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RESEARCH ARTICLE

Demographic change and climate change

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Abstract

This paper uses a continuous-time overlapping-generations model with endogenous growth and pollution accumulation over time to study the link between longevity and global warming. It is seen that increasing longevity accelerates climate change in a business-as-usual scenario without climate policy. If a binding emission target is set exogenously and implemented via a cap-and-trade system, the price of emission permits is increasing in longevity. Longevity has no effect on the optimal solution of the climate problem if perfect intergenerational transfers are feasible. If these transfers are absent, the impact of longevity is ambiguous.

Keywords: climate change; demographic change; endogenous growth; environmental policy; mortality and longevity

1. Introduction

Climate change is one of the major challenges faced by humankind in the 21st century. Increasing emissions of CO_2 and other greenhouse gases have induced a rise in global temperature, which is expected to continue or even accelerate. Due to limited participation and lacking compliance, the Kyoto Protocol of 1997 had only minuscule impact on slowing down the trend. The pledges of the Paris Accord of 2015 are currently mere declarations of good will and it remains to be seen whether they will be implemented consistently to effectuate the radical changes in the way we use energy that are needed to seriously combat global warming. As another trend of the ending of the 20th and beginning of the 21st centuries, demographic change is affecting the world. Increasing longevity and lower fertility lead to population ageing globally, to long-term shrinking of population in developed countries and to a slowdown of population growth in most developing countries (see Bretschger (2018) for an overview of these issues). Tables A1–A4 in appendix A present evidence on this for a variety of countries. It is seen that longevity has increased almost everywhere, the only exception being African countries affected by AIDS/HIV, and that fertility rates have been declining in most countries, the main exceptions being countries located in or near the Sahel zone. The UN predicts a slowing of global population growth, with the possibility of stabilisation around 10

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billion around the year 2100 being the most likely scenario of population development (United Nations, 2017).

This paper is about the impact of demographic change on the environment in general and on climate change in particular. Of course, there are other important links between the environment and demography, in particular the potential of migration induced by the deterioration of living conditions to be expected in countries negatively affected by global warming, but also increasing mortality due to higher frequency of heat waves and crop failures. There is a growing literature on this, but this paper is concerned with the reverse causality.

The impact of population size on climate change is simple. According to the Kaya or IPAT identity, everything else being equal, there is a one-to-one relationship between population and greenhouse gas emissions. Since, by definition, impact (I) equals population (P) times affluence (A) times technology (T), or

$$I = P \cdot A \cdot T,$$

greenhouse gas emissions and population are proportional if affluence (measured by GDP per capita) and technology (measured by greenhouse gas emissions per unit of GDP) remain unchanged. Matters become more interesting if population structure is entered into the picture. Let $\boldsymbol{S}$ be a row vector of age cohorts and $\boldsymbol{A}$ the corresponding column vector of the corresponding per capita incomes. Then the identity is changed to:

$$I = P \cdot \boldsymbol{S} \cdot \boldsymbol{A} \cdot T.$$

This paper is about the impact of $\boldsymbol{S}$. Empirical work by O'Neill *et al.* (2010), Lugauer (2014) and Zagheni (2011) suggests that a shift of population structure towards a larger share of older cohorts might reduce the impact. O'Neill *et al.* (2010) use the Kaya identity and argue, on the basis of simulations, that ageing might reduce emissions in industrialised countries by up to 20 per cent due to lower labour force participation and lower productivity. Similar effects are obtained by Dalton *et al.* (2008), in a simulation model with different dynasties. The low income of an increasing share of old people reduces emissions. Lugauer (2014) uses an international panel of country data to show that, everything else (population, GDP, country and year fixed effects) being equal, countries with larger shares of 29–45 age cohorts have higher emissions than countries with lower shares of this age group. Zagheni (2011) uses 2003 US household data and shows that the CO_2 emissions incorporated in individual consumption are hump-shaped in age and decline substantially after age 65. Although both results seem to suggest that population ageing might slow down climate change, this is far from clear. What if age is just a proxy for other variables that are outside the model (e.g., individual income, family status or consumption behaviour)? Carlhoff (2019) controls for these effects and still finds a hump-shaped profile, which is, however, flatter than Zagheni's. On the other hand, Andor *et al.* (2018) use German data to show that older people are less concerned about climate change than younger ones. This result suggests that, under identical conditions particularly regarding income, older people may behave in a less climate-friendly way than younger ones.

