2):271–287.

de la Croix, D. and Doepke, M. (2003). Inequality and growth: Why differential fertility matters. *American Economic Review*, 93(4):1091–1113.

Galor, O. (2005). From stagnation to growth: Unified growth theory. *Handbook of Economic Growth, edited by Philippe Aghion and Steven Durlauf Chapter 4*, 1.

Gerlagh, R. (2006). Itc in a global growth-climate model with ccs: The value of induced technical change for climate stabilization. *The Energy Journal*, 0(Special I):223–240.

Gerlagh, R., Jaimes, R., and Motavasseli, A. (2017). Global demographic change and climate policies. Technical Report 6617, CEsifo.

Hajat, S., O'Connor, M., and Kosatsky, T. (2010). Health effects of hot weather: from awareness of risk factors to effective health protection. *The Lancet*, 375(9717):856 – 863.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D. J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., and Houser, T. (2017). Estimating economic damage from climate change in the united states. *Science*, 356(6345):1362–1369.

Huang, C., Barnett, A., Wang, X., Vaneckova, P., FitzGerald, G., and Tong, S. (2011). Projecting future heat-related mortality under climate change scenarios: a systematic review. *Environmental Health Perspectives*, 119:1681–1690.

IPCC (2007). Climate change 2007: Synthesis report. Technical report, Intergovernmental Panel on Climate Change.

IPCC (2014). Climate change 2014. Technical report, Intergovernmental Panel on Climate Change.

KC, S. and Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, 42:181–192.

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., and Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new

approach based on shared socio-economic pathways. *Global Environmental Change*, 22:807–822.

Leimbach, M., Baumstark, L., and Edenhofer, O. (2010). Mitigation costs in a globglobal world: climate policy analysis with remind-r. *Environmental Modeling and Assessment*.

Lutz, W. (2010). What can demographers contribute to understanding the link between population and climate change. Technical report, IIASA.

Lutz, W. (2014). A population policy rationale for the twenty-first century. *Population and Development Review*, 40(3):527–544.

Meadows, D. H., Meadows, D. L., Randers, J., and III, W. W. B. (1972). *Limits to GrowthA: Report for the Club of Rome's Project on the Predicament of Mankind*. Potomac Associates - Universe Books.

Medina-Ramon, M., Zanobetti, A., Cavanagh, D. P., and Schwartz, J. (2006). Extreme temperatures and mortality: Assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis. *Environmental Health Perspectives*, 114(9):1331–1336.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries B, B., and et al., F. J. (2000). *Special report on emissions scenarios (SRES): a special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Nordhaus, W. D. and Sztorc, P. (2013). Dice 2013r: Introduction and user's manual. Technical report, Yale.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W. (2017). The roads ahead: narratives for shared socioeconomic pathpath describing world futures in the 21st century. *Global Environmental Change*.

Panayotou, T. (2000). Population and environment. *CID Working Papers 54, Center for International Development at Harvard University*.

Riahivan, K., Vuurenb, D., Kriegler, E., Edmonds, J., O'Neill, B., Fujimori, S., Bauer, N., Calvin, K., R.Dellink, O.Fricko, Lutz, W., Popp, A., Cuaresma, J., KC, S., Leimbach, M.,

Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebik, K., Hasegawa, T., Havlik, P., Humpender, F., Silva, L. D., S.Smith, Stehfest, E., Bosetti, V., Eom, J., D.Gernaat, T.Masui, Rogelj, J., Streer, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., K.Takahashi, Baumstark, L., Doelman, J., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., A.Tabeau, and M.Tavoni (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, 42:153–168.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., (WUR), H. B., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., (PIK), C. M., and Prins, A. G. (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3 0.* PBL Netherlands Environmental Assessment Agency.

UN (1972). Report of the united nations conference on the human environment. Technical report, United NAtions.

UN (1992). The united nations conference on environment and development. Technical report, United NAtions.

UN (2015). World population prospects. the 2015 revisions. Technical report, Department of Economic and Social Affairs. Population Division.

UN (2017). World population prospects. the 2017 revisions. key findings and advanced tables. Technical report, Department of Economic and Social Affairs. Population Division.

UNEP (2002). Global environmental outlook 3. Technical report, United Nation Environment Program, London.

UNEP (2007). Global environmental outlook 4: Environment for development. Technical report, United Nation Environment Program, NAirobi.

UNFPA (2012). Population matters for sustainable development. Technical report, United Nations Department of Economic and Social Affairs , Population Division.

Yu, W., Vaneckova, P., Mengersen, K., Pan, X., and Tong, S. (2010). Is the association between temperature and mortality modified by age, gender and socio-economic status? *Science of the Total Environment.*

CHAPTER 2

Population Growth and Climate Change: a Dynamic Integrated model of Climate, Economy and Demography (DICED)[1]

[1]This Chapter is based on the paper "Population Growth and Climate Change: a Dynamic Integrated model of Climate, Economy and Demography (DICED)" by Veronica Lupi (L.A.S.E.R. Doctoral School, Universities of Milan, Pavia, Bergamo and Brescia) and Simone Marsiglio (University of Wollongong, School of Accounting, Economics and Finance).

Abstract

We analyze the mutual relation between population growth and climate change: on the one hand, population is a driver of carbon emissions which is an important determinant of climate change; on the other hand, climate change affects the mortality rate which determines the net rate of population growth. Such population-climate feedback suggests that demographic policy may be an alternative instrument to reduce the social costs associated with climate change. We explore this possibility by introducing endogenous fertility choices and temperature-related mortality in a global integrated assessment model of climate-economy, and we consider a population policy aimed at imposing a ceiling on population growth. We show that accounting for endogenous population change substantially increases the social costs of environmental policies, but relying on demographic policy reduces such costs by 16% by 2050. This clearly shows that population change does matter and demographic policy may be a valid tool to promote sustainable development.

2.1 Introduction

Since Malthus (1789) economists have extensively debated on the role of human population dynamics in determining economic growth and environmental outcomes, but still nowadays a clear understanding of their mutual relations has not arisen yet. Since population growth determines the size of the labor force it may positively contribute to production, but since it also gives rise to a dilution of resources in per-capita terms it may have negative consequences on economic activities.[2] For exactly the same reasons, through the interactions between economic production and pollutant emissions, population growth may be harmful for the environment.[3] 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 for sustainable development is a current 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 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, by focusing on the mutual feedback between population growth and climate change, 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 environment outcomes, explicitly accounting for the role of population growth and eventual demographic policies.

Issues related to climate change are traditionally analyzed through integrated assessment models (IAMs) which are computable general equilibrium models extended to account for a climatic sector. In the simplest climatic framework, emissions generated by economic production activities accumulate 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 (Nordhaus and Sztorc, 2013), but none of them focuses the attention on population trends. In traditional IAMs population dynamics is taken as exogenously given to eventually mimic the UN projections (UN, 2017), which predict that human population growth will gradually decrease over time in order for the world population

[2] See Bloom et al. (2003) for a survey of the relationship between population and economic growth.
[3] See Panayotou (2000), for a survey of the relationship between population and environment.

size to stabilize at a level of about 12 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, represent serious challenges for sustainability (UN, 2017; UNFPA, 2012). We do not wish to question UN population projections but instead we wish to stress that taking demographic patterns as 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 work 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-2016 by Nordhaus and Sztorc (2013), and allow for population growth to interact non-trivially with both the economic and climatic sectors. Specifically, population growth results to be the endogenous result of agents' optimal decisions regarding their fertility rates (i.e., how many children to have), which is determined by balancing the utility gained from having children and the cost of raising children. Since Becker's seminal works (Becker, 1960; Becker and Barro, 1988), optimal fertility decisions have been analyzed extensively in growth theory in a setting similar to ours (Palivos and Yip, 1993; Marsiglio, 2017) but to the best of our knowledge they have never been included in the assessment of climate change. Moreover, in our framework population growth is endogenous also because 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); to the best of our knowledge temperature-induced mortality has been only seldom included in the analysis of climate change (Akhtar et al., 2013). 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 or complementary mitigation tool.

The social cost of carbon summarizes the cost of mitigation policies by measuring the welfare effect of an additional ton of carbon dioxide emissions in terms of consumption (Nordhaus, 2017). Since welfare is 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 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 on 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 (Marsiglio, 2017). Analyzing these delicate issues, which can play an important role in effectively promoting sustainable development, is our main goal in this paper.

This paper proceeds as follows. Section 2.2 describes some stylized facts about climate change and population dynamics. Section 2.3 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 on the emissions and thus on temperature which in turn affects mortality, determine the net growth rate of population. We also describe our calibration strategy and the scenarios considered, which include also a demographic policy aiming to impose a ceiling on demographic growth. Section 2.4 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. We show how different policies affect such variables and in particular how population policy might be an important mitigation policy since allowing for substantially reduce the social cost of carbon. Section 2.5 shows through sensitivity analysis how our results are affected by uncertainty in the value of some specific parameters. Section 2.6 presents concluding remarks and suggests directions for future research. Appendix 2.A describes in full our model's equations and the parameter values employed in our analysis.

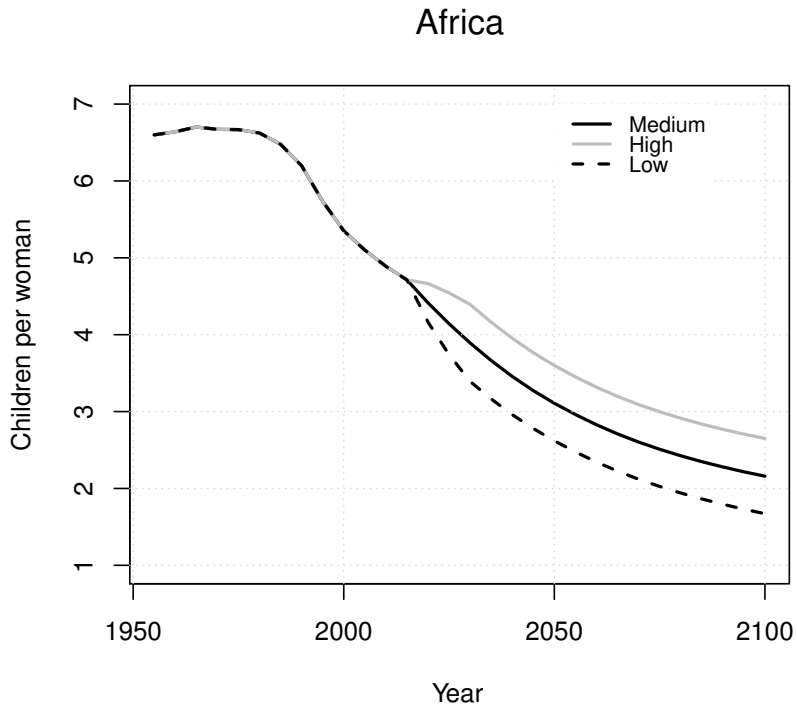
2.2 Population Dynamics and Climate-Change Risk

This section reports some stylized facts about fertility patterns[4], the consequences of the increase in temperature in several countries and the effects of temperature-induced mortality on human health.

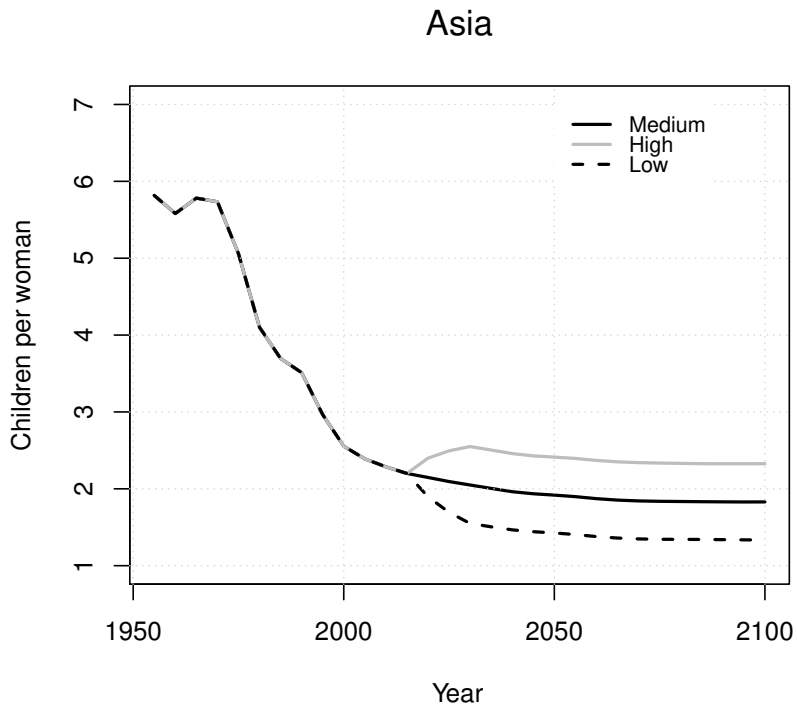
Figures 2.2.1, 2.2.2 and 2.2.3 show historical fertility and future projections based on the low, high and medium variant scenarios by the United Nations (UN, 2017). All population projections are constraint by the imperfect knowledge of current and future demographic settings and trends. Although the demographic momentum inherent in population dynamics allow demographers to produce projections with a comparatively high quality, it is impossible to be certain about future demographic change. The medium variant is the most plausible scenario, while the low and the high ones are the reasonable upper and lower bounds of realistic projections and indicate the margin of uncertainty.

We consider fertility data for Africa, Asia, Latin America, Europe, North America and Oceania. Fertility is decreasing everywhere, in both developed and developing countries. Possibly, it will stabilize by the end of the century. Notice that, though the pattern of fertility is similar, i.e. positive but decreasing, the number of children per woman is different, depending on the country considered. Given the high uncertainty of projections, the impact of fertility on total population may vary significantly.

[4]Total fertility rate (TFR) compares figures for the average number of children that would be born per woman if all women lived to the end of their childbearing years and born children according to a given fertility rate at each age. TFR is a more direct measure of the level of fertility than the crude birth rate, since it refers to births per woman.

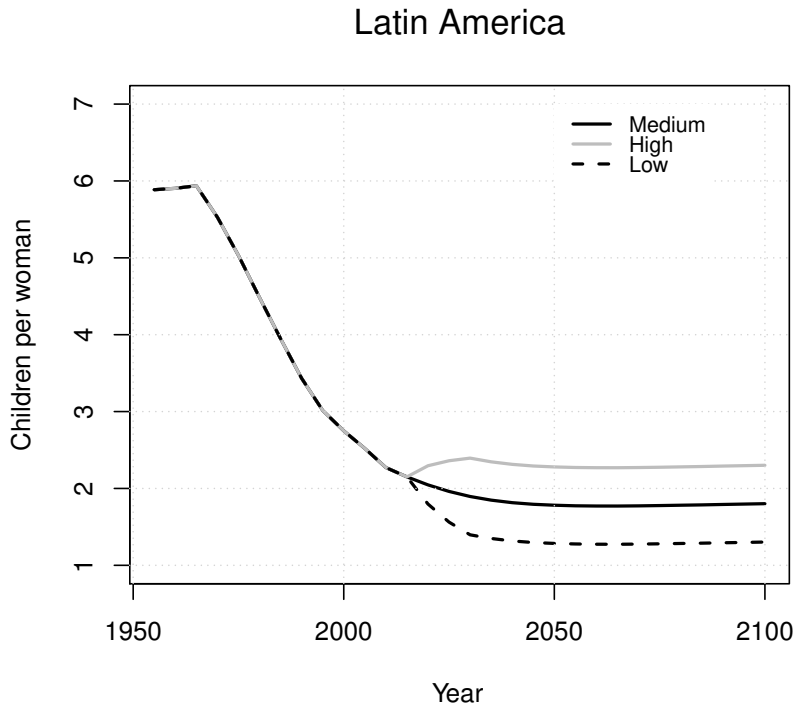


(a)

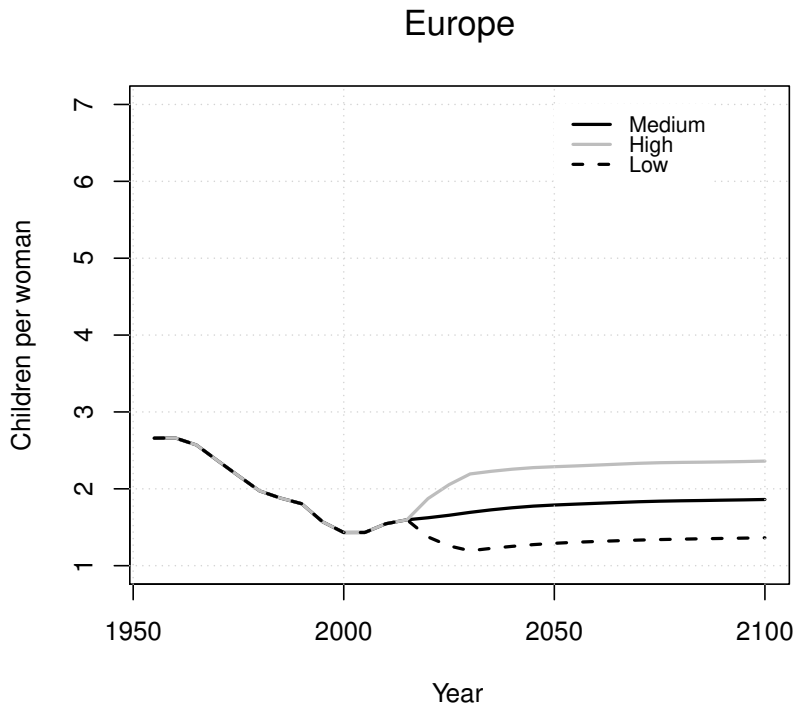


(b)

Figure 2.2.1: **Total Fertility Rate**: Africa and Asia. Estimates and Projections. *Source UN Population Division Database*

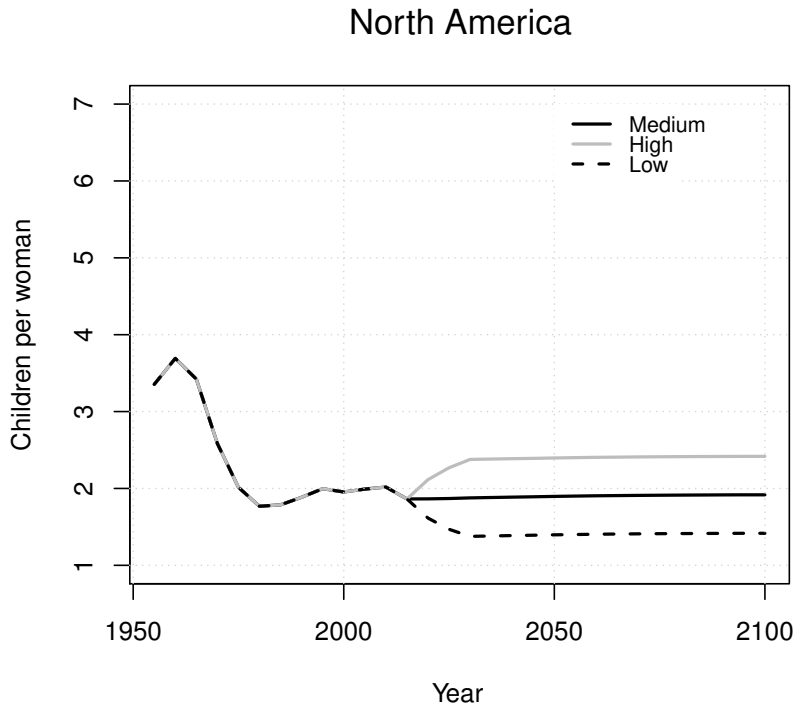


(a)

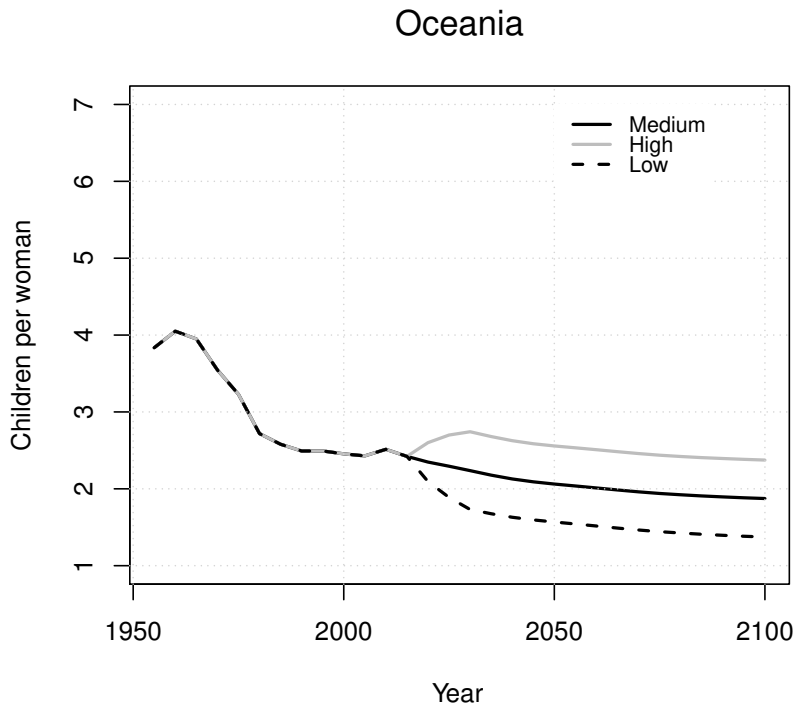


(b)

Figure 2.2.2: **Total Fertility Rate**: Latin America and Europe. Estimates and Projections. *Source UN Population Division Database*



(a)



(b)

Figure 2.2.3: **Total Fertility Rate**: North America and Oceania. Estimates and Projections. *Source UN Population Division*

Several countries are already suffering due to climate change events, especially in Asia and Africa. In Table 2.2.1 we report some data from the Climate Change Knowledge Portal (CCKP).[5] The CCKP is constantly updated: at the moment Bangladesh heads the list of countries most at risk of flooding. Once every three to five years, up to two-thirds of Bangladesh is inundated by floods. Moreover, cyclones, earthquakes and droughts devastate the country during the year. With per capita GDP of about 1.220$, the economic losses in Bangladesh over the past 40 years have been estimated around 12 billion, depressing GDP annually by 0.5 to 1 percent. Vietnam is threatened by rising sea levels: given its high exposure to floods and storms, and the fact that two of its most important economic sectors- industry and agriculture - are located in coastal lowlands and deltas, Vietnam has been listed by the World Bank as one of the five countries that will be worst-affected by climate change. Overall, studies indicate that climate change could reduce annual rice production by 2.7 to 9.1 million tons by 2050. Most of Sudan, Africa's largest country, is arid land or desert and most at risk of food deficits resulting from the impact of climate change on agriculture. The Philippines, a middle-income country in South east Asia, consisting of over $7,000$ islands, leads the list of nations most in danger of facing frequent and intense storms. Finally, China is a country highly vulnerable to climate change, in particular due to sea-level rise. In Table 2.2.1 we consider the five countries just mentioned and other five that are already enduring the effects of climate change. We also show the corresponding fertility rate in 2010-2015, total population in 2015 and total population projection in 2050. The last column shows the expected percentage change in total population between 2015-2050. The aim of this Table is to highlight that poor countries are the most hit by climate change effects. Moreover, except from China, are the ones in which population is expected to expand significantly in the next years. In this thesis population dynamics is considered a driver of emissions and so of climate change. If this is the case, how many people there will be on the planet becomes an important question in terms of sustainability.