In the theoretical literature as well, the link between demographic variables and the environment has been important. There are papers that look at the impact of population growth on long-term resource use and/or pollution (e.g., Bretschger, 2013). The approach in this paper is closer to the one chosen by Stephan *et al.* (1997), who compare

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a dynastic model of growth with an overlapping-generations model and show that differences between the models are small under business as usual, but that in the presence of climate policy the intergenerational distribution of tax revenues becomes decisive.

This paper tries to isolate the effects of age structure in a theoretical modelling framework and leaves other relevant variables constant (and therefore unconsidered), e.g., population size, preferences for specific consumption goods and family status. We do this in an overlapping-generations model à la Blanchard (1985), in which Yaari bonds (Yaari, 1965) are used by individuals as insurance against longevity. See Heijdra (2017, chapter 15) for an overview. We employ the learning by-doing model with capital-externalities (Romer, 1986) to endogenise economic growth. Although other modelling strategies are possible (e.g., Prettner, 2013), they do not yield substantially different results.

The paper is organised as follows. Section 2 outlines the model and presents its solution for a laisser-faire market economy. Section 3 looks at exogenous environmental policy imposing an upper limit on emissions. Section 4 derives optimality results and section 5 wraps up and discusses potential extensions of the model.

2. The model: a laisser-faire economy

We start by considering a world inhabited by selfish individuals interacting in competitive markets without any government intervention. We do not consider population growth and thus assume that population size, L, is constant. Without loss of generality we can normalise $L = 1$. A constant population implies that the birth rate equals the mortality rate and that fertility is at the replacement level. Let us, for simplicity, assume that the mortality rate, μ, is constant and independent of age. Although this is unrealistic,[1] it is a standard assumption in continuous-time overlapping-generations models. More realistic models with age-dependent mortality do exist (e.g., Faruqee, 2003; Heijdra and Romp, 2008), but they are cumbersome to solve and have been used mainly for simple settings like the small open economy case, in which all prices are fixed exogenously. Moreover, the major effect driving the results of this paper, the so-called turnover effect, would be prevalent in more complex models as well. Regarding notation, we employ the convention that lowercase letters represent individual variables whereas the corresponding uppercase variables are the corresponding aggregates.

2.1 Households

An individual born at time $v < t$ ($v =$ vintage), expecting to die with probability μ, maximises the present value of his/her expected future welfare,

$$\int_{v}^{\infty} \left(\ln c\,(v, t) - \frac{P\,(t)^{1+\varphi}}{1+\varphi} \right) e^{-(\rho+\mu)\,(t-v)} dt,$$

where ρ is the rate of time preference, $c\,(v, t)$ is the individual's consumption, $P\,(t)$ is the level of pollution and $\varphi > 0$ is a preference parameter determining the curvature of the environmental-damage function, which is increasing and strictly convex. Pollution is an externality and is taken as given by the individual. It will, however, play a role later in

[1]For example, $\mu = 0.01$ would imply that 50 per cent of the population reach age 70, 25 per cent reach age 140, 12.5 per cent reach age 210, and so forth.

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the paper, when optimal solutions are investigated. The individual owns capital – which includes insurance à la Yaari (1965) and depreciates at rate δ – and is endowed with one unit of labour and self-employed in his/her own firm. This simplifying assumption, which does not affect the results, allows us to neglect the labour market. The individual owns capital $k(v, t)$, earns profits $\pi\,(t)$, a return on investment $r\,(t)\,k\,(v, t)$, a return on Yaari bonds $\mu\,(t)\,k\,(v, t)$, with the capital owned by dying individuals being redistributed to the surviving ones without transaction costs. Thus, the individual's wealth accumulates according to

$$\dot{k}\,(v, t) = \pi\,(t) + r\,(t)\,k\,(v, t) - c\,(v, t) - \delta k\,(v, t) + \mu k\,(v, t).$$

Moreover, the initial level of wealth at birth is $k\,(v, v) = 0$. Inheritance motives are absent. Utility maximisation over the infinite horizon subject to the wealth constraint gives the usual Euler equation of individual consumption growth,

$$\frac{\dot{c}\,(v, t)}{c\,(v, t)} = r\,(t) - \delta - \rho,$$

where the impact of mortality is cancelled out due to the existence of Yaari bonds (see appendix B for the derivation of the result). Thus, a change in longevity has no impact whatsoever on the individual's consumption and saving behaviour, although it affects the discounting of future utility.