[5]The Climate Change Knowledge Portal is updated by the World Bank to be a hub of information, data and reports about climate change around the world

	Fertility Rate (2010-2015)	Pop.2015, thousands	Pop.2050, thousands	%
Niger	7.63	19899	72238	263
Malawi	5.25	17215	43155	151
Afghanistan	5.13	32527	55955.35	72
Ethiopia	4.59	99391	188455	90
Sudan	4.46	12340	25855	110
Philippines	3.04	100699	148260	47
India	2.34	1311051	1705333	30
Bangladesh	2.23	160996	201953	25
Vietnam	1.96	93448	112783	21
China	1.59	1376049	1348056	-2

Table 2.2.1: Climate Change Risks: drought, flood, storm, coastal, agricultural. Fertility rates, population (million) and population growth of some of the most vulnerable countries and regions of the world. *Source: World Bank, UN population division (medium variant).*

Apart the importance of population dynamics in terms of climate change, emissions growth is expected to persist driven by economic activities. Baseline scenarios, depending on the assumptions, may result in global mean surface temperature increases between 3.7-4.8 degrees by in 2100 (IPCC, 2014).

Figure 2.2.4 shows the average increase in temperature by country in the last 50 years. The light-gray line represents the average temperature increase overall which is slightly less than 1.5 degrees.

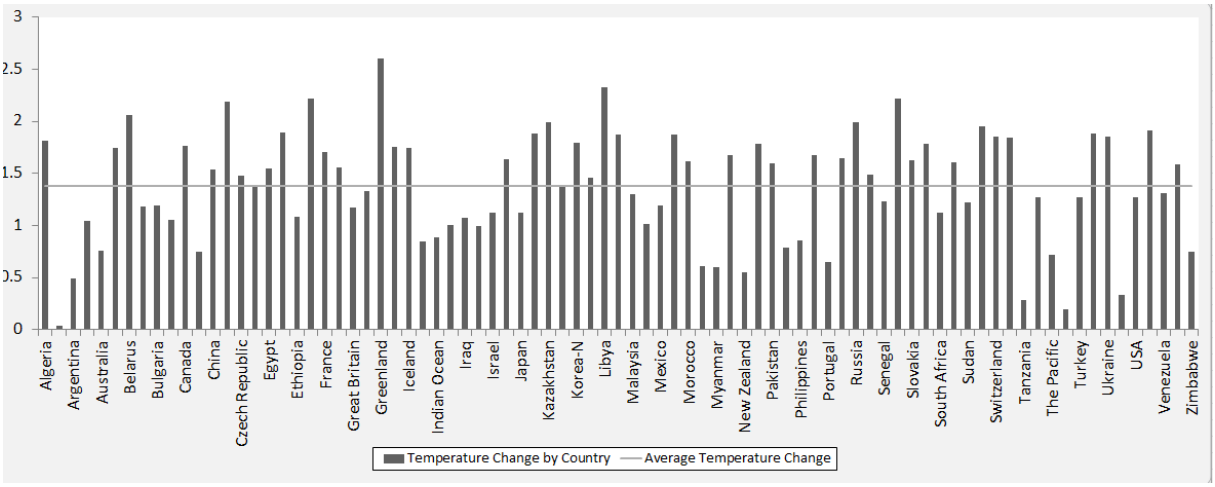


Figure 2.2.4: World. Average Temperature Change in the Last 50 Years by Country. *Source: Elaboration of RIMFROS Data.*

In Figure 2.2.5, instead, we report the average increase in temperature of the top 10 emitters in the world. Notice that four out of ten (i.e. China, India, Brazil, Mexico) are defined as

developing countries by the United Nations Development Programme (UNDP).

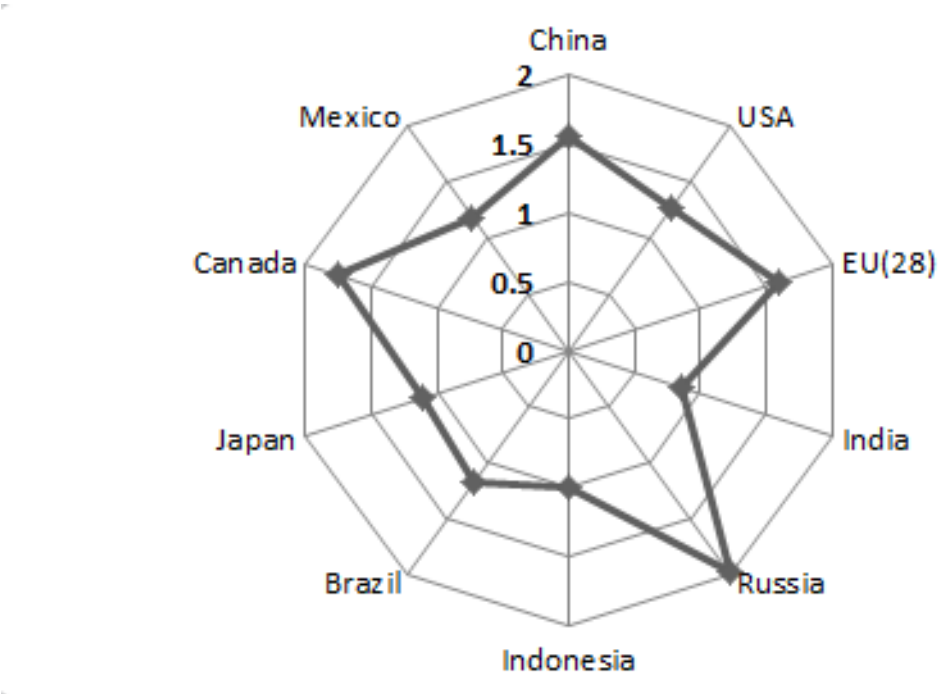


Figure 2.2.5: Top 10 Emitters. Average Temperature Change in the Last 50 Years. *Source: Elaboration of RIMFROST Data.*

Another relevant dimension of climate change is its possible impact on human health. Climate change currently contributes to the global burden of disease and premature deaths (IPCC, 2007). Human beings are exposed to climate change through changing weather patterns. i.e. more intense and frequent extreme events, and indirectly through changes in water, air, food quality and quantity, ecosystems, agriculture and economy. These effects are projected to progressively increase in all countries and regions. Temperature changes could aggravate some diseases with obvious consequences on human health. In Figure 2.2.6 the arrows give the direction and the magnitude of climate change influence on some selected diseases.

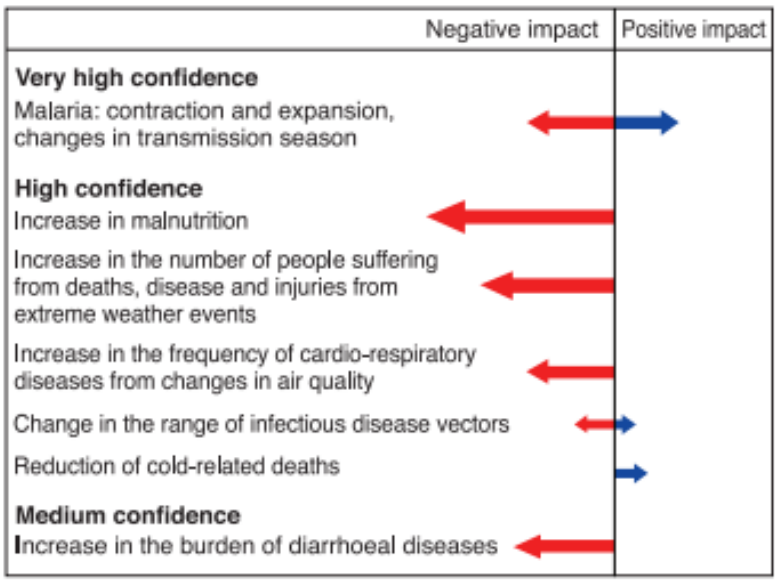


Figure 2.2.6: Direction and magnitude of change of selected health impacts of climate change. *Source: IPCC, 2007*

This broad picture wants to suggests that economy, climate and demography are linked to each other. Though our climate-economy model is global and can't reproduce in detail all the facts exposed in this section, it considers endogenous fertility choices and temperature-mortality relationship.

2.3 The Model

We extend the simplest integrated assessment model 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 in its 2016 revised version (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. In all integrated assessment models population growth is assumed to be exogenous and generally 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 economic incentives. 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:

$$N_{t+1} = N_t(1 + g_t) \tag{2.3.1}$$

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

$$g_t = \frac{g_{(t-1)}}{1 + \delta_N} \tag{2.3.2}$$

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. 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:

$$N_{t+1} = N_t[1 + n_t - d(T_t)] \tag{2.3.3}$$

The fertility rate is endogenously determined and we assume that it affects the instantaneous utility function (Barro and Sala-I-Martin, 2005; Palivos and Yip, 1993), which is specified as follows:

$$u(c_t, n_t) = \frac{(c_t n_t^{\kappa})^{1-\zeta} - 1}{1 - \zeta}, \tag{2.3.4}$$

where $c_t = \frac{C_t}{N_t}$ is per-capita consumption, ζ the marginal elasticity of consumption and $\kappa \in (0, 1)$ the relative weight of fertility in the utility function. The traditional setting in integrated assessment models is 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. Similarly to Voorhees et al. (2011), we model mortality as follows:

$$d(T_t) = d_1 exp^{d_2 T_t} \tag{2.3.5}$$

where d_1 and d_2 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 never been considered in integrated assessment models, except for Akhtar et al. (2013). Several papers document the existence of a positive association between temperature and health conditions, suggesting how increases in frequency and intensity of heat waves may be detrimental for health, affecting thus mortality (IPCC, 2007). 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:

$$Y_t = C_t + I_t + R_t, \tag{2.3.6}$$

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:

$$R_t = hn_t K_t, \tag{2.3.7}$$

where h is a scale parameter and K_t is the aggregate capital stock. The above formulation entails a trade-off between income per capita at disposal and quantity of children, since raising children subtracts resources to capital investment. In order to look at this, note that with some straightforward algebra the economy's resource constraint in per-capita terms can be expressed as follows:

$$k_{t+1} = \frac{y_t + (1 - \delta_K)k_t - hn_t k_t - c_t}{1 + n_t - d_t}, \tag{2.3.8}$$

where lower-case letters denote per-capita variables. Specifically y_t is output per capita, k_t capital per capita, c_t is consumption per capita and δ_K denotes the depreciation rate of capital. From equation (2.3.8), it is clear that an increase in the fertility rate negatively affects the future per-capita level of capital by reducing the resources left for investment and by increasing capital dilution; this tends to let income decrease at a lower rate and therefore consumption too in the following period, affecting thus future fertility decisions. This stresses the existence of a clear

trade-off between per consumption and quantity of children

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:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha}, \tag{2.3.9}$$

where Y_t is aggregate output, K_t is aggregate capital, 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 factors 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 through mortality. 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 2.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 on 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 integrated assessment models, 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.

2.3.1 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. Regarding the parameters, we only need to calibrate those related to the demographic peculiarities of our setting, that is κ, d_1, d_2, and h. We 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, h 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 $h = 1.3$. All other parameters are exactly the same as in the standard DICE model and are listed in Table 2.A in appendix 2.A. For what concerns the scenarios, we rely on the three basic DICE scenarios plus an additional one to account for demographic policy. Following DICE, we analyze a baseline scenario, an optimal scenario and a temperature scenario; following the rationale behind this latter scenario we propose a population stabilization policy scenario. Each of these scenarios is briefly described below.

(a) Baseline: the business as usual scenario (BAU) assumes no changes in the climate policy with respect to the 2015 levels. This means that current policies are extended indefinitely.

(b) Optimal: the optimal scenario optimally determines climate policy by determining which share of emissions to abate in order to maximize social welfare, accounting for the impacts of climate change on output and therefore consumption. This scenario assumes the most efficient climate-change policies; in this context, efficiency involves a balancing of the present value of the costs of abatement and the present value of the benefits of reduced climate damages. Although unrealistic, this scenario provides an efficiency benchmark against which other policies can be measured.

(c) Temperature: this scenario imposes a constraint on the global temperature level, requiring temperature not to exceed 2 degree with respect to the average temperature in the pre-industrial era. This scenario is consistent with 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 degrees. In order for this goal to be effectively achieved, the cooperation 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 skeptics about the effective ability to achieve such a goal, and as Nordhaus (2017) highlights, it will be almost impossible to achieve the target even if drastic climatic policies are introduced since today. This scenario allows us to quantify the efforts and the costs needed to effectively reach such a goal.

(d) Demography: 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. 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 decrease emissions and to combat climate change.

The results of our scenario analysis are presented in the next section. We focus on some key variables, and in particular on per-capita GDP net of climate costs, per-capita consumption, industrial emissions, temperature level, atmospheric CO2 concentrations, emission control rate, fertility and mortality.

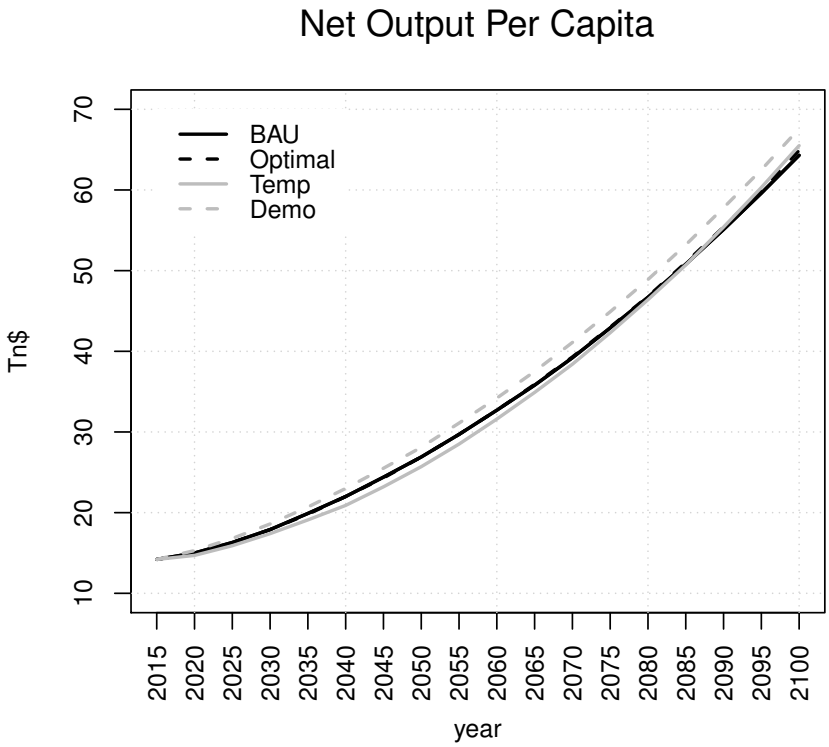
2.4 Results

Our model starts from 2015 and each period lasts five years. Table 2.4.1 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 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 DICED and DICE have the same initial level of income and consumption per capita, of industrial emissions and temperature. Starting from 2020 projections change: this is the result of endogenizing population in DICED. The level of fertility determines population differently from DICE, though in the long-run total population converges to the same level. This strongly affects the medium

and long run outcomes: by 2050 in the baseline scenario the DICED model predicts lower industrial emissions (-23%), lower net output (-11.5%) and consumption per-capita (-14.1%) and lower atmospheric concentration level (-4.2 percentage) compared to the baseline of the DICE. Similar conclusions extend also to the optimal and the temperature scenarios. In order to understand to what extent demographic policies might be effective in combating climate change, we now compare the Demography scenario with the other scenarios implemented in DICED. We can note that the demographic policy guarantees higher per-capita output ($+4.4\%$) and consumption ($+5\%$) by 2050. As far as industrial emissions are concerned, the temperature scenario is the most effective scenario, in which industrial emissions are predicted to reach zero in 2050; this highlights a complete shift of our economy from fossil fuel-based production to renewable. Nowadays this option still seems quite unrealistic. The differences of the demography scenario from the optimal one are small; this suggests that a demographic policy may help in mitigating climate change and, at the same time, increase the living standards of people. Regarding temperature, we can note that in the demography scenario the temperature level increases by 2 degree by the mid century.

		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 dollars)	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 dollars)	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
degree 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
Atmospheric Concentration(ppm)	Baseline	399.5	418.5	438.3	459.1	552.4	399.5	418.5	436.1	453.5	528.8
	Optimal	399.5	418.5	434.3	450.6	517.4	399.5	418.5	432.1	445.4	498.3
	Temperature	399.5	408.5	416.5	423.1	425.0	399.5	418.5	422.9	426.5	424.5
	Demography						399.5	418.5	432.7	446.6	501.2

Table 2.4.1: Main results from the DICE and DICED models.



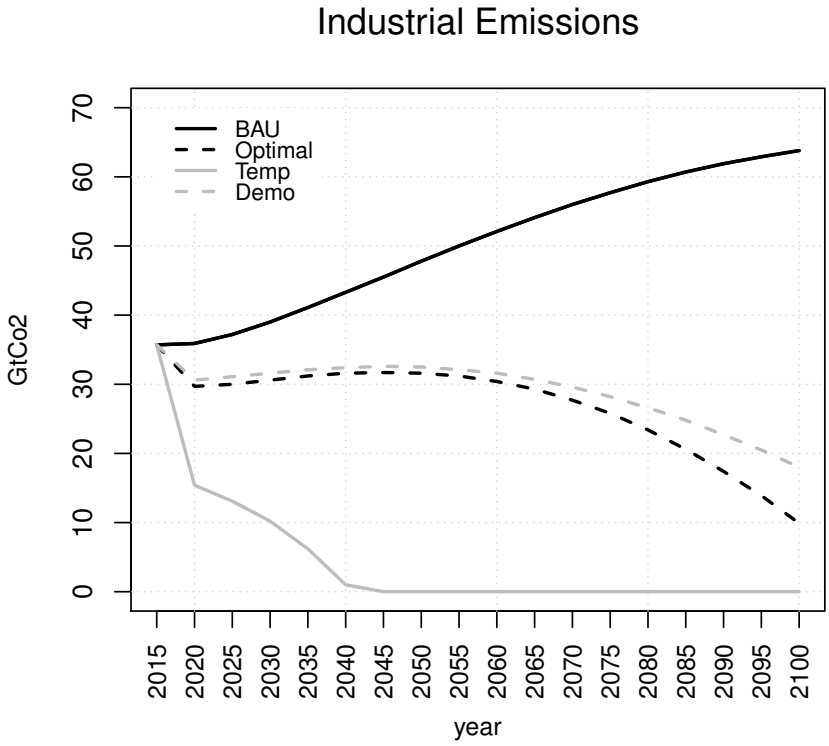


Figure 2.4.1: Simulation's Results: Net Ouput Per capita amd Industrial Emissions