2.2 Fossil fuels and global warming

Fossil fuels are extracted at a constant marginal extraction cost z measured in terms of GDP. Exhaustibility is neglected, which can be justified by the fact that, if coal deposits are taken into account, the supply of fossil fuels is abundant and the limits to using them are on the consumption side: climate change will be disastrous long before the resource base is exhausted. Units of measurement are chosen such that one unit of fossil fuels generates one unit of greenhouse gas emissions, $E(t)$. Greenhouse gases are stock pollutants accumulating over time with a constant decay rate θ. Assuming an initial pollution level of $P\,(0) = P_0$, the change in the stock is

$$\dot{P}\,(t) = E\,(t) - \theta P\,(t). \tag{1}$$

2.3 Firms

Individuals own firms, in which they work as self-employed entrepreneurs. Firms are identical and each owner rents capital, $k\,(t)$, on the capital market and pays interest, $r\,(t)$. Note that $k\,(t)$ is the capital stock of a representative firm whereas $k\,(v, t)$ is the capital stock owned by an individual born on date versus From the fact that population size is unity, it follows that $k\,(t) = \int_{-\infty}^{t} k\,(v, t)\,dv$. Firms maximise their profits,

$$\pi\,(t) = f(K\,(t), k\,(t), e\,(t)) - r\,(t)\,k\,(t) - ze\,(t),$$

where $f\,(.,.,.)$ is a constant returns to scale (CRS) production function and its first argument, $K\,(t) = L\,(t)\,k\,(t) = k\,(t)$, is the economy-wide capital stock, generating a Romer-type externality (Romer, 1986). The capital market is in equilibrium, i.e., $K\,(t) = \int_{-\infty}^{t} k\,(v, t)\,dv.e\,(t)$ denotes a representative firm's use of fossil fuels, with one unit of fossil fuels generating one unit of emissions, and z is the market price of fossil fuels, equaling the constant marginal extraction cost of the resource. Firms pay z, but they do not internalise the social cost of pollution. Profit maximisation yields $f_k = r(t)$ and $f_e = z$. With CRS, marginal productivities are homogenous of degree zero and the factor-price frontier is constant, i.e., $r(t)$ is a function of z. Moreover, the ratio of $k(t)$ and $e(t)$ is fixed: $e(t) = bk(t)$.

2.4 Aggregation

Let uppercase letters denote the aggregate levels of the variables denoted by corresponding lowercase variables on the individual level. Since the mass of firms is 1, total emissions equal those of the individual firm, $E(t) = e(t)$. Regarding consumption, we have to take into account that dying individuals have other consumption levels than the newborn individuals replacing them. As population is constant, each dying individual is replaced by exactly one newborn and the rate of replacement is μ. Newborns have no wealth and finance their consumption, $c(t,t)$, from current income only, whereas the average individual in the economy has accumulated some wealth and therefore has a higher consumption level, $C(t)$. This implies that

$$\frac{\dot{C}(t)}{C(t)} = r - \delta - \rho - \mu \frac{C(t) - c(t,t)}{C(t)}.$$

Since in models with logarithmic utility functions, the share of consumption derived from wealth is proportional to the wealth, the proportionality factor being the individual discount rate, $\rho + \mu$, we have

$$\frac{\dot{C}(t)}{C(t)} = r - \delta - \rho - \mu(\rho + \mu)\frac{K(t)}{C(t)}. \tag{2}$$

The last term on the right-hand side is called the turnover effect in the literature (Heijdra, 2017, chapter 16). This suggests that the higher the mortality rate, the larger the turnover effect and the smaller the consumption growth rate. However, this is not totally clear since a change in μ does not leave $c(t)$ and $K(t)$ unaffected. Aggregation of the capital stocks of individual firms yields

$$\dot{K}(t) = f(K(t), K(t),\ E(t)) - C(t) - \delta K(t) - zE(t). \tag{3}$$

Note that there is no term $\mu K(t)$ in this equation since Yaari bonds are pure transfers from the dying to the survivors. Using the proportionality of $E(t)$ and $K(t)$, we can rewrite (3) as:

$$\dot{K}(t) = AK(t) - C(t) - \delta K(t) + zbK(t). \tag{3'}$$

Finally, the stock of greenhouse gases evolves according to

$$\dot{P}(t) = bK(t) - \theta P(t). \tag{1'}$$

In a long-run steady state, consumption and capital grow at the same rate and are proportional to each other. Let this rate be g and let $q = C(t)/K(t)$ be the consumption-capital ratio. Then,

$$g = r - \delta - \rho - \frac{\mu(\rho + \mu)}{q}, \tag{4}$$

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and

$$g = A - \delta - zb - q. \tag{5}$$

Total differentiation of (4) and (5) yields

$$\frac{dg}{d\mu} = \frac{-q(\rho + 2\mu)}{q^2 + \mu(\rho + \mu)} = -\frac{dq}{d\mu},$$

i.e., the economic growth rate is negatively affected by an increase in general mortality and the consumption-to-capital ratio is positively affected. See Prettner (2013) for the same result in a different modelling context.