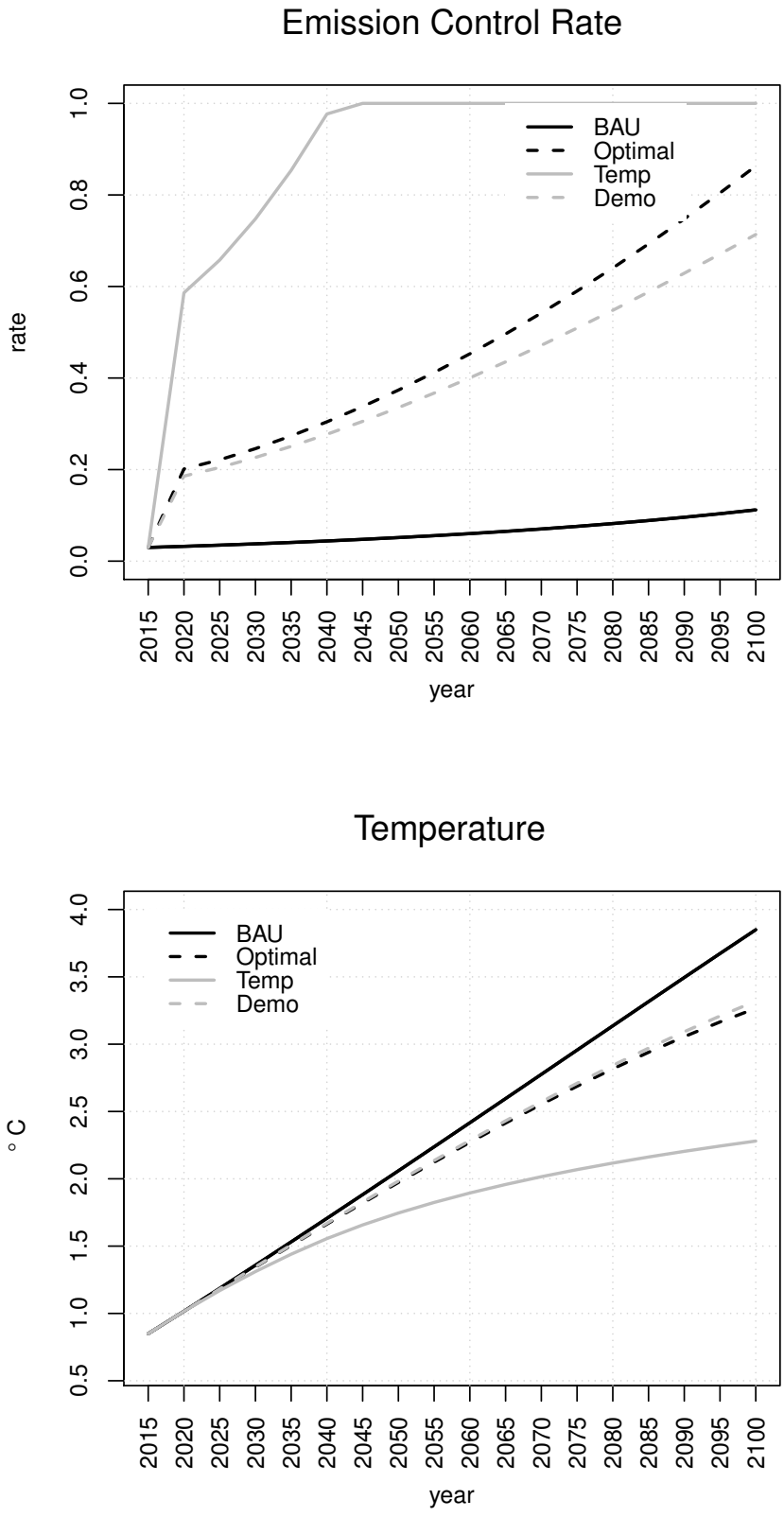


Figure 2.4.2: Simulation's Results: Emission Control Rate and Temperature

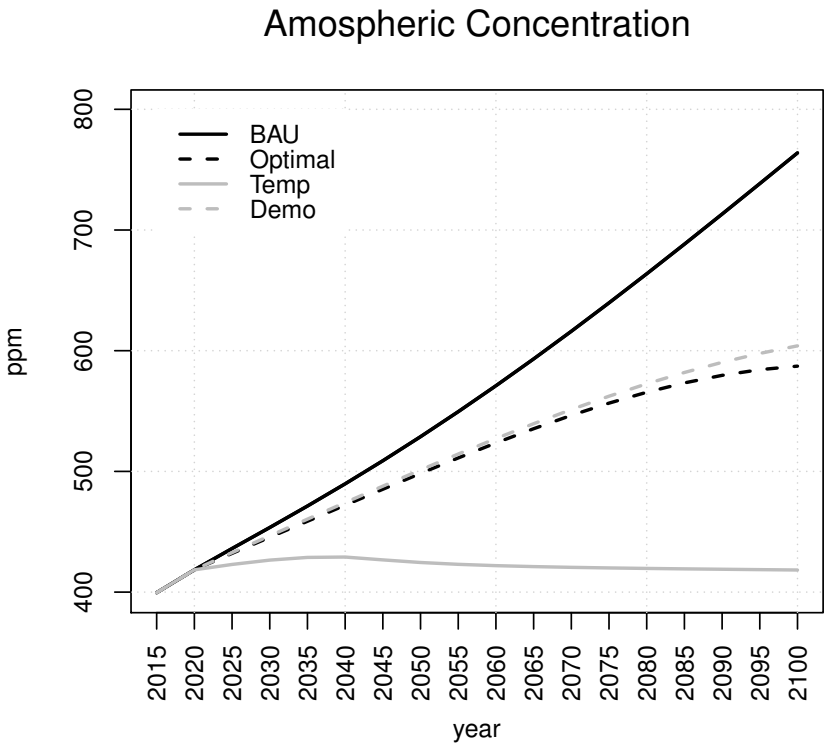


Figure 2.4.3: Simulation's Results: Atmospheric Concentration.

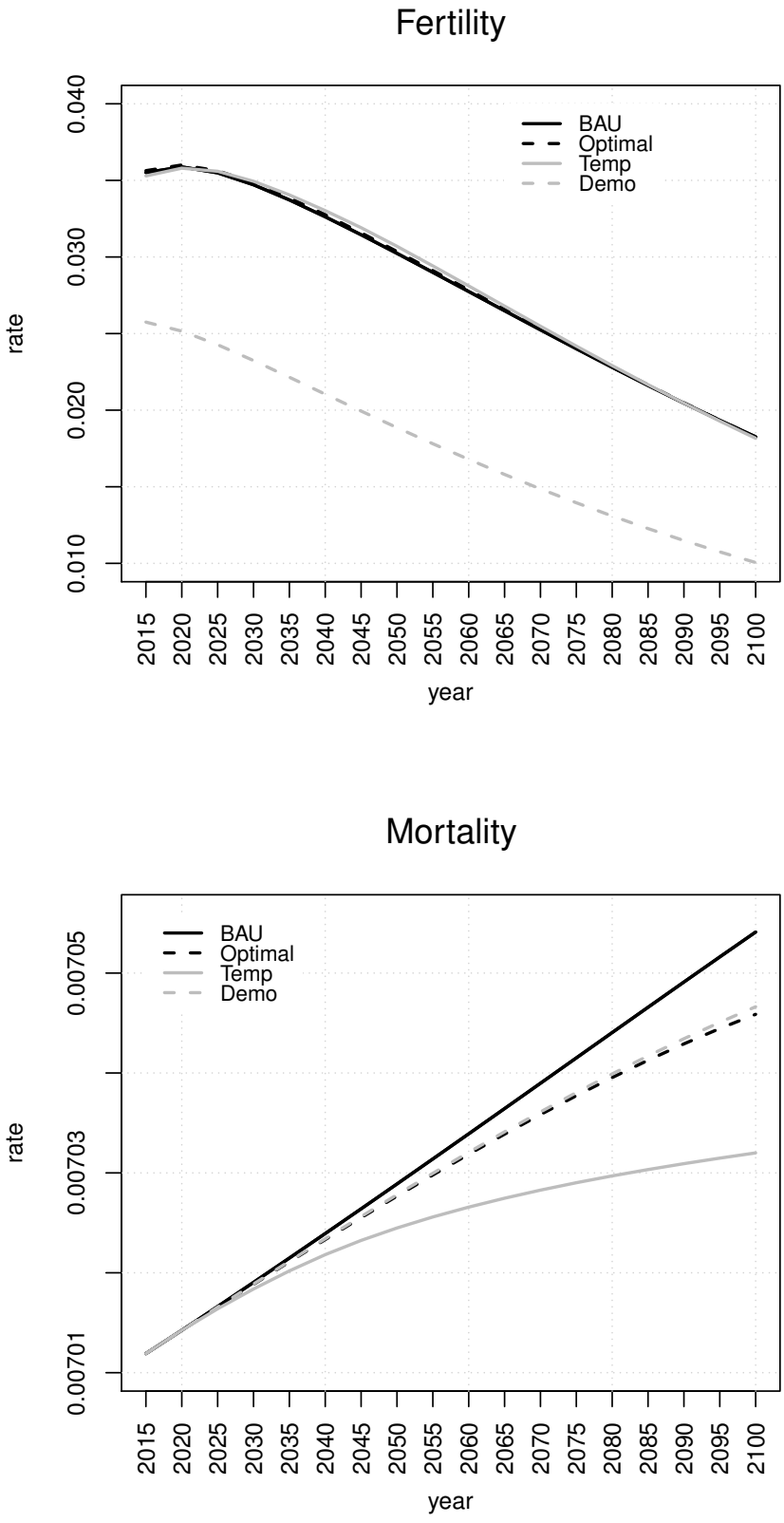


Figure 2.4.4: Simulation's Results: Fertility and Mortality.

The evolution of our key variables is presented in Figures 2.4.1- 2.4.4. The black curve represents the baseline scenario, the dashed black curve the optimal scenario, the gray curve the temperature scenario and the dashed-gray curve the demography scenario. The demographic policy guarantees the highest net income per-capita during the entire planning horizon; since fertility is lowest in such a scenario, the dilution effect is lowest allowing aggregate output to be split between fewer people. The most effective policy in abating emissions is the temperature one; the demographic policy performs quite well and it is close to the optimal case, though emissions are slightly higher. The rationale behind this result can be understood by focusing on the evolution of the emission control rate. In the case of the temperature scenario the emission control rate reaches 100%, meaning full abatement by 2050. The optimal scenario determining the most efficient climate policy, predicts an increasing emission control rate without ever achieving full abatement. Since in the demography scenario, the planner has another instrument at his disposal to decrease emissions (i.e., limiting fertility), a lower level of the emission control rate can be used. This is still effective, compared to the BAU scenario and has the advantage to guarantee higher level of income per-capita with respect to the optimal scenario. Temperature is a key variable: imposing a limit on population growth prevents us to reach a temperature above 3.5 degree Celsius by the end of the century. The evolution of the fertility rate is quite the same both in the optimal and the temperature scenarios, while it gets substantially smaller in the demographic scenario. The mortality rate is lowest in the temperature scenario, but still substantially smaller than in the BAU also in the other two scenarios. Overall, we can conclude that the demographic policy is an effective tool, as it is close to the optimal policy but guarantees higher standards of living. Nevertheless, this is still not enough to keep the temperature well below 3 degree Celsius increase with respect to pre-industrial levels.

Finally, Table 2.4.2 presents the social cost of carbon (SCC) computed from the DICE and our DICED model. We can note that in the baseline version of DICE the SCC in 2015 is about 31.2\$/$tCO2$, 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. It is interesting to note the effects of demographic policy which helps to substantially reduce (by around 15\$/t with respect to the baseline) the social cost of carbon. Indeed, in the case of demographic policy the SCC is 32.6\$/t. This suggests that demographic

policies can be an effective means to combat climate change at lower social costs.

Variable	Scenario	2015	2020	2025	2030	2050
SCC, DICE	Baseline	31.2	37.3	44.0	51.6	90.5
(USD dollars)	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 dollars)	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 2.4.2: Social cost of carbon in the DICE and DICED models.

2.5 Sensitivity Analysis

In the following section we analyze the extent to which uncertainty about some parameter impacts the main results, summarized by emissions and the social cost of carbon (SCC). 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, h. We decrease (increase) these parameters by 5%, separately. Overall, our sensitivity analysis suggests that our main results are not significantly affected by perturbations in some parameters.

Table 2.5.1 shows the results of varying κ on emissions and on the social cost of carbon (SCC). The variation is expressed in percentage terms with respect to the baseline values. A decrease in κ leads to a decrease in emissions through time and to a lower SCC, compared to the baseline case. Note that the quantitative effects of an increase or decrease in the parameter are identical, and particularly small. An increase in κ leads exactly to the opposite effect. Table 2.5.2 is related to the effects on emissions and on the SCC of changing κ. A lower value of h leads an increase in emissions and a subsequent increase in the SCC. Exactly the opposite occurs when h increases. Also in this case the quantitative effects of an increase or decrease in the parameter are identical, and particularly small.

Parameter	Variable	2015	2020	2025	2030	2050
κ 'low'	Emissions	0	-0.052	-0.059	-0.039	0.13
	SCC	-0.4	-0.53	-0.6	-0.61	-0.63
κ 'high'	Emissions	0	0.005	0.006	0.004	-0.012
	SCC	0.046	0.057	0.062	0.064	0.065

Table 2.5.1: Effects of changes in κ.

Parameter	Variable	2015	2020	2025	2030	2050
h 'low'	Emissions	0	0.34	0.49	0.55	0.57
	SCC	0.05	0.48	0.65	0.71	0.68
h 'high'	Emissions	0	-0.34	-0.48	-0.54	-0.56
	SCC	-0.05	-0.48	-0.64	-0.70	-0.67

Table 2.5.2: Effects of changes in h.

2.6 Conclusions

Population growth and climate change are mutually related: on the one hand, by determining the size of the labor force, the population growth determines the output and therefore the level of emissions, which in turn contribute to climate change; on the other hand, climate change affects health conditions through the mortality rate, which in turn determines the population growth rate. Despite the existence of such important channels, no IAM has thus far analyzed the extent to which 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) in order to allow for endogenous population change where agents optimally determine their fertility rates. This adds reality to our model and 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 substantially increases the estimates of the social costs of environmental policies (measured by the social cost of carbon), and (ii) relying on demographic policy reduces the costs associated with climate change (precisely by 16% by 2050). This clearly suggests that population change does matter in the assessment of climate change and related policies, and that demographic policy may be a valid tool to promote sustainable development.

Given the complexity of this topic, 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 a more detailed demographic setting, like an overlapping generations one, the assessment of regional costs and the analysis of migration.

Indeed, in a regional setting it might be possible to identify 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. Extending the analysis along these directions is on top of our future research agenda.

Bibliography

Akhtar, M. K., Wibe, J., Simonovic, S. P., and MacGee, J. (2013). Integrated assessment model of society-biosphere-climate-economy-energy system. *Environmental Modelling and Software*, 49:1 – 21.

Barro, R. J. and Sala-I-Martin, X. (2005). *Economic growth*. MIT Press.

Becker, G. S. (1960). *An Economic Analysis of Fertility*. Columbia University Press.

Becker, G. S. and Barro, R. J. (1988). A reformulation of the economic theory of fertility. *The Quarterly Journal of Economics*, 103(1):1–25.

Bloom, D. E., Canning, D., and Sevilla, J. (2003). The demographic dividend: a new perspective on the economic consequences of population change. Technical report, Santa Monica, CA: Rand, MR-1274.

Boikos, S., Bucci, A., and Stengos, T. (2013). Non-monotonicity of fertility in human capital accumulation and economic growth. *Journal of Macroeconomics*, 38, Part A:44 – 59. Dynamics, Economic Growth & International Trade.

Growiec, J. (2006). Fertility Choice and Semi-Endogenous Growth: Where Becker Meets Jones. *The B.E. Journal of Macroeconomics*, 6(2):1–25.

Huang, C., Barnett, A. G., Wang, X., Vaneckova, P., FitzGerald, G., and Tong, S. (2011). Projecting future heat-related mortality under climate change scenarios: A systematic review. *Environmental Health Perspectives*, 119(12).

IPCC (2007). Climate change 2007: Impacts, adaptation and vulnerability. technical summary. Technical report, Intergovernmental Panel on Climate Change.

IPCC (2014). Climate change 2014: Synthesis report. contribution of working groups i, ii and iii to the fifth assessment report of the intergovernmental panel on climate change [core writing team, r.k. pachauri and l.a. meyer (eds.)]. Technical report, IPCC.

Malthus, T. (1789). *An Essay on the Principle of Population. As it Affects the Future Improvement of Society with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers*. Penguin Classics.

Marsiglio, S. (2014). Reassessing Edgeworth's conjecture when population dynamics is stochastic. *Journal of Macroeconomics*, 42(C):130–140.

Marsiglio, S. (2017). A simple endogenous growth model with endogenous fertility and environmental concern. *Scottish Journal of Political Economy*, 64:263–282.

Nordhaus, W. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114:1518–1523.

Nordhaus, W. D. and Sztorc, P. (2013). Dice 2013r: Introduction and user's manual. Technical report, Yale.

Palivos, T. and Yip, C. K. (1993). Optimal population size and endogenous growth. *Economics letters*, 41:107–110.

Panayotou, T. (2000). Population and Environment. CID Working Papers 54, Center for International Development at Harvard University.

UN (1992). Report of the united nations conference on environment and development, rio de janeiro, 3-14 june 1992, annex i: Rio declaration on environment and development. *A/CONF.151/26 (Vol. I), 12 August 1992, New York, NY.*

UN (2017). World population prospects: The 2017 revision, key findings and advance tables. *Working Paper No. ESA/P/WP/248.*

UNFPA (2012). Population matters for sustainable development. Technical report, United Nations Department of Economic and Social Affairs , Population Division.

Voorhees, A. S., Fann, N., Fulcher, C., Dolwick, O., Hubbell, B., Bierwagen, B., and Morefield, P. (2011). Climate change-related temperature iimpact on warm season heat mortality: A proof-of-concept methodology using ben map. *Environmental Science and Technology*, 45:1450–1457.

Appendix

2.A The Equations of 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:

$$\max_{c_t, n_t} W = \sum^{T} u(c_t, n_t) N_t (1+\rho)^{-t} \tag{2.A.1}$$

In equation (2.A.1) per-capita utility depends on per-capita consumption c_t and fertility n_t and it is specified as follows:

$$u(c_t, n_t) = \frac{c_t^{1-\zeta} n_t^{\kappa(1-\zeta)} - 1}{1-\zeta} \tag{2.A.2}$$

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:

$$c_t = \frac{C_t}{N_t}. \tag{2.A.3}$$

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

$$N_t = N_{t-1}[1 + n_t - d(T_t)] \tag{2.A.4}$$

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:

$$d(T_t) = d_1 e^{d_2 T_t}, \tag{2.A.5}$$

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:

$$Q_t = \frac{[1 - \Lambda_t]Y_t}{1 + \Omega_t}, \tag{2.A.6}$$

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:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha} \tag{2.A.7}$$

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

$$A_t = A_{t-1}(1 + g_t^A) \tag{2.A.8}$$

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

$$g_t^A = \frac{g_{t-1}^A}{(1 + \delta_A)} \tag{2.A.9}$$

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

$$Y_t = C_t + I_t + R_t, \tag{2.A.10}$$

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

$$R_t = h n_t K_t, \tag{2.A.11}$$

where h is a scale parameter. The law of motion of capital depends on investment and capital

depreciation as follows:

$$K_{t+1} = (1 - \delta_K)K_t + I_t \tag{2.A.12}$$

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:

$$E_t = EI_t + ELU_t \tag{2.A.13}$$

where land-use emissions are exogenous and modelled as:

$$ELU_t = ELU_{t-1}(1 - \delta_L). \tag{2.A.14}$$

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:

$$EI_t = \sigma_t(1 - \mu_t)Y_t \tag{2.A.15}$$

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

$$\sigma_t = \sigma_{t-1}e^{g_{\sigma t}} \tag{2.A.16}$$

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

$$g_{\sigma t} = g_{\sigma t-1}(1 + \delta_\sigma) \tag{2.A.17}$$

where δ_σ is the exogenous rate of energy efficiency.

Equations (2.A.18) - (2.A.20) reflect the accumulation of emissions in the atmosphere, MAT_t, upper atmosphere, MUP_t, and lower oceans, MLO_t:

$$MAT_t = E_t + \phi_{11}MAT_{t-1} - \phi_{12}MAT_{t-1} + \phi_{21}MUP_{t-1} \tag{2.A.18}$$

$$MUP_t = \phi_{22}MUP_{t-1} + \phi_{12}MAT_{t-1} + \phi_{32}MLO_{t-1} \tag{2.A.19}$$

$$MLO_t = \phi_{33}MLO_{t-1} + \phi_{23}MUP_{t-1} \tag{2.A.20}$$

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:

$$F_t = \eta \left\{ log_2 \left[\frac{MAT_t}{MAT_t^{PI}} \right] \right\} + O_t \tag{2.A.21}$$

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:

$$T_t = T_{t-1} + c_1 F_t - \lambda T_{t-1} - c_2(T_{t-1} - TLO_{t-1}) \tag{2.A.22}$$

$$TLO_t = TLO_{t-1} + c_3(T_{t-1} - TLO_{t-1}) \tag{2.A.23}$$

TLO_t is the increase of temperature in the deep oceans, λ is a feedback parameter, σ_i are transfer coefficients reflecting the rates of flow and the thermal capacities of different sinks.

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

$$\Omega_t = \psi_1 TAT_t^{\psi_2} A_t K_t^{\alpha} N_t^{1-\alpha} \tag{2.A.24}$$

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:

$$\Lambda_t = (\epsilon_1 \mu_t^{\epsilon_2}) K_t^{\alpha} N_t^{1-\alpha} \tag{2.A.25}$$

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:

$$SCC_t = -\frac{dW/dE}{dW/dC} \tag{2.A.26}$$

where the numerator is the marginal impact of emissions at time t on welfare, while the de-

nominator 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 2.A.

Parameter	Value	Definition
h	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	1.18	Feedback parameter
$c1$	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 2.A.1: Complete list of parameters and their values.

CHAPTER 3

Endogenous Fertility and Climate Change Policies[1]

[1]This chapter is based on the paper "Endogenous Fertility and Climate Change Policies" by Veronica Lupi (L.A.S.E.R. Doctoral School, Universities of Milan, Pavia, Bergamo and Brescia). I am grateful to professor Reyer Gerlagh (CentER, Tilburg School of Economics and Management) for his valuable suggestions and supervision.

Abstract

We investigate the role of endogenous fertility in an overlapping generation model with climate change. We adopt a standard quality-quantity trade off framework, with endogenous investment in children's education. We explicitly model the channels between fertility choices and emissions. Beyond the global negative externality generated by climate change, our model produces a second externality, i.e. a population externality, which has to be corrected for. We compare the effects of a standard climate policy and of a mixed climate-population policy on emissions, demography and economy.