Since long-run growth of the stock of pollutants is affected by the long-run growth of emissions, which grow at the same rate as the capital stock, we have the following proposition.

Proposition 1. *An increase in longevity leads to a faster growth of greenhouse gas emissions and to a faster growth of the stock of greenhouse gases in the atmosphere.*

The underlying reason is the turnover effect. If a smaller number of dying wealthy people are replaced by poorer newborns in every period, the growth of aggregate consumption is larger. And if the economy is growing faster, this has a negative effect on the global environment. Note that, in addition, the population will grow during the transition from high to low mortality if fertility is at the replacement level as it has been assumed here. This will of course exert additional pressure on the environment.

3. Environmental policy: an exogenously given target

The Paris Accord has the goal of keeping human-generated global warming well below 2°C compared to pre-industrial times and strives for a target of 1.5°C. Translated into the terminology of our model, this implies restriction of the pollution stock such that $P(t) \leq \bar{P}$. It follows that, in the long run, $E(t) \leq \theta\bar{P}$.[2] Since emissions would grow to infinity under laisser faire, this is a binding constraint. Therefore $E(t)$ is replaced by $\theta\bar{P}$ in the production function. It follows that $f_e > z$. The difference between marginal productivity and the fuel price, $f_e - z$, is the permit price in a cap-and-trade system with cap $\theta\bar{P}$ or the carbon tax implemented by the government to keep emissions at $\theta\bar{P}$. With a fixed energy input, the production function exhibits decreasing returns to scale and capital accumulation and consumption growth will go to zero. From (2) and (3), we have the long-term steady-state conditions:

$$\dot{C} = 0: \quad f_k(K, K, \theta\bar{P}) = \delta + \rho + \mu(\rho + \mu)\frac{K}{C}$$

and

$$\dot{K} = 0: \quad C = f(K, K, \theta\bar{P}) - \delta K - z\theta\bar{P}.$$

[2]The Paris Accord has set its 1.5°C and 2°C targets as long-term objectives, but it does not require the signatory parties to implement $E(t) \leq \theta\bar{P}$ immediately. Various trajectories of transition are possible and it might be interesting to consider different scenarios. This paper, however, just looks at the long run where emissions have been stabilised at sustainable levels.

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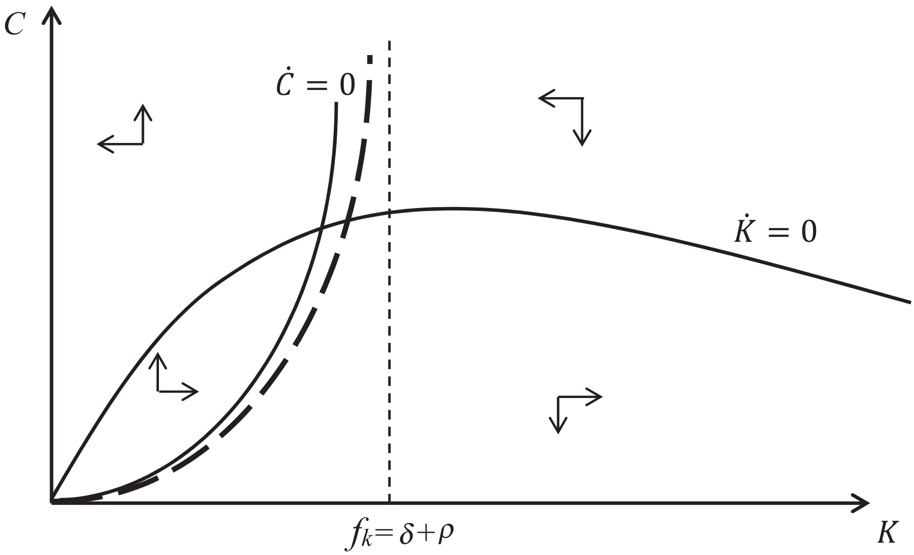

Figure 1. Increased longevity and economic growth when emissions are constant.

These two conditions are isoclines in a (K, C) phase diagram and standard procedures show that the optimum solution is an increasing saddle path approaching the unique intersection point of the two curves (Blanchard, 1985: 232; Heijdra, 2017: 569), the only difference being that in our case the production function contains an externality, which, however, does not affect the qualitative result. Figure 1 depicts the isoclines and the equilibrium.