3.1 Introduction

After the Paris conference on climate (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. Governments all over the globe agreed on integrating climate change measures into national policies, strategies and planning. Nevertheless, planetary warming continued in 2016, setting a new record of about 1.1 degree above the preindustrial period, according to the World Meteorological Organization (WMO) Statement on the State of the Global Climate in 2016 (WMO, 2017). The debate among researchers and policymakers is focused on studying efficient mechanisms to reduce emissions as the transition from a fossil fuels production to one based on renewables is extremely expensive. Several signals induce to think that it might be fundamental to focus on the interplay between environmental issues and population dynamics Despite a declining fertility, global population is still growing at about 80 million per year (RoyalSociety, 2012). An uncontrolled population growth increases the level of emissions, worsening climate change consequences. In fact, fertility choices impose external costs to society as a whole. Parents may not be fully informed or may not have access to means for controlling births. The adoption of demographic policies can therefore be justified on economic grounds.

Population control is a controversial topic. Philosophers and economists have been asking themselves if the idea of an "optimal population" could be justified in ethic terms. People's freedom (not) to procreate is an inviolable right. Our idea of population policies is related to programs promoting 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). History has shown that population growth can slow down without coercion.

We investigate the role of endogenous fertility in an overlapping generation model with climate change. We follow the literature on quality-quantity trade off framework, with endogenous investment in children's education. We explicitly model the channels between fertility choices and emissions. Beyond the global negative externality generated by climate change, our model produces a second externality, i.e. a population externality, which has to be corrected for. We compare the effects of a standard climate policy and of a mixed climate-population policy on emissions, demography and economy. Population policies such as investments in education of children, particularly on girls' education, are not only desirable in their own right, but also accelerate fertility decline, which may have significant benefits in the context of climate change.

O'Neill et al. (2001) state that slower population growth in developing countries will not only tend to reduce emissions but is also likely to increase the ability of societies to adapt to the impacts of climate change.

Models of endogenous fertility and education are based on the idea that parents derive satisfaction from having children and in supporting their course of studies. As education is expensive, however, parents face a trade-off between the number of children to generate and the amount of education to provide them with. A trade-off emerges between quantity and quality of children. Since the seminal contribution by Becker et al. (1973), several papers have addressed fertility decisions and analyzed the so called quality-quantity trade-off. The relationship between fertility, human capital and economic growth has been subsequently studied by Becker et al. (1990) and Galor (2005), among others. Recently de la Croix and Doepke (2003) developed a new theoretical link between inequality and growth in a model with interdependent fertility and education decisions. Poor parents decide to have many children and invest little in their education. They show that an increase in inequality lowers average education and, therefore, income growth and find that this fertility differential effect accounts for most of the empirical relationship between inequality and growth. Only 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. 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 is called population externality. Based on this theoretical contribution, 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. The authors find that, under certain assumptions, the population externality is quite large.

In this paper we use a simplified version of the model by de la Croix and Doepke (2003), integrating climate change dynamics and its effects on the economy. Compared to Harford (1998) we design an education policy to control fertility since a policy which directly tax each children may be controversial for policymakers. With respect to Bohn and Stuart (2015), we analyse

the transitional dynamics of the endogenous fertility model and we improve upon the climatic module partially following Golosov et al. (2014). We calibrate our model in order to assess to which extent an education policy contribute to climate policy, compared to a benchmark climate policy that has laissez-faire fertility choices. In particular, considering endogenous fertility, we ask how much family size should decrease as part of climate change policy and whether an education policy affecting fertility is an efficient mitigation mechanism. Our results shows that endogenous demography increases the social cost of carbon compared to the classical literature on climate change and the economy, suggesting that this dimension is extremely important. In this setting, a climate policy is not sufficient to internalize the externality induced by endogenous population; including a policy directed to increase global education, instead, help in reaching a win-win outcome: the carbon tax is optimal and a subsidy on education decreases fertility level helping in lowering emissions and, at the same time, boosting economic growth.

The remainder of the chapter proceeds as follows. In Section 3.2 we outline a few stylized facts on economic growth, fertility, education and climate change that provide some background for the analysis. In Section 3.3 we clarify the links between fertility, education and climate change. In Section 3.4 we present a model of endogenous fertility decisions with quality-quantity trade-off features to which we add a climate module. Section 3.5 outlines the calibration procedure. In Section 3.6 we describe the scenarios and the policies implemented. In Section 3.7 we present the results. In Section 3.8 we perform a sensitivity analysis on key parameters. Section 3.9 concludes with some indications of future research avenues.

3.2 Stylized Facts

The United Nations calculates that there are more than 7 billion living humans on earth nowadays (UN, 2015b), yet 200 years ago we numbered less than 1 billion. This is the most conspicuous fact about world population growth: for thousands of years, population grew only slowly, but in recent centuries it has jumped dramatically.

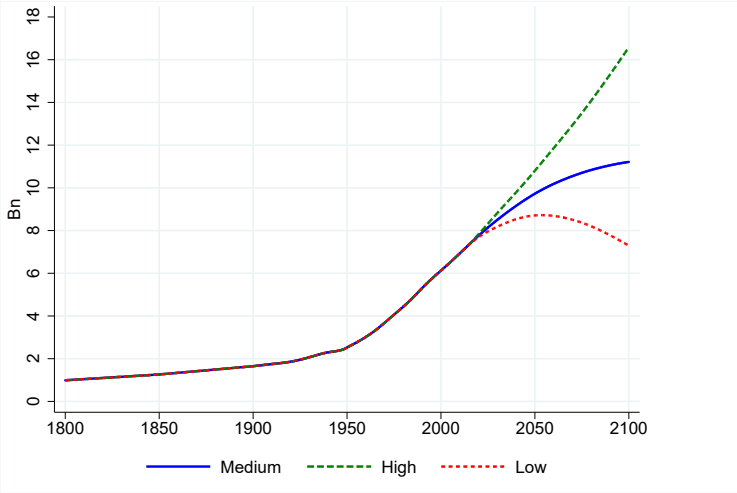
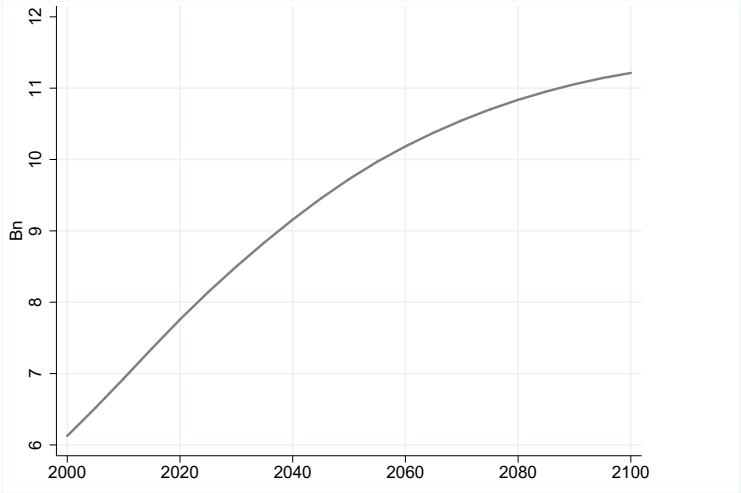
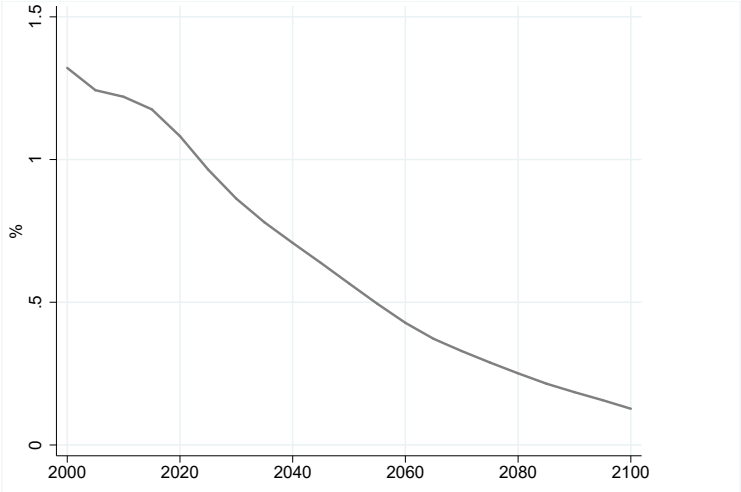


Figure 3.2.1: Population: Estimates and Projections. *Source: History Database of the Global Environment (HYDE) until 1950. UN Population Division after 1950, including the UN projections after 2016.*

As Figure 3.2.1 shows, historical population trend is non-linear. The increase in world population between 1900 and 2000 was three times greater than the entire previous history of humanity. The world faced an increase from 1.5 to 6.1 billion of people in just 100 years (Roser and Ortiz-Ospina, 2017). Nevertheless, there is a high degree of uncertainty as concern future population growth, which depends on assumptions about specific demographic variables. In particular, the factors governing population dynamics are mortality rates, migration and most importantly fertility which is the most uncertain variables. Depending on the scenario considered (low, medium, high) and the corresponding fertility pattern assumed, we may end up by 2100 between 8 (low variant scenario) and 16 (high variant scenario) billion of people (UN, 2015b). Currently, the world population continues to grow though more slowly than in the recent past.



(a)



(b)

Figure 3.2.2: Medium Variant Scenario. Panel (a) represents Total Population and Panel (b) Population Growth. Annual Estimates and Projections (2000-2100). Medium Variant. *Source UN Population Division.*

Figure 3.2.2 is based on the medium variant scenario and considers the evolution of historical population in the last 20 years and its projections until 2100. The results presented in Panels (a) and (b), which report, respectively, total population and population growth rate, assumes a decline of fertility for countries where large families are still prevalent, as well a slight increase of fertility in several countries where women have fewer than two live births on average over a lifetime. Survival rate are projected to increase in all countries as death rates are expected to continuously declining. The uncertainty surrounding projected fertility and mortality rates is addressed by the United Nation using statistical methods to test the plausibility of each outcome. The UN (2017) analysis has concluded that, with a certainty of 95 per cent, the size of global population will stand between 8.4 and 8.7 billion in 2030, between 9.4 and 10.2 billion

in 2050 and between 9.6 and 16 billion in 2100. Concluding, it is quite certain that the size of population will increase, there is a roughly probability that world's population could stabilize or even begin to fall before 2100.

Several papers in the economic literature (Galor and Weil, 2000; Galor, 2005) study population trends and factors governing the demographic transition. Mortality is highly affected by the improvement of living standards and the availability of public health systems. Nevertheless, considering that mortality rates are declining all over the world and that their future trends are less uncertain, the main variables to study is fertility. On the one hand, fertility choices are influenced by the use of contraceptives: to realize a substantial reductions in fertility it is essential to invest in reproductive health and family planning, particularly in the least developed countries where the need for such policies seems extremely important. On the other hand, developed countries show lower fertility rates not only as a result of easier access to contraceptive methods, but also because of different stage of development. If we plot fertility against income per capita at the global level, we can see that the two variable are negatively correlated.

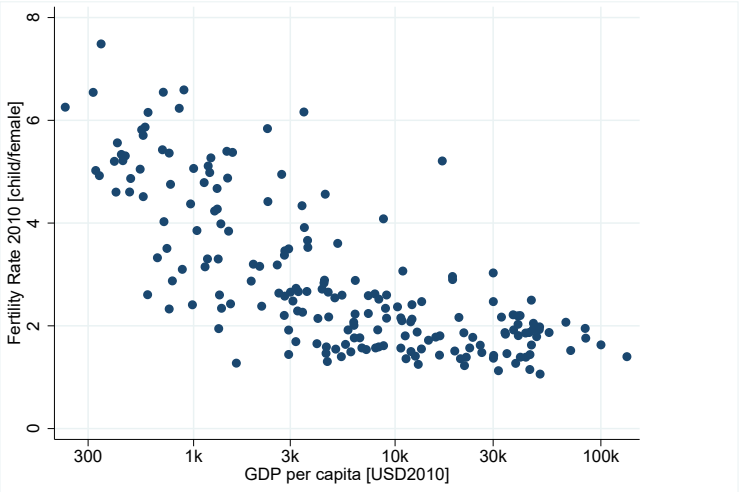


Figure 3.2.3: Fertility Rates and GDP per capita. *Source: GDP per capita (constant 2010 US$) is taken from the WDI database, World Bank; Fertility Rates are taken from United Nation Population Division database.*

Figure 3.2.3 shows that stylized fact. There are many drivers behind this relationship and we can find several explanations: first, the opportunity cost of child-rearing is high in developed countries, especially for women (Jones and Tertilt, 2009); second, if women are better educated tend to have less (or none) children, matching their desired family size (UN, 2017). Finally, a symptom of economic growth is that parents substitute quantity for quality of children (Becker et al., 1990; Becker and Barro, 1988; de la Croix and Doepke, 2003). In this regard, Figure 3.2.4

correlates education (proxied by average years of schooling) and income per capita.

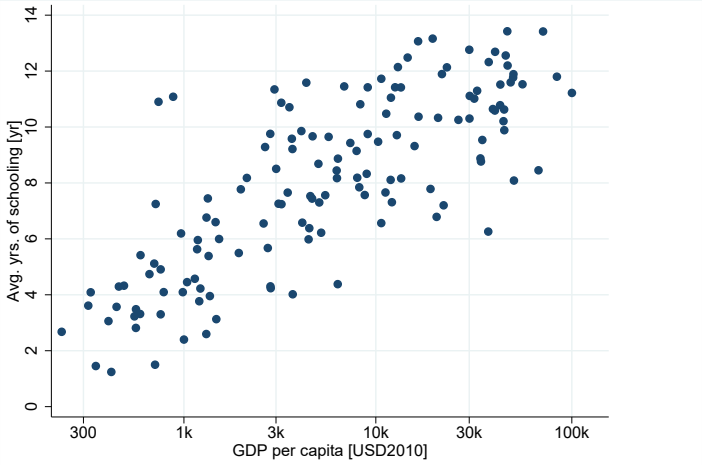


Figure 3.2.4: Fertility Rates and Education. *Source: Fertility Rates are taken from United Nation Population Division database.; average hours of education in 2010 are taken from the Barro and Lee database.*

Figure 3.2.5 shows that countries with the higher hours spent in education are those presenting lower fertility rate. This correlation suggests that influencing education could be effective to lower fertility rates while boosting economic growth.

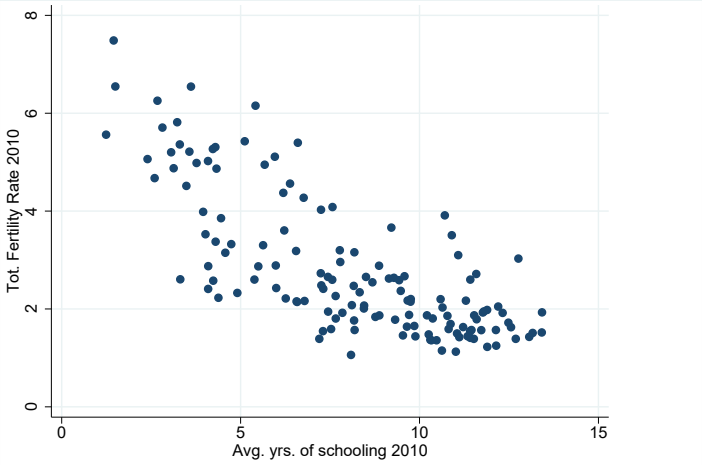


Figure 3.2.5: GDP Per Capita and Education. *Source: GDP per capita (constant 2010 US$) is taken from the WDI database, World Bank; average hours of education in 2010 are taken from the Barro and Lee database.*

Finally, to clarify the relationship between economy, population and environment, we consider historical emission data. In order to understand the links between those dimensions, we rely on a simplified Kaya identity, which decomposes changes in CO2 emissions as follows:

$$CO2 \equiv P \times \frac{GDP}{P} \times \frac{CO2}{GDP} \tag{3.2.1}$$

Equation (3.2) states that CO2 emissions can be expressed as a product of the following factors: population, P, income per-capita, $\frac{GDP}{P}$, and carbon intensity (emission per unit of energy consumed), $\frac{CO2}{GDP}$. If we think about those three factors as the drivers of CO2 emissions, we can learn something interesting.

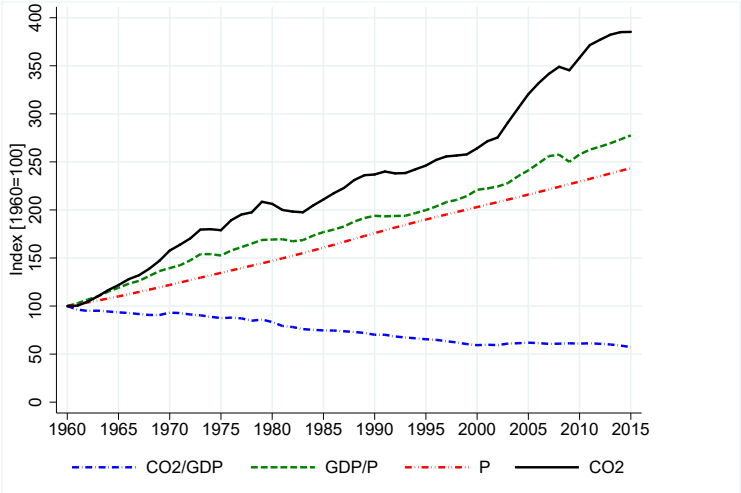


Figure 3.2.6: World Emissions (1960-2014) and Kaya's decomposition (1960-2014).
Source: Carbon Dioxide Information Analysis Center (2015 Data), United Nation Population Division and World Bank. *Notes*: CO2 emissions are emissions from fossil fuels and cement production. Carbon in tonnes is converted to CO2 in tonnes using the conversion factor 3.664. GDP is constant, 2010 US dollars

.

Figure 3.2.6 shows that total CO2 emissions (solid line) almost tripled from 1960 to 2014. Though the carbon intensity (dashed-dotted line) of the economy has been decreasing, there are two counteracting forces: income per capita (dashed line) and population (dotted line). The increases in possibilities of consumption boost emissions. The average per capita emissions, at the world level, is 4.5 tonnes while in the United States is around 18 tonnes; in poor countries the picture is different: for example in Africa the per capita emissions are around 1.20 tonnes (International Energy Statistics). Figure 3.2.6 shows that population is one driver of emissions. Since most of the future population growth will occur in developing countries, this will imply that the most populous countries will be at the same time the one fastest growing and therefore with growing level of consumption-per capita and emissions. The latest projections by the World Bank (WBG, 2017) state that the emerging market and developing economies are anticipated to grow 4.1 percent faster than advanced economies during the year 2018/2019 and that probably this will be the trend also in the future.

3.3 Fertility, Education and Climate Change

The model described in this work is a dynamic model. Therefore, our results will be influenced by both the relationships we imposed when building the model and the time dimension. The aim of this section is to highlight the links between the most significant variables, namely fertility, investment in education, income and emissions.

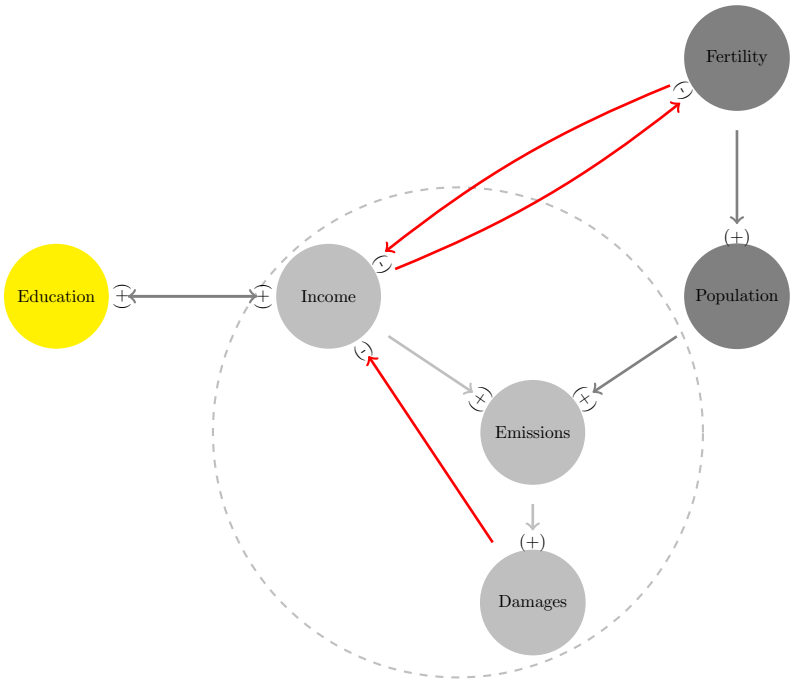


Figure 3.3.1: Links between fertility, the economy and climate change

Figure 3.3.1 gives an intuition about the main channels of the model. The arrows describe the direction of causality. We specify how we model the impact of each variables on the other one (positively or negatively) to replicate the stylized facts and evidence. Income and emissions are expressed per parents. Population and cumulative emissions, instead, are aggregates. Investment in education are expressed per child. Damages are represented as percentage loss in gdp. The relationship between income, emissions and damages is the "core" of climate-economy models: an increase in income boosts emissions, causing damages which in turn (negatively) impact "gross" income itself. Economic damages or impacts of climate change, is the thorniest issue in climate-change economics. These estimates are indispensable for making sensible decisions about the appropriate balance between costly emissions reductions and climate damages. However, providing reliable estimates of the damages from climate change over the long run has proven extremely difficult. In our model we follow Nordhaus and Sztorc (2013).