The $(\dot{C} = 0)$ line approaches the vertical golden-rule line, $f_k = \delta + \rho$, asymptotically for $C \to \infty$. It can be seen that the golden rule does not hold in the equilibrium. This is a standard result of the Blanchard-Yaari model and it is due to the turnover effect. The turnover term affects aggregate consumption growth negatively, and therefore less capital is accumulated in the long run. The dashed line shows location of $\dot{C} = 0$ for a decrease in mortality and it can be seen that with lower mortality, long-run capital and long-run consumption are larger. Since an increase in capital implies that the marginal productivity of fossil fuels is increased (due to $f_{ek} > 0$ and $f_{eK} > 0$), it follows that the carbon tax or emission permit price, $f_e > z$, will also rise.

Proposition 2. *If there is an emission-trading system with a fixed cap, a reduction in mortality increases long-run capital, long-run consumption and the long-run level of the emission permit price.*

A tightening of the environmental standard, i.e., a reduction in $\bar{P}$, would shift the $(\dot{K} = 0)$ line downwards and would lead to less capital accumulation and lower consumption in the long run.

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4. Optimal policies

Let us assume that there is a social planner discounting future welfare at the same rate as the representative individual.[3] The objective is to maximise

$$\int_{-\infty}^{\infty}\left(\int_{v}^{\infty}\left(\ln c\,(v,t)-\frac{P\,(t)^{1+\varphi}}{1+\varphi}\right)e^{-(\rho+\mu)\,(t-v)}dt\right)e^{-\rho v}dv,$$

subject to

$$\dot{K}\,(t)=f\,(K(t),\,K\,(t),\;\;E\,(t))-\int_{-\infty}^{t}c\,(v,t)\,e^{-\mu\,(t-v)}dv-\delta K\,(t)-zE\,(t)$$

and

$$\dot{P}\,(t)=E\,(t)-\theta P\,(t).$$

Calvo and Obstfeld (1988) have shown that $\partial c\,(v,t)/dv=0$ in the optimum, i.e., a transfer scheme has to be implemented such that all individuals living at time t enjoy the same level of consumption irrespective of their age. This is very intuitive since otherwise marginal utilities would differ across individuals and huge welfare gains could be made by transferring income from persons with low marginal utilities to persons with high marginal utilities. The potential of welfare gain is exhausted if all marginal utilities are equal, i.e., if all individuals consume at the same level. Moreover, Calvo and Obstfeld (1988: 416) have shown that the social planner's problem can be regarded as a two-stage optimisation problem, the first stage being the allocation of consumption across cohorts at each moment of time and the second one being the optimal intertemporal choice of the aggregate variables. Thus, the second-stage problem is to maximise

$$\int_{v}^{\infty}\left(\ln C\,(t)-\frac{P\,(t)^{1+\varphi}}{1+\varphi}\right)e^{-\rho t}dt,$$

with respect to the stock pollution constraint, (1), and aggregate capital accumulation, (4). Since neither the objective function nor the constraints contain μ, it follows that the optimal policy is independent of mortality. The Euler equation now is

$$\frac{\dot{C}\,(t)}{C\,(t)}=f_k+f_K-\delta-\rho,$$

and does not contain a turnover effect. The additional term f_K indicates that the planner takes the knowledge spillover into account and that this raises the growth rate (Acemoglu, 2009, chapter 11.4).

Proposition 3. *In the case of optimal intergenerational transfers, the turnover effect vanishes and the optimum paths of all variables are independent of mortality/longevity. This implies that global warming is not affected by the age structure of society either.*

Intergenerational transfers that shift huge incomes from older cohorts – which have been economically active as workers and entrepreneurs for many years – to young ones

[3]Otherwise, optimal policies would be time-inconsistent, i.e., the planner would revise the policy continuously as new cohorts are born (Calvo and Obstfeld, 1988).

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without similar merits, may be difficult to implement as they are likely to be regarded as unjust. So let us look at a planner without access to such intergenerational transfers. Appendix B derives the optimality conditions and the corresponding dynamics of the economy are characterised by

$$\dot{P} = E - \theta P. \tag{1}$$

$$\dot{K} = F(K, E) - C - \delta K - zE, \tag{6}$$

$$\frac{\dot{C}}{C} = F_K(K, E) - \delta - \rho - \mu(\rho + \mu)\frac{K}{C}, \tag{7}$$

$$\dot{F}_E = (F_E - z)(F_K - \delta + \mu + \theta) + CP^{\varphi}, \tag{8}$$

where the time argument has been omitted for the sake of brevity and where $F(K, E) \equiv f(K, K, E)$, $F_E(K, E) = f_e(K, K, E)$ and $F_K(K, E) = f_k(K, K, E) + f_K(K, K, E)$. From (8) we have that the optimal environmental policy in the long run must satisfy

$$F_E(K, E) - z = \frac{P^{\varphi} C}{F_K(K, E) - \delta + \mu + \theta}. \tag{9}$$

The left-hand side of (9) is the marginal productivity of fossil fuels minus the marginal cost of providing them. This not only measures the marginal benefit to society from using additional fossil fuels, it also measures the cost arising from foregoing the use of a marginal unit, i.e., the marginal abatement cost. In the optimum, the marginal abatement cost must equal the present value of marginal environmental damage. The marginal environmental damage at time t is the marginal rate of substitution between pollution and consumption, $P^{\varphi} C$. Future damages are discounted at the gross rate of interest, $F_K(K, E) - \delta + \mu$, including the return on Yaari bonds, plus the natural rate of decay of pollution, θ. Given that μ is part of the discount rate, it follows that increased longevity (a lower μ) raises the willingness to pay for avoiding climate change. However, there is also an indirect effect as a change in longevity affects aggregate savings behaviour and this affects the long-run interest rate.

Before this indirect effect is determined, note that (9) is incompatible with balanced growth, i.e., with a scenario in which all variables grow at the same positive rate. In this case, the left-hand side would be constant (since $F_E(K, E)$ is homogenous of degree zero under constant returns to scale), whereas the right-hand side would go to infinity. Thus, condition (9) can only be satisfied as a long-run optimality condition if the growth rate goes to zero and the economy approaches a steady state in the far future. The underlying reason is simple: the marginal benefits from growth are decreasing since the marginal utility of consumption declines, whereas the marginal cost of growth is increasing due to increasing marginal environmental damage.

By setting $\dot{P} = \dot{K} = \dot{C} = 0$ in (1), (6) and (7) and using (9), the steady state is determined. Appendix C shows that the comparative statics with respect to μ are ambiguous.

Proposition 4. *In the absence of intergenerational transfers, the impact of mortality on long-run pollution, emissions, capital and consumption is ambiguous. There is a positive direct effect and an ambiguous indirect effect.*

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One of the reasons for the ambiguities is that the effects of changes in emissions and capital on condition (9) are unclear. An increase in capital raises the marginal abatement cost due to $F_{KE} > 0$, but it also reduces the rate at which future environmental damages are discounted since $F_{KK} < 0$ and thus raises the present value of environmental damages as well. A similar argument holds for increases in emissions. In appendix C it is shown that the direct effect has the expected sign if the determinant of the Jacobian matrix is positive. The indirect effect is ambiguous even in this case.

5. Discussion

This paper has shown that in a world in which Yaari bonds provide insurance against longevity, the central results concerning the impact of increased longevity on long-term pollution are driven by the turnover effect. Wealthy people who die are replaced by poorer young persons. The rate at which they are replaced is the mortality rate and thus increased longevity has a positive impact on long-term growth and a negative effect on the environment. If a cap-and-trade system for emission permits is introduced and if the cap is fixed, increased longevity leads to higher demand for emission permits and, thus, to a higher permit price. Turning to optimal policies, one can show that welfare maximisation requires intergenerational transfers that eliminate intergenerational income inequality, and therefore, the turnover effect. Without a turnover effect, longevity does not affect aggregate economic variables including long-term pollution. If intergenerational transfers are not available (since, for instance, it is not possible to introduce them against the will of the older generation), the model becomes so complex that unambiguous results cannot be derived any more. Some of the results are empirically testable. For example, by controlling for other variables that have been set constant in this paper, one could check whether higher longevity indeed has positive effects on emissions, pollution and emission tax rates.

A main criticism of the modelling framework chosen here is that Yaari bonds are of limited relevance in the real world. Insurance of this type does exist, but only a few individuals make use of it in a manner suggested by theoretical models. Even people without children rarely use this opportunity. People with children usually have bequest motives, but it is questionable whether such motives translate into perfect dynastic preferences that completely eliminate the impact of an individual's mortality on his/her saving behaviour. Thus, it seems reasonable to assume that an individual's behaviour is influenced by his/her mortality such that

$$\frac{\dot{c}(v,t)}{c(v,t)} = r(t) - \delta - \rho - \varepsilon\mu,$$

where ε is a positive parameter less than one. It is clear that if individuals behave in this way, the aggregate economy will do so as well. Mortality risk slows down economic growth and this tends to be good for the environment.