In Figure 3.3.1 this last relationship is represented by light-gray variables, which are included in a dashed circle. We add endogenous population's dynamics in this context. In the top-right of Figure 3.3.1 fertility choice affects total population where obviously higher fertility corresponds to larger population, abstracting from mortality. Moreover, fertility itself (negatively) impacts income: parents decide between time spent working or raising children. The more children they have, the less they work. Finally, investment in education (positively) affect income (increasing human capital) and the higher the income is, the more parents invest in their children's education.

The key contribution is the clear connections between economic, climatic and demographic variables. Population is a determinant of emissions. An increase in fertility boost emissions even if, at the same time, it reduces income allowing emissions to partially decrease. Therefore fertility is a indirect driver of climate change. To which extent it is an open question, addressed in this paper.

3.4 An Endogenous Fertility Model

We consider a 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) has put such a trade-off at the heart of the explanation of long-run growth and development. We then incorporate into this framework a climate module that enables us to investigate fertility decisions and its effect on climate change. As in standard growth models, variables are expressed in intensive form. In the present case we normalize by the number of parents N_t. We take all adults to be parents, even if it needs not to be the case in practice. We assume that only the current generation of parents work, whereas children are inactive. Thus, $l_t = L_t/N_t$ is the employment rate and L_t is the total labor force; $q_t = Q_t/N_t$is output per parent and Q_t is gross aggregate output; $c_t = C_t/N_t$ is consumption per parent and C_t is aggregate consumption; $s_t = S_t/N_t$ is education expenditures per parent and S_t are aggregate education expenditures. Thus, upper case letters denote aggregate variables.

3.4.1 Demographics

One period lasts 30 years in our model. Results will be expressed in terms of variables per period, so that aggregates are multiplied by M, where $M = 30$. Within a period, parents are of

age 15-45, the range that correspond to the fertility period of a woman. Total population, P_t, is given by:

$$P_t = N_{t-1} + N_t + \epsilon N_{t+1} \tag{3.4.1}$$

where old parents are represented by N_{t-1}, the current generation of parents is given by N_t and the future generations of parents N_{t+1}. The size of the generation in the next period, N_{t+1}, is multiplied by $\epsilon = \frac{1}{2}$, as babies are born uniformly over the period.[2] Given fertility f_t, the next generation's size (number of parents) is:

$$N_{t+1} = f_t N_t \tag{3.4.2}$$

3.4.2 Production technology

The economy produces one homogeneous good whose price is normalized to one. The linear technology is defined as

$$Q_t = \omega_t H_t \tag{3.4.3}$$

where Q_t is the production function determined by H_t which is human capital and ω_t the exogenous level of technology. Technology evolves according to:

$$\omega_{t+1}/\omega_t = \hat{\omega} \tag{3.4.4}$$

Productivity growth $\hat{\omega}$ is assumed to be constant and exogenous.[3] Following Lucas (1988), aggregate human capital is given by $H_t = h_t L_t$, so that the labor input is expressed in quality-adjusted or efficiency units. Substituting in (3.4.3) yields:

$$Q_t = \omega_t h_t L_t \tag{3.4.5}$$

Gross output per parent is given by:

$$q_t = \omega_t h_t l_t \tag{3.4.6}$$

where, as noted, l_t is the employment rate and h_t the "quality" of workers. Letting w_t be the wage rate, expressed in per quality workers, firms are assumed to maximize profits in a competitive environment:

[2] ϵ is the expected value of a uniform distribution.
[3] To keep the framework simple we do not model human capital accumulation.

$$\pi_t = q_t - w_t h_t l_t \tag{3.4.7}$$

The optimality conditions imply:

$$\omega_t = w_t \tag{3.4.8}$$

Wages are equated to the marginal productivity of workers. The dynamics of wages is governed by the evolution of the technology, which is exogenous.

3.4.3 Preferences

Our representation of the households sector follows de la Croix and Doepke (2003). Parents make decisions concerning the level of consumption c_t, the number of children, f_t and the expenditure in 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 earned wage.

The economy is composed by infinite overlapping generations who live for two periods: childhood and parenthood. Generations overlap as, at each point in time, two different generations are alive. Figure 3.4.1 shows how generations appear over the period. The superscript represents the period in which a generation was born and the subscript the period in which the generation is alive.

		Periods		
		t-1	t	t+1
Generations	t-2	$Adults_{t-1}^{t-2}$		
	t-1	$Children_{t-1}^{t-1}$	$Adults_{t}^{t-1}$	
	t		$Children_{t}^{t}$	$Adults_{t+1}^{t}$
	t+1			$Children_{t+1}^{t+1}$

Figure 3.4.1: Overlapping Generations

It is assumed here that adults do not save for their future consumption when old, but they save in terms of current consumption in order to provide education to their children. As said, adults are the only active agents. The preferences of each generation of parents t are represented

by the following logarithmic utility function, u_t:

$$u_t = ln(c_t) + \gamma ln(f_t h_{t+1}) \tag{3.4.9}$$

where c_t is consumption per parent, $\gamma > 0$ is the weight attached to children in the utility function, f_t is the fertility level chosen by parents and h_{t+1} represents the human capital, i.e. the quality of children.[4] Following de la Croix and Doepke (2003), the level of human capital of children, h_{t+1} is determined by:

$$h_{t+1} = (\delta + s_t)^{\eta} \tag{3.4.10}$$

we assume that all children are endowed with an exogenous positive level of quality captured by parameter $\delta > 0$ and interpreted as compulsory education; $\eta \in (0, 1)$ is the elasticity of human capital to education. The variable s_t is the investment choice of parents in the education of their children.[5] The level of human capital of children is an increasing strictly concave function of parental investment in children's education, so that $\frac{\partial h_{t+1}}{\partial s_t} > 0$ and $\frac{\partial^2 h_{t+1}}{\partial^2 s_t} < 0$. Notice that equation (3.4.10) does not depend on the level of human capital of parents, h_t. Parents can transmit wealth to children only by providing them with education.[6] Looking at equation (3.4.10), we can think of δ as compulsory education which is provided for free: if parents decide not to invest in the quality of their children, δ guarantees a minimum level of quality.

Parents are endowed with one unit of time which they allocate between child rearing and labor force participation. All parents supply one unit of labour inelastically. Their budget constraint is:

$$c_t + s_t f_t = w_t h_t l_t \tag{3.4.11}$$

where total income earned $w_t h_t l_t$ is spent in consumption and in education s_t multiplied by

[4]Notice that parents do not care about their children's well being, as would be in case of dynastic altruism. Instead, in this formulation, parents value directly the future human capital of their children. In other words, altruism is limited to one generation. Following Becker et al. (1973) and Galor and Weil (2000) this form of 'imperfect altruism' is called joy of giving or warming-glow.

[5]We have in mind college education: parents have to support their children economically, as long as the course of study does not end. That means, investment in education absorbs resources from parents' income. Belley and Lochner (2007) employing NLSY97 data, demonstrate that family income is an important determinant of college attendance and quality of college.

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

fertility f_t. The labour supply, l_t is inelastic, given by:

$$l_t = 1 - \phi f_t \tag{3.4.12}$$

where f_t is the number of children and ϕ is the time per child. Notice that the time parents spend raising their offespring, $\phi f_t < 1$, is deducted from labour supply. Parents maximize their utility (3.4.9) subject to the budget constraint (3.4.11), definition (3.4.10) and condition (3.4.12). Substituting (3.4.12) into (3.4.11) eliminates l_t. In turn, using the resulting budget constraint and definition (3.4.10) into the objective function yields an optimization problem with s_t and f_t as decision variables. The necessary conditions can be manipulated to yield the following closed-form expressions for optimal fertility and education expenditures:

$$f_t = \frac{(1-\eta)\gamma w_t h_t}{(\phi w_t h_t - \delta)(1+\gamma)} \tag{3.4.13}$$

$$s_t = \frac{\eta\phi w_t h_t - \delta}{1-\eta} \tag{3.4.14}$$

Plugging these expressions in (3.4.10) and (3.4.11) yields the following closed-form expressions for optimal human capital and consumption:

$$h_{t+1} = \left[\frac{\eta(\phi h_t w_t - \delta)}{1-\eta}\right]^{\eta} \tag{3.4.15}$$

$$c_t = \frac{h_t w_t}{1+\gamma} \tag{3.4.16}$$

Notice that all the optimal levels of the problem's choice variables (3.4.13)-(3.4.16) are functions of the wage adjusted by labour quality, $w_t h_t$, and of parameters η, δ, ϕ and γ.[7] In particular, equations (3.4.13) and (3.4.14) can be studied to see if our model is able to capture the quality-quantity children's trade-off highlighted by Becker et al. (1973). Equation (3.4.14) shows that parents decide not to invest in education if their wage falls below or is equal to a certain threshold. Specifically, if $w_t h_t \leq \frac{\delta}{\eta\phi}$ then:

$$s_t = 0 \tag{3.4.17}$$

$$f_t = \frac{\gamma}{\phi(1+\gamma)} \tag{3.4.18}$$

[7] See Appendix 3.B for the first order conditions of the problem.

If instead $w_t h_t > \frac{\delta}{\eta\phi}$ we obtain the interior solution shown in equations (3.4.13)-(3.4.14). If we consider the impact of $h_t w_t$ on f_t and s_t we see that:

$$\frac{\partial f_t}{\partial w_t h_t} = \frac{\overbrace{(1-\eta)\gamma[(\phi h_t w_t - \delta)(1+\gamma)] - \phi(1+\gamma)(1-\eta)\gamma h_t w_t}^{<0}}{\underbrace{[(\phi h_t w_t - \delta)(1+\gamma)]^2}_{>0}} \tag{3.4.19}$$

$$\frac{\partial s_t}{\partial w_t h_t} = \frac{\overbrace{\eta\phi}^{>0}}{\underbrace{(1-\eta)}_{>0}} \tag{3.4.20}$$

Concluding:

$$\frac{\partial f_t}{\partial w_t h_t} < 0 \tag{3.4.21}$$

$$\frac{\partial s_t}{\partial w_t h_t} > 0 \tag{3.4.22}$$

When $h_t w_t > \frac{\delta}{\eta\phi}$ parents indeed substitute quantity for quality of children. Thus the present model is able to generate the well-known quality-quantity trade-off.

3.4.4 Climate change

We now account for climate change into the above model of endogenous fertility choices. This enables us to allow for both environmental and population externalities and to analyse the interactions between demographic and climate policies. Following Nordhaus and Sztorc (2013), we begin by distinguishing per parent gross output, q_t, and net output, y_t, the latter being obtained after subtracting abatement, α_t, and climate damages, d_t. Net output is thus given by:

$$y_t = (1 - d_t)(1 - a_t)q_t \tag{3.4.23}$$

where a_t is the abatement rate. In turn, abatement is defined as follow:

$$a_t = \theta_1 \mu_t^{\theta_2} \tag{3.4.24}$$

where μ_t is the endogenous emission control rate and θ_1 and θ_2 are parameters.[8] Climate damages, d_t are given by:

$$d_t = 1 - exp(-\beta_1 CE_t) \tag{3.4.25}$$

This formulation of climate damages follows Golosov et al. (2014), where damages depends on cumulated historical emissions, CE_t.[9] Wages have to be scaled for the gap between gross and net output, so that equation (3.4.8) now reads:

$$w_t^{'} = (1 - d_t)(1 - a_t)w_t \tag{3.4.26}$$

This is the new profit maximizing condition associated with the optimal choice of quality workers. If damages and abatement impact output, wages will be affected too. The household budget constraint (3.4.11) has to be revised such that:

$$c_t + s_t f_t = y_t \tag{3.4.27}$$

where y_t is output net of damages and abatement costs. Only a fraction of the carbon dioxide (CO2) emitted stays in the atmosphere forever, thus inducing an increase in temperature (e.g. climate change) and ultimately causing a loss of output. Cumulative emissions, CE_t, evolve over time according to:

$$CE_{t+1} = CE_t + e_t M N_t \tag{3.4.28}$$

where CE_{t+1} represents cumulative emissions in period $t+1$, given by cumulated emissions in period t, CE_t, plus emissions per parents, e_t, multiplied by the total number of parents, N_t, and by $M = 30$, the number of years within a period. We are thus tracking the total stock of emissions per period. Cumulative emissions affect damages according to (3.4.25). Therefore, both emissions and fertility choices affect indirectly damages through their effect on cumulative emissions. Equation (3.4.28) represents the channel through which fertility decisions impact cumulative emissions and via equations (3.4.23) and (3.4.25) the whole economy.

Finally, emissions per parent, e_t, are proportional to gross output per parent and are reduced by abatement via the emission control rate:

[8] To obtain total abatement costs multiply equation (3.4.24) by gross output per parents, q_t, which yields a convex abatement cost function in abatement levels.

[9] Compared to Nordhaus and Sztorc (2013) we do not temperature dynamics, thus simplifying the climate module.

$$e_t = \sigma_t q_t (1 - \mu_t) \tag{3.4.29}$$

where σ_t represents the carbon intensity of the economy which is taken to exogenously decline at a certain rate as in Nordhaus and Sztorc (2013).

3.5 Calibration

We define a Balanced Growth Path (BGP) of this economy which serves the main purpose of calibrating five parameters $(\eta, \delta, \gamma, \phi, \hat{\omega})$ and three variables (N_1, ω_1, h_1) for the first period. Calibration is discussed at length in the following subsection.

3.5.1 Balanced Growth Path

In this model economy a BGP is a path along which the growth factor of the human capital, $\hat{h}$, and the growth factor of the exogenous technology level, $\hat{\omega}$, are constant. A "hat" denotes growth rates of variables. The dynamic system is governed by two difference equations:

$$\Lambda(h_{t+1}, h_t, \omega_t) = h_{t+1} - \left[\frac{\eta(\phi h_t w_t - \delta)}{1 - \eta}\right]^{\eta} \tag{3.5.1}$$

$$\Gamma(\omega_{t+1}, \omega_t) = \omega_{t+1} - \hat{\omega}\omega_t \tag{3.5.2}$$

where in equation (3.5.2), the growth factor of technology $\hat{\omega}$ is assumed to be exogenous and constant. In the long-run the fixed level of free education δ is negligible.[10] In this event (3.5.1) reduced to:

$$\hat{h} = (\hat{\omega})^{\frac{\eta}{1-\eta}} \tag{3.5.5}$$

Along the BGP, fertility, employment rate and the share of investments in education over output

[10] Nesting the production function (3.4.10), into equation (3.4.9), we see that preferences in this model are non homothetic, i.e. Stone Geary Utility function. In particular, the exogenous positive threshold δ implies that good s_t is income elastic. In a growing economy this means that parent will spend more than proportionally for s_t, as income grows. Therefore, in equation (3.4.10), δ will become progressively irrelevant. When $t \to \infty$ preferences become homothetic. From equation (3.4.10) we rearrange as:

$$h_{t+1} = s_t^{\eta} \left(\frac{\theta}{s_t} + 1\right)^{\eta} \tag{3.5.3}$$

$\lim t \to \infty$ of equation (3.5.3):

$$h_{t+1} = s_t^{\eta} \tag{3.5.4}$$

are all constant, depending only upon the model's parameters. Denoting with (x^*) constant variables along the BGP, we have:

$$f^* = \frac{(1-\eta)\gamma}{\phi(1+\gamma)} \tag{3.5.6}$$

$$l^* = (1-\phi f^*) \tag{3.5.7}$$

Taking the ratio between (3.4.6) and (3.4.14) yields:

$$\left(\frac{s}{q}\right)^* = \frac{\eta\phi}{(1-\eta)(1-\phi f^*)} \tag{3.5.8}$$

In addition:

$$\hat{s} = \hat{h}\hat{\omega} \tag{3.5.9}$$

We see that the growth factor of investments in education, $\hat{s}$ is constant and equal to the growth rate of the product between human capital and technology level, $\hat{h}\hat{\omega}$, which are constant along the BGP. Consumption is given by:

$$\hat{c} = \hat{h}\hat{\omega} \tag{3.5.10}$$

which shows that the growth factor of consumption, $\hat{c}$, is constant and equal to the growth factors of the product between human capital and technology $\hat{h}\hat{\omega}$. From equations (3.5.9) and (3.5.10) we get:

$$\hat{s} = \hat{c} = \hat{h}\hat{\omega} \tag{3.5.11}$$

Along the BGP the growth factors of investment in education and of consumption are constant and equal to the growth rate of the product between human capital and technology level.[11]

3.5.2 Calibration

The first year of our model is 2035 and each period lasts 30 years. We calibrate the initial number of parents, N_1 using equation (3.4.1). We start the first period $(2020-2050)$ with 8 billion people. Thus $P_1 = 8 = N_0 + N_1 + 0.5N_2$. In the 30 years before our starting date,

[11] See **Appendix 3.B** for the above derivations.

$1990-2020$, the fertility rate was around 33 % implying $N_0 = N_1/(1+0.33)$. In the first period of our model, population growth is about 25 %. Thus:

$$N_2 = (1+0.25)N_1 \tag{3.5.12}$$

which, together with equation (3.4.1), yields:

$$8 = \frac{N_1}{1+0.33} + N_1 + 0.5(1+0.25)N_1 \tag{3.5.13}$$

Solving for the initial number of parents we obtain N_1 equal to 3.5 billion parents: $N_1 = 3.5$.

In the literature ϕ, the time-cost of children, is between 15% and 30% (Haveman and Wolfe, 1995; Knowles, 1999; de la Croix and Doepke, 2003). We set $\phi = 0.2$, implying that parents spend about 20 % of their time raising children. We make the assumption that, in the long-run, fertility is equal to one, i.e. $f^* = 1$. Recalling that fertility in our model represents number of children per parent, in the long-run each couple will have two children and total population will stabilize around its replacement level. Considering $f^* = 1$, the share of education expenditures over output in equation (3.5.8) becomes constant:

$$\frac{s}{q} = \frac{\eta\phi}{(1-\eta)(1-\phi)} \tag{3.5.14}$$

We take the ratio $\frac{s}{q}$ equal to 0.2, meaning that parents spend on average 20% of their income in the education of children. [12]

Given our assumptions on fertility and education expenditure share, together with the imputed value of ϕ, we determine η equal to 0.445. This value is in the range of estimates of returns from education (de la Croix and Doepke, 2003). Substituting for the values of ϕ, η and $f^* = 1$ we can solve for the parameter representing the preference of parents for children, $\gamma = 0.5625$. From equation (3.5.5):

$$\hat{h}\hat{\omega} = (\hat{\omega})^{\frac{1}{1-\eta}} \tag{3.5.15}$$

A long run output growth of 60% per parent implies $\hat{\omega}\hat{h} = 1.6$; together with the assumed value of η we find the growth factor of the technology level to be $\hat{\omega} = 1.24$. This is consistent with the growth of GDP per capita rate in 2016 reported by the World Bank national accounts data.

[12] These expenditures in education are relative to tertiary education. The average of household's expenditure in education for OECD countries is even higher (30%).

According to the United Nations database on population, instead, the fertility rate in the first period is equal to $f_1 = 1.25$. Then, from (3.4.12), we calculate the initial value of the employment rate, $l_1 = 0.75$. The initial value of per parent output is calculated as $q_1 = Q_1/N_1$, so it is the fraction between Q_1, gross output in the initial period and N_1, the number of parents in the initial period. We know that $N_1 = 3.5$ billion whereas the value for $Q_1 = 75.54$ trillions of dollars is taken from the World Bank database. This yields the ratio 0.0216 million of dollars. From equation (3.4.6) we then obtain $q_1/l_1 = \omega_1 h_1 = 0.0288$ million of dollars. Next, substituting all known values in equation (3.4.13) we are able to isolate δ which is equal to 0.00115 million dollars. The value of δ is the public expenditure of governments in education, meaning the minimum level granted by the institutions. Substituting the optimal expression for s in (3.4.16) into (3.4.10) it is possible to determine the initial level of children quality, $h_1 = 0.08286$ where we have assumed $\omega_0 h_0 = \omega_1 h_1$.[13] Finally, from the production function (3.4.6) we obtain the initial level of technology equal to $\omega_1 = 0.34730$.

We now turn to the calibration of the climate module. Total world industrial emissions from fossil fuels, E_t, were in 2015 equal to 36 $GtCO2$ (giga tonnes), so that $E_1 = 0.036$ $TtCO2$ (tera tonnes). Emissions per parent, e_t, are given by E_t/N_t. Since $N_1 = 3.5$ billions, we obtain $e_1 = E_1/N_1 = 0.010$ $KtCO2$ (kilo tonnes) per parent per year. Assuming now $\mu = 0$, from (3.4.29) we can calculate the initial value of $\sigma_1 = e_1/q_1 = 0.463$. Thus 0.538 $tCo2$ per thousand euros is the initial level of carbon intensity of the economy. In the very long-run we impose $\mu = 0$, implying that we assume no abatement due to improvements in carbon-saving technology and past climate policy.

The last step is to calibrate the parameters of abatement and damage functions. To this end we note that the pre-industrial level of GHG concentrations in the atmosphere was 280 $ppmv$ of carbon (see Chapter 8.3.2 of IPCC, 2014), which corresponds to 2.17 $TtCO2$. Doubling this value may lead to irreversible climate events due to the subsequent increase in temperature. The IPCC (2014) Chapter 6, page 472 states that about 50% of a CO2 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. Nevertheless scientist are uncertain regarding these percentages: Archer et al. (2009) suggest that between 20% and 35% of CO2 remains in the atmosphere for centuries. To calibrate β_1 we assume that about 30% of cumulated emissions remain in the

[13] The quality of children is a function of the level of education obtained. Moreover, this will affect the future wage the children will be able to earn.

atmosphere for thousands of years. The amount of cumulated emissions necessary to double the concentration level of CO2 in the atmosphere is equal to $2.17\ TtCO2/0.30 = 7.23\ TtCO2$. So we need to emit about $7.23\ TtCO2$ in order to double the concentration level of this pollutant in the atmosphere. If that happens, we may reach a temperature increase of at least 3 degrees relative to pre-industrial levels. Early estimates projected that a doubling of atmospheric concentration would yield damages equal to few percentage points of GDP. In his paper, Tol (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% and 5%. For all these reasons we impose that doubling concentration level in the atmosphere may cost up to 3% of world GDP. We calibrate β_1 by solving (3.4.25), i.e. $exp(\beta_1 CE) = 1 - d = 0.07$ or $exp(7\beta_1) = 1 - 0.03 = 0.97$, which yields $\beta_1 = 0.0042$.