The results of the model concerning the reconciliation of climate policies and economic growth are probably overly pessimistic. The underlying reason is the absence of a true backstop technology providing the possibility of production without emissions or with very low emissions. If this technology is more expensive or more capital-intensive than existing fossil-fuel technologies, growth will be slower in a climate-friendly world, but major results of this paper would probably carry over. Of course, with more research and development into such technologies, the cost disadvantage could be mitigated. It

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would therefore be interesting to see how changes in longevity affect the incentives to do such research and development, and the resources allocated for this purpose.

An important extension of the model would be to introduce trade. What if low-mortality countries trade with high-mortality countries? Would this have a positive or a negative impact on emissions and long-run pollution? Moreover, one could include trade in fossil fuels in the modelling framework. Leakage effects would enter the picture and one could ask whether and how they interact with effects of increased longevity. Finally, one could make the model more realistic by considering time-dependent mortality and median-voter decisions. Of course, the assumption of a constant rate of mortality is standard in the Blanchard-Yaari world of overlapping generations in continuous time. An interesting question would be whether it makes a difference if people move into the stage of high mortality at the age of 60 or at the age of 80. One could, for example, use the modelling frameworks based on Gompertz's law to introduce age-dependent mortality (Faruqee, 2003; Heijdra and Romp, 2008). Although one might expect that some results will not be changed since the turnover effect will continue to affect aggregate growth, additional insights might be gained as consumption and saving behaviours will look completely different, both on the individual and on the aggregate levels (Heijdra and Romp, 2008), and the impact of this on emissions and climate is unclear. As an additional extension, a median-voter framework would be useful as one would be able to model political decisions more realistically than with the fiction of a benevolent planner. It is obvious that increased longevity will have an impact on who the median voter is and which policy – be it intergenerational redistribution or be it environmental policy – she will prefer.

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Appendix A: tables

Table A1. Life expectancy in Europe, the USA and Japan

Country	1960	1980	2000	2014
Romania	65.6	69.1	71.2	75.1
Russian Federation	66.1	67.0	65.3	70.4
Poland	67.7	70.1	73.7	77.3
Japan	67.7	76.1	81.1	83.6
Greece	68.2	73.6	77.9	81.3
Spain	69.1	75.3	79.0	82.4
Italy	69.1	73.9	79.8	82.7
Bulgaria	69.2	71.2	71.7	75.4
Germany	69.3	72.7	77.9	80.8
United States	68.8	73.6	76.6	78.9
France	69.9	74.1	79.1	82.4
United Kingdom	71.1	73.7	77.7	81.1
Switzerland	71.3	75.5	79.7	82.8
Sweden	73.0	75.7	79.6	83.1

Sources: http://data.un.org/Data.aspx?d=WDI&f=Indicator_Code%3ASP.DYN.LE00.IN; UN DATA, United Nations Statistics Division.

Table A2. Life expectancy in developing countries and emerging economies

Country	1960	1980	2000	2014
Niger	35.5	39.4	50.7	61.5
Nigeria	37.2	45.5	46.6	52.8
Malawi	37.8	44.4	46.0	62.7
Chad	38.0	44.7	46.7	51.6
Mauritania	43.5	54.2	59.7	63.0
Algeria	46.1	58.2	68.9	74.8
Kenya	46.4	57.8	52.8	61.6
Morocco	48.4	57.5	68.1	74.0
South Africa	49.0	57.0	55.8	57.2
Botswana	50.5	60.7	50.5	64.4
Zimbabwe	51.5	59.4	43.9	57.5
Brazil	54.7	62.7	70.3	74.4
Chile	57.5	67.9	76.8	81.5
Argentina	65.2	69.5	73.7	76.2
India	41.4	55.4	62.2	68.0
China	43.5	67.0	72.1	75.8
Indonesia	44.8	58.6	67.3	68.9
Bangladesh	47.0	54.9	65.3	71.6

Sources: http://data.un.org/Data.aspx?d=WDI&f=Indicator_Code%3ASP.DYN.LE00.IN; UN DATA, United Nations Statistics Division.