Following Nordhaus and Sztorc (2013), suppose now that 100% of abatement costs equals 7% of aggregate GDP and that the abatement function (3.4.24) is quadratic, so that $\theta_2 = 2$. This in turn implies $\theta_1 = 0.07$, where we have assumed, as said, that $\mu = 0$. World cumulative emissions between 1750 and 2011 amount to 405 GtC, corresponding to 1.48 $TtCO2$ (IPCC (2014), p. 474). All parameters and initial values of the model variables are listed in Table 3.5.1 and Table 3.5.2 respectively.

Parameters	Description	Value
α_t	Welfare Weights	0.8
γ_1	Preference for children	0.5625
ϕ	Opportunity cost of children	0.2
η	Elasticity of human capital to education	0.445
δ	Compulsory school	0.00115
$\hat{w}$	Long-run economic growth	1.24
β_1	Exponent in damage equation	0.0042
θ_1	Abatement Coefficient	0.07
θ_2	Abatement Exponent	2

Table 3.5.1: List of Parameters

Parameters	Description	Value
N_1	Number of Parents [bn]	3.5
q_1	Output [mn \$/per parents yr]	0.0216
f_1	Fertility [children per parents]	1.25
$(s/q)_1$	Investment in education [fraction of per parents output]	0.2
l_1	Employment rate [FTE per parents]	0.75
w_1	wage/labor productivity [K\$/labourer]	0.34730
$w_1 h_1$	wage/labor productivity adjusted by quality [K\$/labourer]	0.0288
h_1	human capital	0.08286
σ_1	Emission Intensity [tCO2/1000 \$ per parents]	0.463
e_1	Emissions [KtCo2/per parents]	0.010
CE_1	Cumulative emissions [TtCo2]	1.48

Table 3.5.2: List of Initial Values

3.6 Scenarios and Policies

3.6.1 Social Welfare Functions and Ethics

Any economic model to estimate an optimal policy requires a social welfare function (SWF) to evaluate the trade-offs the society faces in its policy choices. There are two main formulations of SWFs in the climate change and endogenous fertility literature: the Millian SWF, which considers the average utility of the representative agent and the Benthamite SWF, which values the total utility distributed in the economy. These formulations represent two different ethical approaches to value human population. Both SWFs have advantages and disadvantages, which are well explored in the economic and philosophical literature on social choice and welfare.[14] The paper by Scovronik et al. (2016) considers the population ethics in relation to climate change mitigation. They notice that integrated models of climate and the economy, like DICE (Nordhaus and Sztorc, 2013), usually consider a Benthamite SWF. Large set of papers dealing with optimality in endogenous fertility models, instead, attribute a Millian objective to the Social Planner.[15] In this paper we chose for simplicity to follow the literature on endogenous fertility and we adopt the Millian's SWF, V of this form:

$$V = \sum_{t=1}^{T} \alpha_t u_t \tag{3.6.1}$$

where α_t are the welfare-weights, i.e. the discount factors of utilities between generations and $T = 21$ periods. The welfare weights are the most uncertain parameters. Their estimates are not unique and the literature is mixed: the values vary between $\alpha_t = 0.970$ (Nordhaus,

[14] See Razin and Yuen (1995); Blackorby et al. (2002, 2005) among others.
[15] See Groezen et al. (2003), Zhang (2003) and Zhang and Zhang (2007), among many other papers.

1993), $\alpha_t = 0.98$ (Weitzman, 2007) and $\alpha_t = 0.999$ (Stern, 2007). Nordhaus (2014) and Gerlagh et al. (2017) show that the discount factor between generations is important in determining the social cost of carbon. In the following simulations, after adjusting for the number of years in each periods (30 years), we assume $\alpha_t = 0.8$.

The first scenario is the *Baseline* run, where emissions are uncontrolled. It is the benchmark scenario, against which the outcomes of other scenarios are compared. Then, the second scenario is the *Climate Policy* run, in which the climate policy is optimally determined. Finally, the third scenario is the *Climate Change and Education Policy* run, where a mixed climate-education policy is implemented. More precisely:

(a) *Baseline ("BAU")*: it projects the levels and growth of economic and environmental variables as would occur without any policy. It does not consider social desirability of income distribution across generation over time.

(b) *Climate Policy ("clim. policy")*: it describes an equilibrium where consumers maximize their own welfare without considering climate change. In this context, the emission control rate μ is optimal and an optimal carbon price, i.e. carbon tax is determined. This scenario shows us the effect of a climate policy in an endogenous fertility model.

(c) *Climate Change and Education Policy ("educ. & clim. policy")*: considering the same social welfare function as in (3.6.1), a mixed climate-education policy is optimally determined. This scenario describes a double set of instruments aimed at mitigating emissions, directly through the climate policy and indirectly via the education policy, which will affect both fertility and emissions.

3.6.2 Education Policy

The idea of a global education policy aimed at increasing quality of children through investment in education is grounded in the reality: the fourth Sustainable Development Goals (SDGs)[16] is to *"ensure inclusive and quality education for all and promote lifelong learning"*. The SDG framework does not distinguish between developed and developing countries, so our model seems a good tool to test the effect of such a policy. Moreover there is extensive evidence (Becker et al., 2010) that fertility and education are negatively correlated, in particular women's education.

[16]The Sustainable Development Goals (UN, 2015a) replaced the Millennium Development Goals (MDGs) which ended in 2015.

So an education policy may obtain two different goals: (1) it lowers the number of children per woman; (2) it may helps in decreasing future emissions.

To implement the education policy, the budget constraint in equation (3.4.11) is modified as follows:

$$c_t + [(1+\tau_t)s_t]\, f_t = w_t h_t (1-\phi f_t) + Z_t \tag{3.6.2}$$

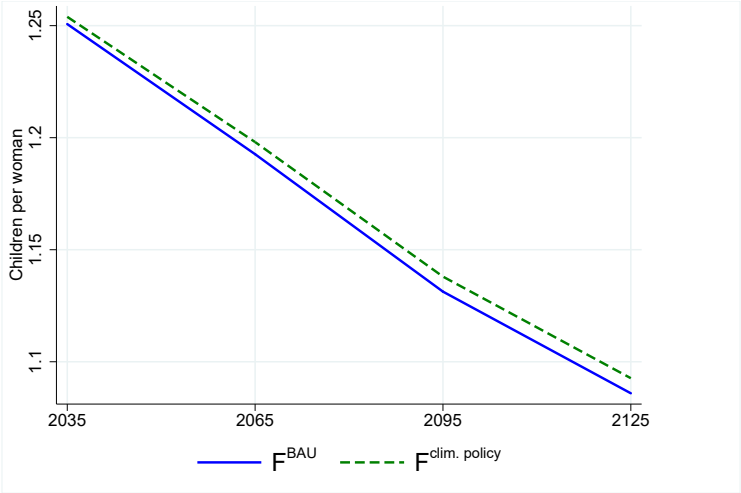
where τ_t represents the education policy and Z_t are the lump-sum transfers from the government, chosen such that $Z_t = \tau_t s_t f_t$. In Appendix 3.B we compute the new first order conditions which will be used to determine the optimal τ_t. The policy variable τ_t is a "free" variable, meaning we do not know *a priori* if it will be optimal to tax or to subsidize education in our context.

3.7 Results

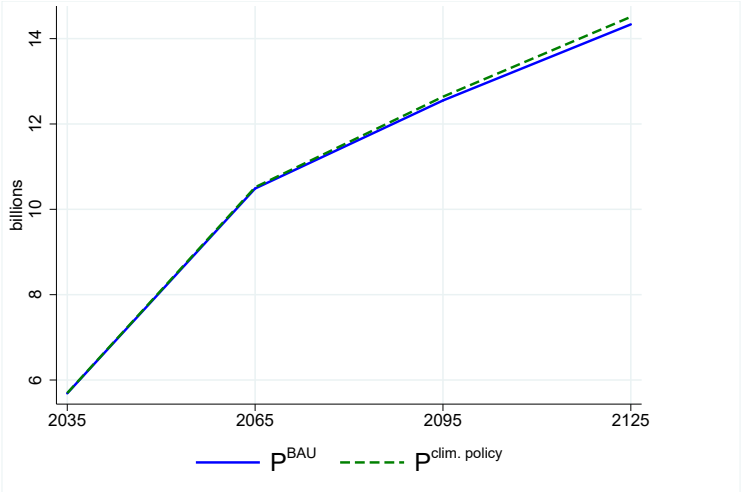
In this section we present the results of our simulations for some key variables. In particular, to understand the implications of each policy on demographic variables, we report the paths of fertility, F and total population, P. Then, we show the projections for two economic variables, income net of damages and abatement costs, GDP and investment in education, $EDU\ EXP$. On the climate side, we consider emissions per parent, E the emission control rate, μ aggregate cumulative emissions, CE and the education policy variable, τ. When possible we discuss about the implications of each policy on the social cost of carbon, SCC and the carbon price, CP.

The inclusion of an overlapping generation structure with endogenous fertility and education choices is non standard in the climate change economics literature. Here below, in Figures 3.7.1-3.7.3 we show the baseline (solid lines) in comparison with the climate policy scenario (dashed lines). Then, in Figures 3.7.5-3.7.7 we carefully investigate the implications of a climate change and education policy scenario (dotted lines), depicting for each variable the three scenarios together. Finally, Figure 3.7.4 and Figure 3.7.8 discuss the implications of endogenous population on the social cost of carbon and the carbon price. Moreover, Figure 3.7.8 shows the resulting optimal policy on education.

The model runs for several periods. In the following figures, we show the results until the end of this century. We are dealing with a global model with global policies, so the choice of representing this length of time is grounded in the fact that such policies need many decades to be effective.



(a)



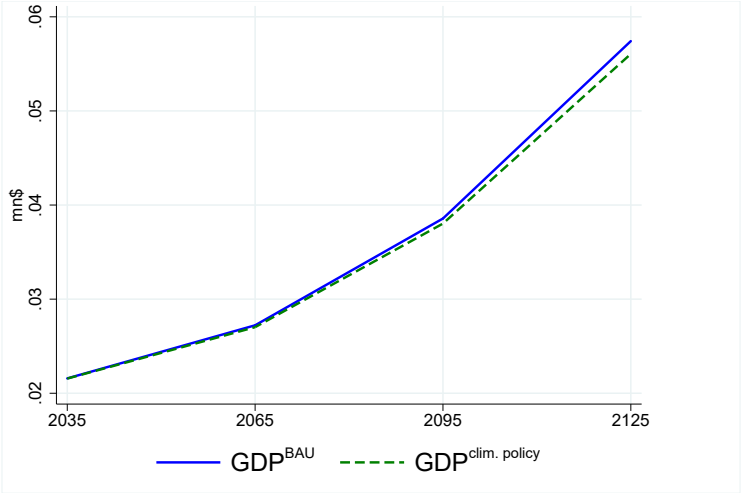
(b)

Figure 3.7.1: Simulation's Results. Panel (a): Fertility. Panel (b): Total Population.

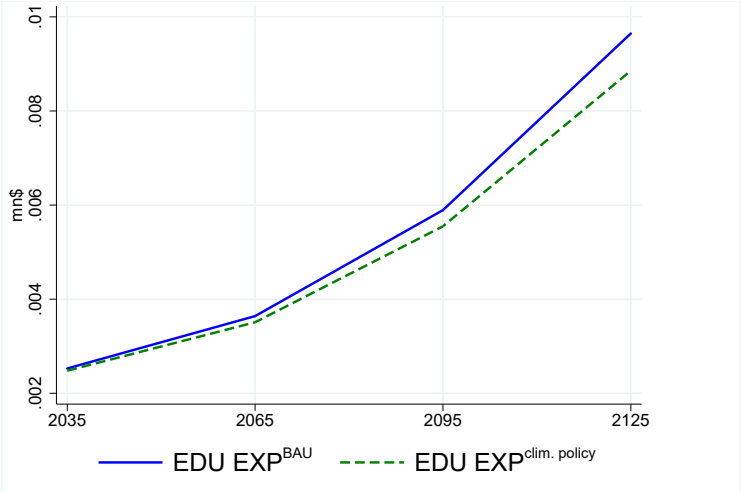
.

As concern the demographic variables, Figure 3.7.1 in Panel (a) reports fertility. Baseline fertility, F^{BAU} is decreasing and by the end of this century it stabilizes at one children per parent. In Panel (b) total population, P^{BAU} reaches 14 billion of people[17] and then it stabilizes in the subsequent periods as a result of constant fertility. Under the climate policy scenario, fertility, $F^{clim.policy}$ and total population, $P^{clim.policy}$ are higher compared to the BAU. An explanation can be found in de la Corix and Gosseries (2012). They demonstrate that, in an endogenous fertility model with a climate externality, a tax on emissions encourages agents to substitute some of the polluting production with tax-free activities, such as procreation. If this intuition is correct, we expect income to be lower in the climate policy scenario.

[17]Consistently with the medium-variant projections of the United Nation (UN, 2017).



(c)

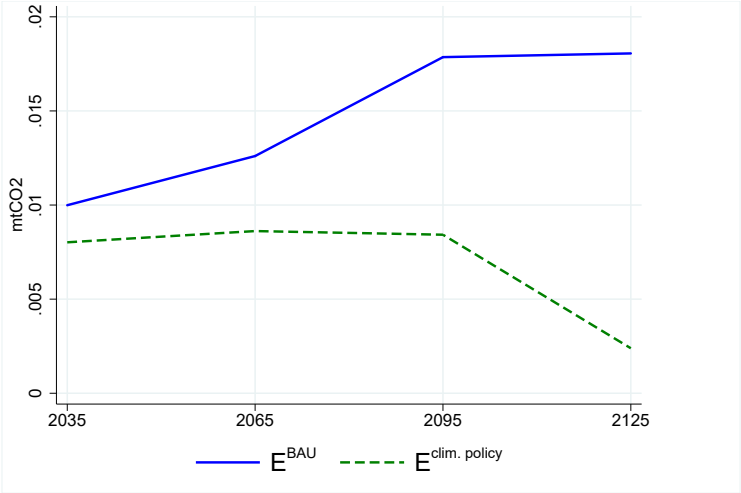


(d)

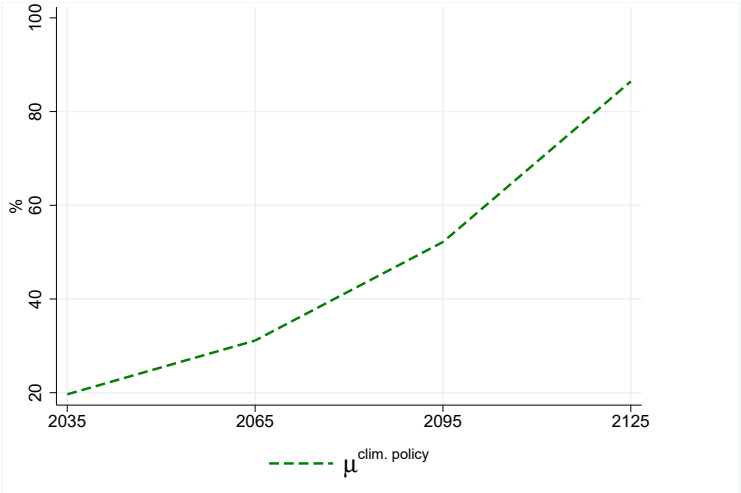
Figure 3.7.2: Simulation's Results. Panel (c): Income net of damage and abatement costs. Panel (d): Investment in education.

.

In Figure 3.7.2, an increasing income, as reported in Panels (c), is associated with growing investment in education, as depicted in Panel (d). This is again consistent with the quality-quantity trade-off mechanism described in Section 3.4.3. The effect of the climate policy is to lower income, $GDP^{clim.policy}$ compared to the baseline, GDP^{BAU}. Due to climate policy parents are poorer, meaning that their income is diminished by the carbon tax, and so fertility increases. As parent have more children and less economic resources at disposal, they decide to invest less in the education of their offspring, as shown by $EDU\ EXP^{clim.policy}$. The climate policy emphasizes the quality-quantity mechanism of our model. So far, the model matches several stylized facts described in Section 3.2. The next figures focus on the climate variables.



(e)



(f)

Figure 3.7.3: Simulation's Results. Panel (e): Emissions. Panel (f): Emission control rate.

.

In the baseline run emissions, E^{BAU} are exogenous, meaning that the link between damages and emissions is not considered as well as the impact of climate change on output. In Figure 3.7.3 in Panel (e), the path of baseline emissions is standard: they increase through time, stabilizing by the end of this century. In the climate policy scenario, instead, emissions, $E^{clim.policy}$ are lower compared the baseline. They slightly increase in the first periods and then decrease, reaching almost zero by the end of this century. When the climate policy is implemented, the level of abatement is endogenously determined by the model. Panel (f) shows the emission control rate, $\mu^{clim.policy}$ which in the first period is around 20%. Though the model never reaches full abatement, i.e. 100%, as time passes by and the economic costs of climate change increase,

optimal abatement increases too and the model reaches 80% of abatement by 2100.

The results in Figures 3.7.1-3.7.3 are a consequence of the inclusion of the endogenous fertility channel. The decrease in emissions due to abatement entails a loss in terms of income for future generations. This loss is even intensified by the quality-quantity mechanism as the decrease in income induces parents to invest less in the education of their children, negatively affecting future economic growth. In such a context fertility is higher and consequently the size of population increases too, boosting future emissions.

Our model shows that a climate policy induces an indirect effect on fertility which may deteriorate the environment further in the long-run. Demographic patterns must be endogenously modeled and proper climate policies should be designed to carefully take this dimension into account. In order to offset the adverse effect of population on emissions, we need a second instrument (Harford, 1998; Bohn and Stuart, 2015). As also de la Corix and Gosseries (2012) highlight, there are two possibilities to achieve lower emissions level: reducing production per capita or containing future population size.

Before describing the mixed climate-education policy scenario, we report the social cost of carbon and the carbon tax computed under the climate policy scenario.

The social cost of carbon (SCC) is an important output of integrated economic models of climate change and economy. The SCC is defined as *"the net present value of future damages associated with one extra unit of emissions"*. It is a measure of the social cost of emissions and is important for policymakers to set the proper carbon price (or carbon tax). The carbon price is defined as *"the additional decrease in GDP when decreasing emissions by an additional unit of CO2"*. This is a concept that measures the market price of CO2 emissions. [18] The "optimal" carbon price is the price on emissions that balances the incremental costs of reducing emissions with the incremental benefits of reducing climate damages. In an optimal regime, the carbon tax coincides with the social cost of carbon (Nordhaus, 2014). The SCC is affected by the discount factor, i.e. the welfare wights, attached to future generations. In Section 3.8 we will perform some sensitivity analysis on this parameter, α_t. In the current simulations, the discount factor is imposed equal to 0.993, a value which lies in the range of estimates usually considered in the literature (Gerlagh et al., 2017). According to Stern's view (Stern, 2007), we give a high weight to future generations. Every period in our model is made by 30 years, so the welfare weights

[18] In a market environment, such as a cap-and-trade regime, the carbon prices would be the trading price of carbon emission permits. In a carbon-tax regime, these would be the harmonized carbon tax among participating regions (Nordhaus and Sztorc, 2013).

should be raised at the power of 30.

(g)

(h)

Figure 3.7.4: Simulation's Results. Panel (g): The Social Cost of Carbon and carbon price with endogenous fertility. Panel (h): The Social Cost of Carbon and carbon price with exogenous fertility.

Figure 3.7.4 in Panel (g) shows the carbon prices, $CP^{end.pop.}$ and the social cost of carbon, $SCC^{end.pop.}$ resulting in our model of endogenous fertility under a climate policy. The interesting result is that the two measures do not coincide. The social cost of carbon in 2035 and 2065 is, respectively, 75$ and 102$, while the corresponding carbon price is 30$ and 60$. The "gap" is due to the presence of endogenous fertility. In order to test this intuition, we impose fertility to be exogenous[19]. In Panel (h) we report the resulting $SCC^{exog.pop.}$ and $SCC^{exog.pop.}$ under the same climate policy as before. Notice that carbon prices and the SCC coincide again.

[19]To impose exogenous fertility, we program and solve the model consecutively two times; after the first solving we fix the level of fertility and we solve the model again. In this way we eliminate the effect of endogenous fertility on carbon prices.

The reason for the discrepancy between the SCC and the CP in Panel (g) is subtle and needs more explanations. In the climate policy scenario with endogenous fertility, the choice of agents about how many children to have is given. Since the planner cannot internalize the effect of fertility on climate policy, she/he sets lower carbon prices with respect to the SCC, as shown in Figure 3.7.4. This is a $second - best$ solution and the result is driven by the presence of endogenous fertility choices. The linkages between fertility and emissions can be understood looking at some equations. In equation (3.4.28), fertility affects total number of parents, which contribute in determining the level of cumulative emissions. The level of atmospheric concentration of CO2 is responsible of damages due to increases in temperature, meaning that cumulative emissions trigger climate change. Considering equation (3.4.29) the effect of fertility on climate is even clearer, as the number of children impacts emissions through the production function.

When choosing how many children to have, individuals do not consider the burden imposed by each newborn on the environment. As (Harford, 1998; Bohn and Stuart, 2015) highlight, there is a population externality problem. In this work we are not explicitly computing the externality[20]. Nevertheless, we can clearly see, through simulations, that endogenous fertility is driving the results. So, in a model of climate, economy and endogenous demography, a climate policy is not sufficient to correct for all the externalities. Moreover, the underlying quality-quantity trade-off in the economic module even emphasize the effect of fertility and, as a matter of fact, carbon prices should be halved as shown in Figure 3.7.4 in Panel (g).

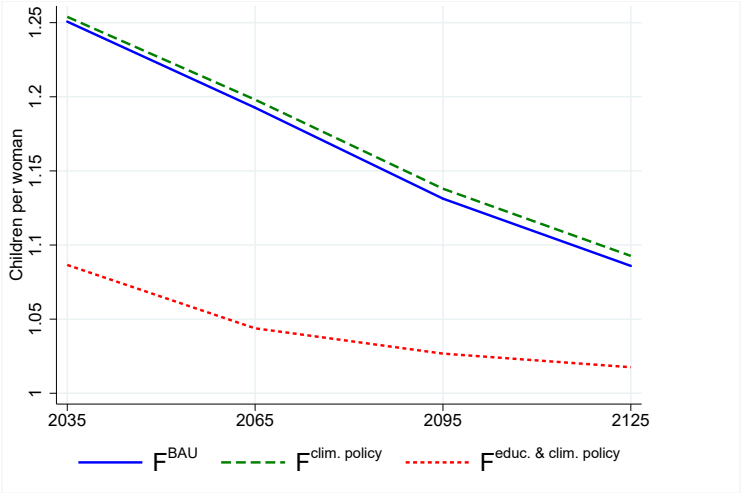
In order to internalize the externality induced by endogenous fertility, we need a second instrument, meaning a population policy. This is the aim of our third scenario where we implement a policy-mixed scenario, so a climate policy together with a demographic one. Instead of directly taxing fertility as in Harford (1998); Bohn and Stuart (2015), we decrease the cost of investment in education through a subsidy.[21] This third scenario is called *Climate Change and Education Policy*.[22]

In order to understand the improvements, if any, we depict together the baseline, the climate policy scenario and the climate change and education policy scenario for each of our key variable.

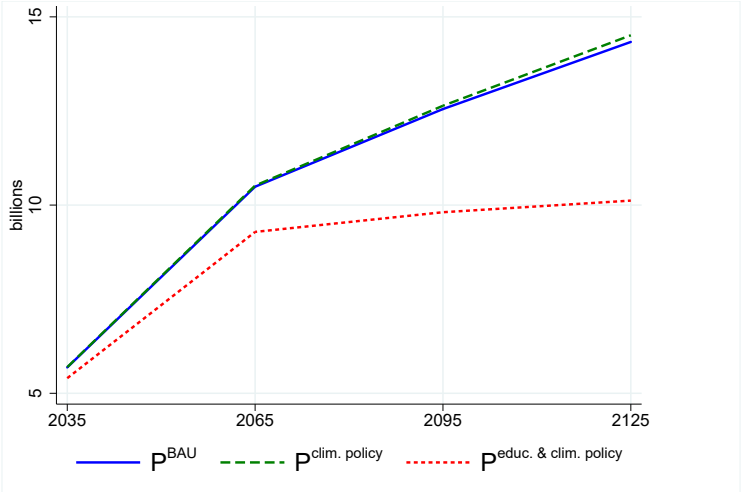
[20]This is the aim of another paper, which is an extension of this chapter, see Gerlagh, Lupi and Galeotti (2018).

[21]The paper by Bauernschuster et al. (2016) explores the effect of a universal childcare on fertility. Their data reveal that increases in public child care have significant positive effects on fertility. We are not dealing with child care in our model. We are just considering the possible effect of a policy which increases education and its effect on fertility choices (IIASA, 2014).

[22]Notice that the education policy is optimally computed, meaning that, through time, it can result in a tax on education or in a subsidy. Anyway, we expect this second instrument to correct for the population externality, so we expect it to be a subsidy.



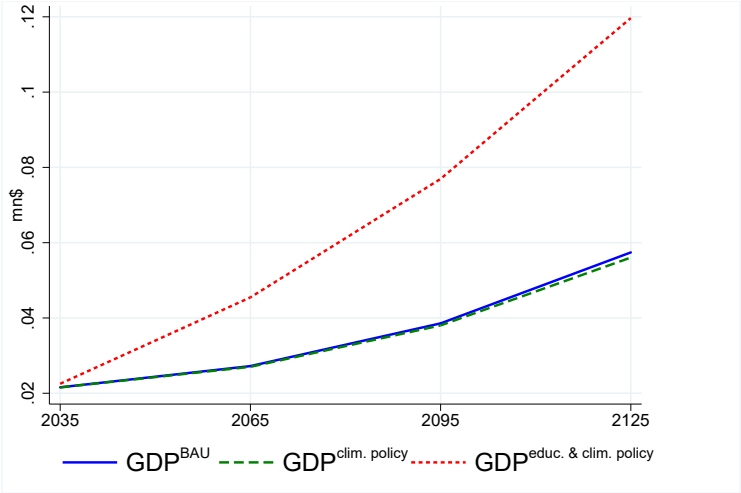
(a)



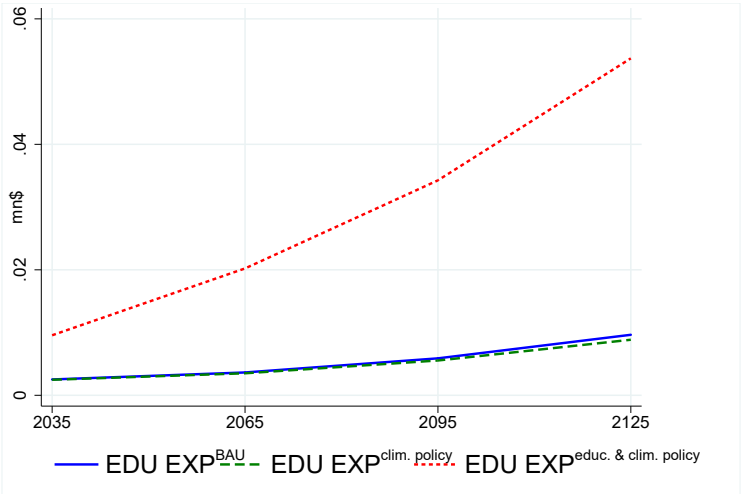
(b)

Figure 3.7.5: Simulation's Results. Panel (a): Fertility. Panel (b): Total Population.

In Figure 3.7.5, Panel (a) optimal fertility, $F^{educ.\&clim.policy}$ is lower compared both to the baseline and the climate policy scenarios. Population, $P^{educ.\&clim.policy}$ in Panel (b) peaks in 2065 and then stabilizes around 10 billion of people, so 4 billions of people less compared to the other scenarios. This outcome is very important in terms of environment preservation and sustainability. An instrument which indirectly affects fertility and then population, is effective in diminishing population's size. In the following figures we show the effects of this mixed policy on income and investment in education.



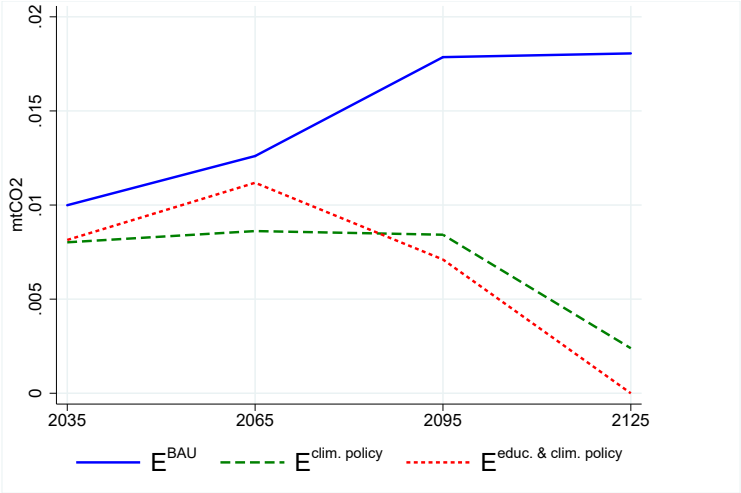
(c)



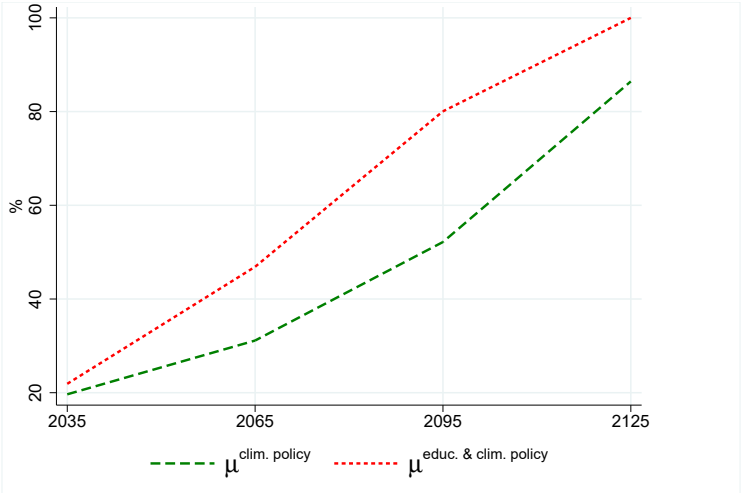
(d)

Figure 3.7.6: Simulation's Results. Panel (c): Income net of damage and abatement costs. Panel (d): Investment in education.

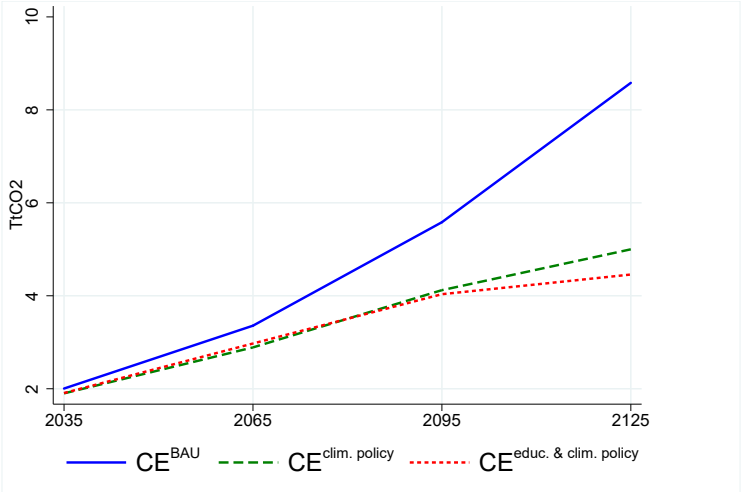
In Figure 3.7.6 Panel (c) income, $GDP^{educ.\&clim.policy}$ doubles with respect to the baseline and the climate policy scenarios. The result is still emphasized by the quality-quantity trade-off underlying the model, as richer people with less children invest more in education. As a matter of fact, In Panel (d) we notice that investment in education, $EDU\ EXP^{educ.\&clim.policy}$ have a similar trend to income. Coherently with the previous analysis, we now turn to the climate variables.



(e)



(f)



(g)

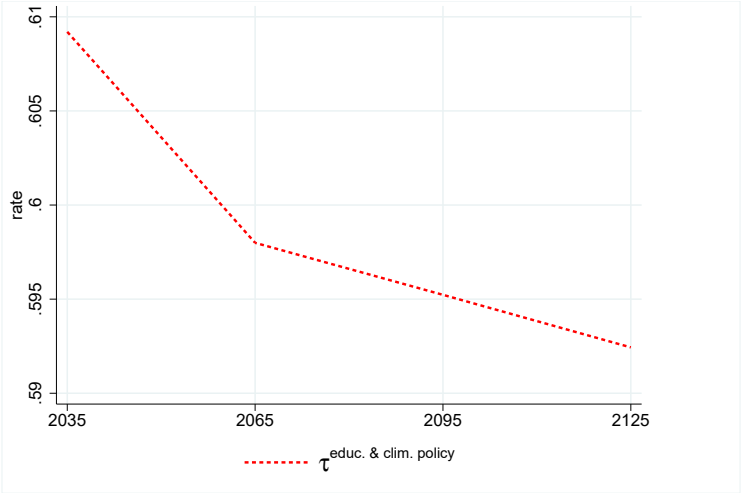
Figure 3.7.7: Simulation's Results. Panel (e): Emissions. Panel (f): Emission control rate. Panel (g): Cumulative Emissions

In Figure 3.7.7 Panel (e) optimal emissions, $E^{educ.\&clim.policy}$ are lower compared to the baseline case, but higher in the first two periods with respect to the climate policy scenario. This is due to the increase in investment in education which boosts the quality, so human capital of future adults. The consequent increase of output[23] determines higher level of emissions in the first two periods. Then, emissions decrease faster compared to the climate policy case as a result of higher abatement, $\mu^{educ.\&clim.policy}$ as shown in Panel (f).

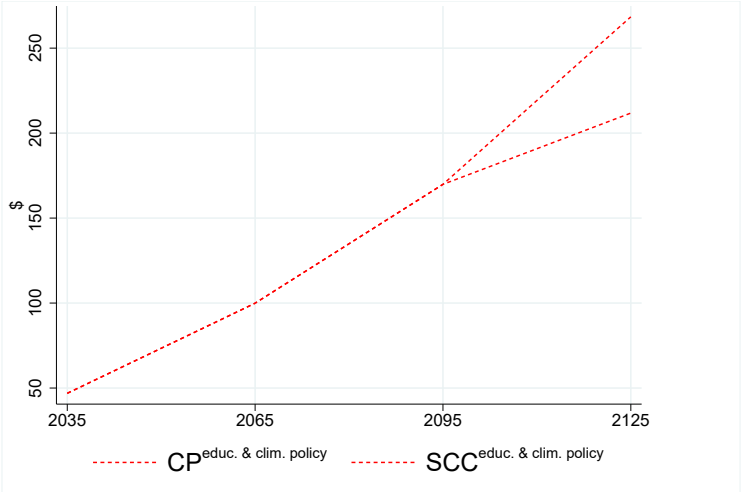
In Figure 3.7.7 Panel (g) we report the cumulative emissions, CE for each scenario. The aim is to gain an intuition about the increase in temperature implied by each scenario. Accordingly with the IPCC analysis (IPCC, 2014), 7 teraton of cumulated emissions in the atmosphere correspond to an increase of 3 degrees Celsius with respect to pre-industrial level. Cumulative emissions, CE^{BAU} in Panel (g) shows that in the baseline scenario the temperature increase is above 3 degrees Celsius by 2100. In the climate policy scenario, $CE^{clim.policy}$, instead, cumulative emissions stabilize at $5Tt$ while in the climate change and education policy scenario, $CE^{educ.\&clim.policy}$ reach $4Tt$. Though we cannot completely avoid an increase in temperature by the end of the century, a mixed climate-population policies may help in decreasing the expected boost in temperature and so climate change.

Then, population and fertility choices are important determinants of climate change. Policies able to influence fertility, like an education policy, should be part of the discussion regarding climate change mitigation and sustainability again. In the remind of this section, we analyze the behavior of the optimal education policy together with carbon price and the social cost of carbon.

[23] Looking at equation 3.4.5, human capital is an input in the production function.



(h)



(i)

Figure 3.7.8: Simulation's Results. Panel (h): Optimal tax on fertility. Panel (i): Optimal Carbon tax.

Figure 3.7.8 in Panel (h) reports the optimal subsidy[24], $\tau^{educ.\&clim.policy}$ to education, which induces parents to have less children and to invest more in their quality. As expected, In Figure 3.7.8 in Panel (i), the carbon prices, $CP^{educ.\&clim.policy}$ coincide with the social cost of carbon, $SCC^{educ.\&clim.policy}$, as all the externalities in the model are internalized.[25]

The following section performs some sensitivity analysis on the discount factor to understand how this will affect our results.

[24]Note that we define the optimal education policy a subsidy as in the optimization procedure the value assumed by τ is negative. In Figure 3.7.8, instead, we report it as positive just for simplicity.

[25]Notice that the two measures diverge again after the third period. The explanation is the following: as soon as the economy reaches full abatement ($\mu_t = 100\%$), there is no point in keep on increasing the carbon prices. When emissions are equal to zero, the carbon price stays constant. From that point onwards the gap between the social cost of carbon and carbon price is meaningless.

3.8 Sensitivity Analysis

The literature on climate change economics always focuses on the discussion about some ethical parameters assumed in IAMs model. Those parameters are difficult to estimate. As our model is a welfare maximizing model, the agents in the model need to discount the future the same way actual people do. Considering a range of values usually assumed in the literature, we conduct a sensitivity analysis on the parameter representing the discount rate between generations, i.e. the welfare weights. This parameter is important as influences the value of the social cost of carbon.

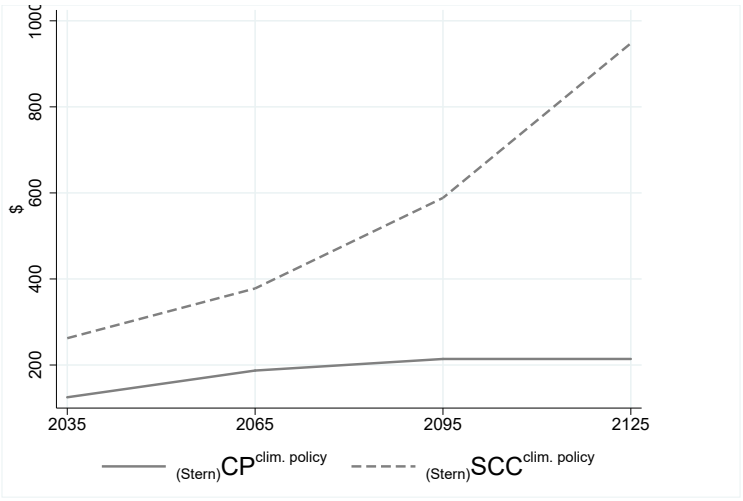
As a first step we vary α_t following the Stern Review on the Economics of Climate Change (Stern, 2007). Stern states that climate change is the greatest market failure ever seen, presenting a unique challenge for economics. In his view the reaction to stop climate change should be immediate. This, practically, correspond to impose a high tax on emissions since today. That means, we give a high value to future generations. Then, we implement a median value as in Weitzman (2007). Finally, we implement Nordhaus' view Nordhaus (1993). Nordhaus argues that the Stern Review exaggerates the effects of global warming because it uses a discount rate that is well below the market rate of return on capital. We can say that Nordhaus's belief in choosing preference parameters for the social planner based on observed market rates of return is equivalent to assign the preferences of a capitalist agents to the social planner. Table 3.8 below resumes the welfare weights considered in the sensitivity analysis on the basis of the studies cited above.

α_t	**References**
0.970	Nordhaus (1993)
0.980	Weitzman (2007)
0.999	Stern (2007)

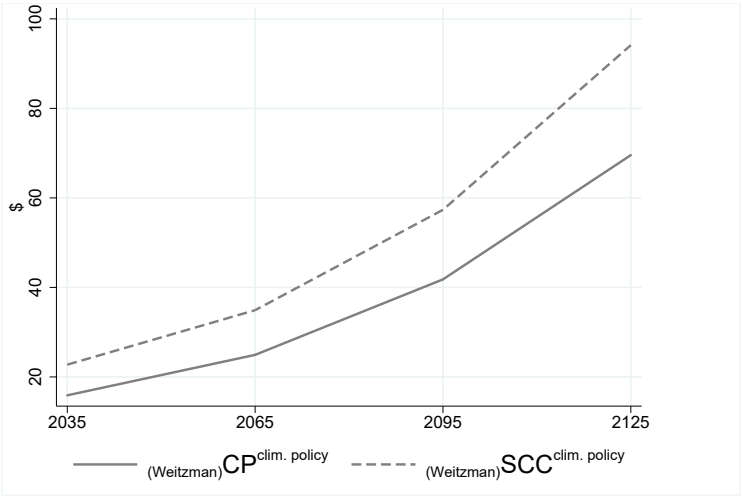
Table 3.8.1: Sensitivity on the Welfare Weights.

The discount factors resumed in Table 3.8 need to be raised to 30, the number of years in each period[26]. In the following figures we analyze how changes in the welfare weights affect the carbon price, the social cost of carbon and the education subsidy under both the climate policy scenario and the climate change and education scenario. The indices S, W and N refer to the studies just cited.

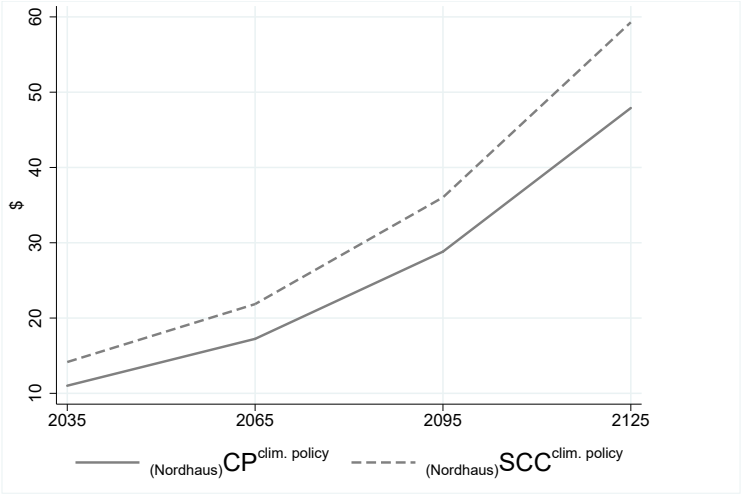
[26]So, the initial values for the welfare weights are, respectively, $\alpha_N = 0.4$, $\alpha_W = 0.545$ and $\alpha_S = 0.97$, where S, W and N represent the different ways of discounting.



(a)



(b)



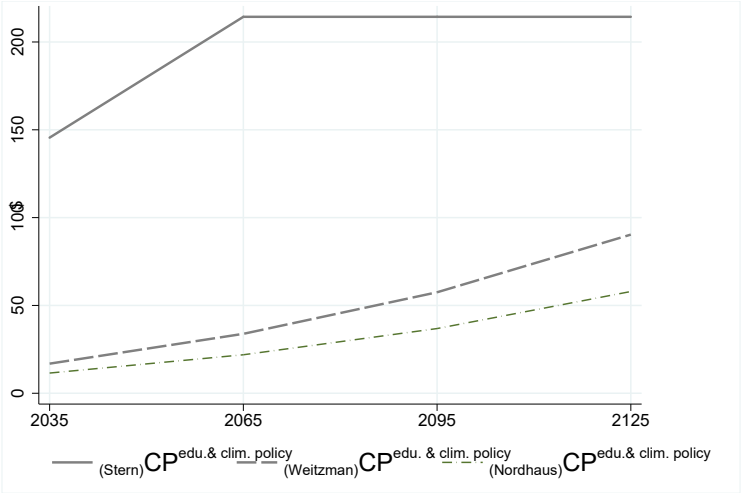
(c)

Figure 3.8.1: Sensitivity Analysis. Social Cost of Carbon and Carbon Price in the climate policy scenario. Panel (a): Stern's welfare weights. Panel (b): Weitzman's welfare weights. Panel (c): Nordhaus' welfare weights.

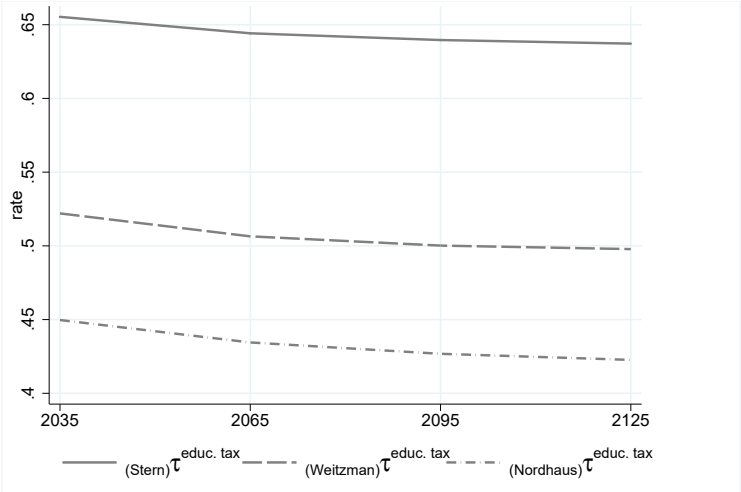
In Figure 3.8.1, the gap between the social cost of carbon and the carbon price diminishes (increases) the more (less) importance is given to present generations. In Panel (a) we consider the Stern's view (Stern, 2007). The social cost of carbon in that case is extremely high: it starts from 240$ and by the end of the century is around 1000$; the initial carbon price is 150$ and stabilizes at 200$, after the second period. Then, the carbon price becomes constant as the economy reaches full abatement. The Stern's discount rate considers future generations extremely important.

The less we care about future generations, instead, the lower is the social cost of carbon: following this view, current generations should not pay a high price for damages due to climate change. It is better to postpone the abatement of emissions: future generations will put more effort and will pay a higher carbon price. This is the case in Figure 3.8.1 in Panel (b) and Panel (c). Panel (c) represents the Weitzman's view (Weitzman, 2007). The social cost of carbon is 21$ in the first period and its value increases until 100$ by the end of the century. The carbon price, instead, is initially around 10$ and reaches 70$ by 2100. Finally, Panel (c) reports the Nordhaus' view (Nordhaus, 1993), where the importance given to future generations is even lower. The social cost of carbon is initially 20$ and reaches 60$ by 2100. The carbon price in the first period is equal to 15$ and then increases through time until 40$.

Finally, we conduct some sensitivity analysis considering the third scenario, namely the climate change and education policy one. We consider again the SCC and the CP. Moreover we report the optimal tax (subsidy) on education necessary to correct for the population effect on emissions. Letting the welfare weights to vary as before, we obtain the results shown in Figure 3.8.2.



(d)



(e)

Figure 3.8.2: Sensitivity Analysis. Panel (d): Social Cost of Carbon and Carbon Price in the Climate Change and education policy scenario. Panel (e): Optimal Education Subsidy.

In Panel (d) we report the carbon prices. The mixed climate-education policy corrects for all the externalities in the model. As a matter of fact, the carbon prices are optimal i.e. equal to the social cost of carbon. The Stern's view determines a high carbon prices since the first period. In this case it is possible to clearly see that, as soon as the economy reaches full abatement, i.e. zero emissions, the carbon price stays constant. As concern Weitzman's and Nordhaus' views, the level of carbon prices diminishes the lower are the welfare weights considered. Figure 3.8.2 in Panel (e), instead, reports the optimal subsidy to education τ. The higher is the concern for the future, the higher is the subsidy to education. The subsidy internalizes the effect of endogenous fertility choices on emissions, resulting in a lower fertility level (as shown in Figure 3.7.5, Panel (a)).

3.9 Conclusions and directions for future research

In a model of climate and economy, endogenous fertility is introducing another source of externality and increases the estimates of the social cost of carbon. Nevertheless, if there is only one policy instrument to counteract climate change, namely a climate policy, carbon prices should be halved compared to the social cost of carbon (*second-best solution*) to mitigate the adverse endogenous fertility effect on emissions. Still, income per capita is lowered as a result of emissions abatement. If, instead, we implement a mixed policy schemes where both the environmental and demographic goals are simultaneously considered, we obtain interesting results in terms of emission abatement, without penalizing per capita income. In this second case, it is optimal to subsidize education: the result is a lower fertility compared to the baseline and the climate policy scenarios. Moreover the double set of policies guarantee that we do not exceed the 2 degrees Celsius increase with respect to pre-industrial levels.

A first extension of our work would be to include pure altruism. So far, parents care only about their children. A fully altruistic model, instead, is a dynastic model where each generation acts as if it cares about all future generations. We expect this extension to produce a different dynamics when designing our policies. Preliminary simulations show that a tax on fertility should complement the subsidy on education as part of climate change policy. This will be a future extension of our work. A further extension would be building a regional model with endogenous population dynamics. Differentiating between ageing and young societies could help in designing appropriate climate and demographic policies, discriminating according to each regions' socio-economic conditions. Most importantly, a regional model allows to consider migration flows. It would be interesting to explore the channels through which climate uncertainty together with demographic imbalances can boost the displacement of people not only to richer, but also to environmentally safer countries. Notice that climate change is only one determinant of migration. Nevertheless, we expect that the importance of this dimension will be growing in the nearest future.

Concluding, this work is a first attempt to highlight the importance of population dynamics in relation to climate change. Climate change economics should look at demographic change and demographic policies as complementary to climate ones.

Bibliography

Abel, G. J., Barakatb, B., C, S. K., and Lutz, W. (2016). Meeting the sustainable development goals leads to lower world population. *PNAS*, 113(50):14294–14299.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., , and Tokos, K. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, 37:117–134.

Bauernschuster, S., Hener, T., and Rainer, H. (2016). Children of a (policy) revolution: The introduction of universal child care and its effect on fertility. *Journal of European Economic Association*, 14(4):975–1005.

Becker, G., Lewis, and Gregg, H. (1973). On the interaction between the quantity and quality of children. *Journal of Political Economy*, 81(issue 2):279–88.

Becker, G., Murphy, K., and Tamura, R. (1990). Human capital, fertility, and economic growth. *Journal of Political Economy*, 98(5):S12–S37.

Becker, G. S. and Barro, R. J. (1988). A Reformulation of the Economic Theory of Fertility. *The Quarterly Journal of Economics*, 103(1):1–25.

Becker, S., Cinnirella, F., and Woessmann, L. J. (2010). The trade-off between fertility and education: evidence from before the demographic transition. *Journal of Economic Growth*, 15(3):177–204.

Blackorby, C., Bossert, W., and Donaldson, D. (2002). Critical level population principles and the repugnant conclusion. Technical report, Department of Economics, University of British Columbia.

Blackorby, C., Bossert, W., and Donaldson, D. (2005). *Population Issues in Social Choice Theory, Welfare Economics, and Ethics. Cambridge University Press.* Cambridge University Press.

Bohn, H. and Stuart, C. (2015). Calculation of a population externality. *American Economic Journal*.

de la Corix, D. and Gosseries, A. (2012). The natalist bias of pollution control. *Journal of environmental economics and management*, 63(2):271–287.

de la Croix, D. and Doepke, M. (2003). Inequality and growth: Why differential fertility matters. *American Economic Review*, 93(4):1091–1113.

Eckstein, Z. and Wolpin, K. I. (1985). Endogenous fertility and optimal population size. *Journal of Public Economics*, 27(1):93–106.

Galor, O. (2005). From stagnation to growth: Unified growth theory. *Handbook of Economic Growth, edited by Philippe Aghion and Steven Durlauf Chapter 4*, 1.

Galor, O. and Weil, D. N. (2000). From malthusian stagnation to modern growth. *American Economic Review*, 89(2):150–154.

Gerlagh, R., Jaimes, R., and Motavasseli, A. (2017). Global demographic change and climate policies. Technical Report 6617, CEsifo.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Groezen, B. V., Leers, T., and Meijdam, L. (2003). Social security and endogenous fertility: pensions and child allowances as siamese twins. *Journal of Public Economics*, 87(2):233–251.

Harford, J. (1998). The ultimate externality. *American Economic Review*, 88(1):260–65.

Haveman, R. and Wolfe, B. (1995). The determinants of children's attainments: A review of methods and findings. *Journal of Economic Literature*.

IIASA (2014). Rethinking population policies. Why education makes a decisive difference *IIASA Policy Brief*, 11.

IPCC (2014). Climate change 2014. Technical report, Intergovernmental Panel on Climate Change.

Jones, L. and Tertilt, M. (2009). *An Economic History of Fertility in the U.S.: 1826-1960*, chapter 5, pages 165 – 230. Peter Rupert, Frontiers of Family Economics.

Knowles, J. (1999). Can parental decisions explain u.s. wealth inequality? Technical report, Working Paper, Department of Economics, University of Pennsylvania.

Lucas, R. E. (1988). On the mechanics of economic development. *Hournal of Monetary Economics*, 22:3–42.

Nordhaus, W. (1993). Rolling the dice: an optimal transition path for contcontrol greenhouse gases. *Resource and Energy Economics*, 15:27–50.

Nordhaus, W. (2014). Estimates of the social cost of carbon: Concepts and results from the dice-2013r model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1(1/2):273–312.

Nordhaus, W. D. and Sztorc, P. (2013). Dice 2013r: Introduction and user's manual. Technical report, Yale.

O'Neill, B. C., MacKellar, F. L., and Lutz, W. (2001). *Population and climate change*. Cambridge University Press.

Razin, A. and Yuen, C.-W. (1995). Utilitarian tradeoff between population growth and income growth. *Journal of Population Economics*, 8:81–87.

Roser, M. and Ortiz-Ospina, E. (2017). World population growth. Technical report, Our World in Data.

RoyalSociety, T. (2012). People and the planet. Technical report, The Royal Society Science Policy Centre.

Scovronik, N., Budolfdon, M. B., Denning, F., Fleurbaey, M., Siebert, A., Socolow, R. H., Spears, D., and Wagner, F. (2016). Impact of population growth and population ethics on climate change mitigation policy. *PNAS*.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press.

Tol, R. S. J. (2009). The economic effects of climate change. *Journal of Economic Perspectives*, 23(2):29–51.

UN (2015a). Transforming our world: the 2030 agenda for sustainable devlopment. Technical report, United Nations.

UN (2015b). World population prospects. the 2015 revisions. Technical report, Department of Economic and Social Affairs. Population Division.

UN (2017). World population prospects. the 2017 revisions. key findings and advanced tables. Technical report, Department of Economic and Social Affairs. Population Division.

WBG (2017). Global economic prospects: Weak investment in uncertain times. Technical report, World Bank Group.

Weitzman, M. L. (2007). A review of the stern review on the economics of climate change. *Journal of Economic Literature*.

WMO (2017). Wmo statement on the state of the global climate in 2016. Technical Report 1189, World Meteorological Organization.

Zhang, J. (2003). Optimal debt, endogenous fertility, and human capital externalities in a model with altruistic bequests. *Journal of Public Economics*, 87(7):1825–1835.

Zhang, J. and Zhang, J. (2007). Optimal social security in a dynastic model with investment externalities and endogenous fertility. *Journal of Economic Dynamics and Control*, 31(11):3545–3567.

Appendix

3.A Competitive equilibrium and optimality conditions

Consider first the model presented in Section 2.4.

Definition 3.A.1 *Competitive Equilibrium without altruism. Given the initial values of population N_1, human capital h_1 and technology ω_1, an equilibrium consists of sequences of prices $\{w_t\}$, aggregate quantities $\{N_t\}$, and decision rules $\{c_t, f_t, s_t, h_{t+1},\}$ such that:*

1 the households' decision rules c_t,f_t,s_t, h_{t+1}, and h_{t+1} maximize utility (3.4.9) subject to the constraints (3.4.10), (3.4.12) and (3.4.11);

2 the firm's choice $h_t l_t$ maximizes profits;

3 the prices w_t are such that markets clear, i.e., (3.4.12) holds;

4 aggregate variable N_t is given by (3.4.1)

The household optimal program is given by the following Lagrangean:

$$L = ln(c_t) + \gamma ln(f_t h_{t+1}) - \lambda_t[c_t + s_t f_t - w_t h_t(1 - \phi f_t)] - \psi_t[h_{t+1} - (\delta + s_t)^\eta] \tag{3.A.1}$$

where λ_t and ψ_t are the Lagrange multipliers (shadow prices) for the equations (3.4.10)-(3.4.11)-(3.4.12). The optimality conditions for the choice variables c_t, h_{t+1}, s_t and f_t respectively are:

$$\frac{1}{c_t} = \lambda_t \tag{3.A.2}$$

$$\frac{\gamma}{f_t} = \lambda_t(s_t + \phi h_t w_t) \tag{3.A.3}$$

$$\eta\psi_t(\delta + s_t)^{\eta-1} = \lambda_t f_t \tag{3.A.4}$$

$$\frac{\gamma}{h_{t+1}} = \psi_t \tag{3.A.5}$$

Manipulation of these expression yields (3.4.13)-(3.4.16) in the text.

3.B Balanced growth path

Consider first the model presented in Section 3.4.

Definition 3.B.1 *Balance Growth Path (BGP). A BGP in this economy is a path along which the growth factor of the human capital, $\hat{h}$, and the growth factor of the exogenous technology level, $\hat{\omega}$, are constant.*

Let $\delta = 0$. If human capital h and technology ω grow at a constant factor along the BGP, using (3.4.8) from (3.4.15) we obtain:

$$\frac{h_{t+1}}{h_t} = \hat{h} = \left(\frac{\eta\phi}{1-\eta}\right)^{\eta} \omega_t^{\eta} h_t^{\eta-1} \tag{3.B.1}$$

Solving for ω_t yields:

$$\omega_t = \left[\hat{h}\left(\frac{\eta\phi}{1-\eta}\right)^{-\eta} h_t^{1-\eta}\right]^{\frac{1}{\eta}} \tag{3.B.2}$$

Because the growth factor of technology $\hat{\omega}$ is constant, from (3.B.2) we have:

$$\frac{\omega_{t+1}}{\omega_t} = \hat{\omega} = \left[\frac{\hat{h}(\frac{\eta\phi}{1-\eta})^{-\eta}\,(h_{t+1})^{1-\eta}}{\hat{h}(\frac{\eta\phi}{1-\eta})^{-\eta}\,(h_t)^{1-\eta}}\right]^{\frac{1}{\eta}} \tag{3.B.3}$$

Which simplifies to:

$$\hat{\omega} = \hat{h}^{\frac{1-\eta}{\eta}} \tag{3.B.4}$$

And in turn:

$$\hat{h} = \hat{\omega}^{\frac{\eta}{1-\eta}} \tag{3.B.5}$$

This shows that the growth factor of h is constant and is equal to the growth factor of exogenous productivity ω raised to the power of $\frac{\eta}{1-\eta}$.

By using equations (3.4.14) and (3.4.6) we obtain the ratio of education investment to output is:

$$\frac{s_t}{q_t} = \frac{\eta\phi h_t w_t}{(1-\eta)(h_t w_t l_t)} \tag{3.B.6}$$

Simplifying $h_t w_t$ and substituting out l_t using equation (3.4.12) gives:

$$\left(\frac{s}{q}\right)^* = \frac{\eta\phi}{(1-\eta)(1-\phi f^*)} \tag{3.B.7}$$

The ratio $\left(\frac{s}{q}\right)$ is constant since f is constant as it is seen from (3.4.13) which, under $\delta = 0$ reduces to the following:

$$f_t = \frac{(1-\eta)\gamma h_t w_t}{(\phi h_t w_t)(1+\gamma)} \tag{3.B.8}$$

or:

$$f^* = \frac{(1-\eta)\gamma}{\phi(1+\gamma)} \tag{3.B.9}$$

From equation (3.4.12) also the employment rate is constant:

$$l^* = (1-\phi f^*) \tag{3.B.10}$$

Consider now the growth factor of s_t. From equation (3.A.4) we have:

$$\frac{s_{t+1}}{s_t} = \frac{\frac{h_{t+1}w_{t+1}\eta\phi}{1-\eta}}{\frac{h_t w_t \eta\phi}{1-\eta}} \tag{3.B.11}$$

which simplifies to:

$$\hat{s} = \hat{h}\hat{\omega} \tag{3.B.12}$$

Hence the growth factor of investment in education is equal to the product of the growth factors of children quality and technology level. From equation (3.4.16) we have that the growth factor of consumption c_t is also constant and equal to:

$$\frac{c_{t+1}}{c_t} = \frac{\frac{h_{t+1}w_{t+1}}{1+\gamma}}{\frac{h_t w_t}{1+\gamma}} \tag{3.B.13}$$

and therefore:

$$\hat{c} = \hat{h}\hat{\omega} \tag{3.B.14}$$

From equations (3.B.12) and (3.B.14) we finally have that:

$$\hat{s} = \hat{c} = \hat{h}\hat{\omega} \tag{3.B.15}$$

Along the BGP the growth factors of investment in education and of consumption are constant and equal to the growth rate of the product between human capital and technology level.

3.C Education Policy

The idea is to consider the effect of an education subsidy on fertility choices and how this impact on climate change. We modify the budget constraint in equation (3.4.11) and the new optimality conditions are the following:

$$f_t = \frac{\gamma h_t w_t (1-\eta)}{(1+\gamma)\left[\phi h_t w_t - \delta(1+\tau_{1t})\right]} \tag{3.C.1}$$

and

$$s_t = \frac{\eta\phi w_t h_t - \delta(1+\tau_{1t})}{(1+\tau_{1t})(1-\eta)} \tag{3.C.2}$$

The third scenario in Section 3.6 is implemented considering equations (3.C.1) when solving for the optimal policies.

3.D Summary of model's equations

3.D.1 Non-altruistic model

Social welfare and preferences

$$W_t = \sum_{t=1}^{T} \alpha_t u_t \tag{3.D.1}$$

$$u_t = ln(c_t) + \gamma_1 ln(f_t h_{t+1}) \tag{3.D.2}$$

Production technology; budget constraint; labor market condition; human capital, working age group dynamics

$$q_t = \omega_t h_t l_t \tag{3.D.3}$$

$$y_t = c_t + s_t f_t \tag{3.D.4}$$

$$l_t = 1 - \phi f_t \tag{3.D.5}$$

$$h_{t+1} = (\delta + s_t)^{\eta} \tag{3.D.6}$$

$$N_{t+1} = f_t N_t \tag{3.D.7}$$

Emissions net of abatement; cumulative emissions; damages; abatement; output net of damages and abatement costs:

$$e_t = \sigma_t q_t (1 - \mu_t) \tag{3.D.8}$$

$$CE_{t+1} = CE_t + e_t MN_t \tag{3.D.9}$$

$$d_t = 1 - exp(-\beta_1 CE_t) \tag{3.D.10}$$

$$a_t = \theta_1 \mu_t^{\theta_2} \tag{3.D.11}$$

$$y_t = exp(-\beta_1 CE_t)(1 - \theta_1 \mu_t^{\theta_2}) q_t \tag{3.D.12}$$

Optimality conditions for effective labour, fertility, and education expenditures

$$w_t^{'} = (1 - d_t)(1 - a_t)\omega_t \tag{3.D.13}$$

$$f_t = \frac{(1 - \eta)\gamma_1 h_t w_t^{'}}{(\phi h_t w_t - \delta)(1 + \gamma_1)} \tag{3.D.14}$$

$$s_t = \frac{\eta \phi h_t w_t^{'} - \delta}{1 - \eta} \tag{3.D.15}$$

Sets

$t \in 1, .., T$, where $T = 10$. Equations (3.D.6), (3.D.7) apply only for $t \in (1, .., T-1)$. For $T = 10$ (3.D.2) becomes:

$$u_t = ln(c_t) \tag{3.D.16}$$

Allocation

max W subject to equations 3.D.1-3.D.12 with $\alpha = 1$.

Reporting

We interpret periods as 30 years, and young as 15-45. Population is defined and computed ex-post as:

$$P_t = N_{t-1} + N_t + \epsilon N_{t+1} \tag{3.D.17}$$