Table A3. Total fertility rates: Europe, USA and Japan

Country	1970	1990	2011
Romania	2.9	1.9	1.4
Spain	2.9	1.3	1.5
France	2.5	1.8	2.0
Italy	2.5	1.3	1.4
Greece	2.4	1.4	1.5
United Kingdom	2.3	1.8	1.9
United States	2.2	1.9	2.1
Bulgaria	2.2	1.7	1.5
Poland	2.2	2.0	1.4
Switzerland	2.1	1.5	1.5
Japan	2.1	1.6	1.4
Sweden	2.0	2.0	1.9
Russian Fed.	2.0	1.9	1.5
Germany	2.0	1.4	1.4

Sources: http://data.un.org/Data.aspx?q=total+fertility+rate&d=SOWC&f=inID%3a127; UN DATA, United Nations Statistics Division.

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Table A4. Total fertility rates in developing countries and emerging economies

Country	1970	1990	2011
Kenya	8.1	6.0	4.7
Niger	7.4	7.8	7.0
Algeria	7.4	4.7	2.2
Zimbabwe	7.4	5.2	3.2
Malawi	7.3	6.8	6.0
Morocco	7.1	4.0	2.2
Mauritania	6.8	5.9	4.5
Botswana	6.6	4.7	2.7
Nigeria	6.5	6.4	5.5
Chad	6.5	6.7	5.9
South Africa	5.6	3.7	2.4
Brazil	5.0	2.8	1.8
Argentina	3.1	3.0	2.2
Bangladesh	6.9	4.5	2.2
China	5.5	2.3	1.6
India	5.5	3.9	2.6
Indonesia	5.5	3.1	2.1

Sources: http://data.un.org/Data.aspx?q=total+fertility+rate&d=SOWC&f=inID%3a127; UN DATA, United Nations Statistics Division.

Appendix B: derivation of the Euler equation and the other optimality conditions

Laisser faire

Under laisser faire, the individual's Hamiltonian is

$$H = \ln c(v,t) - \frac{P(t)^{1+\varphi}}{1+\varphi} + \kappa(v,t)\,(\pi(t) + r(t)\,k(v,t)$$
$$- c(v,t) - \delta k(v,t) + \mu k(v,t)),$$

with $\kappa(v,t)$ as the costate variable or shadow price of capital. As pollution is exogenous to the individual, the optimality conditions are

$$\frac{1}{c}(v,t) = \kappa(v,t),$$
$$\dot{\kappa}(v,\ t) = (\rho + \delta - r(t))\,\kappa(v,t)$$

where μ has cancelled out. The standard procedures yield the Euler rule.

The optimum without transfers

To determine optimal environmental policies, we consider an individual of birth year v taking the technical and the environmental externalities into account. That is, the individual

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knows that there are positive spillovers of capital in production and negative spillovers from emissions, which result in pollution. Dropping the arguments v and t for simplicity, the Hamiltonian is

$$H = \ln c - \frac{P^{1+\varphi}}{1+\varphi} + \kappa\,(f\,(k,k,e) - ze - c - \delta k + \mu k) + \lambda\,(E - \theta P)$$

with λ as the (negative) shadow price of pollution. The individual knows that $e = E$. Then the first-order conditions are

$$\begin{aligned}
&\frac{1}{c} = \kappa,\\
&\kappa\,(f_e - z) + \lambda = 0,\\
&\dot{\kappa} = (\rho + \delta - f_k - f_K)\,\kappa,\\
&\dot{\lambda} = \ (\rho + \mu + \theta)\,\lambda + P^{\varphi}.
\end{aligned}$$

From the first equation we have the individual Euler equation. Taking the time derivative in the second equation and using the two remaining equations to eliminate the costate variables, we have

$$\frac{\dot{f}_e}{f_e - z} = f_k + f_K - \delta + \mu + \theta + \frac{P^{\varphi}}{\lambda}.$$

Substituting for λ, we have

$$\dot{f}_e = \ (f_e - z)\,(f_k + f_K - \delta + \mu + \theta) + cP^{\varphi}.$$

The problem here is that individuals of different birth cohorts have different levels of consumption and their willingness to pay for avoiding global warming, cP^{φ}, is proportional to their consumption. Samuelson's rule states that the marginal value of a public good is the sum of all individual rates of substitution. Thus, replace c by C to obtain equation (8).

Appendix C: comparative statics of the steady state

To determine the impact of the mortality rate on the long-run steady state, use $E = \theta P$ in (6), (7) and (9) to replace E and set $\dot{K} = \dot{C} = 0$ in (6) and (7), respectively:

$$\begin{aligned}
&C = F\,(K,\ \theta P) - \delta K - z\theta P,\\
&(F_K\,(K,\theta P) - \delta - \rho)C = \mu\,(\rho + \mu)\,K,\\
&(F_E\,(K,\theta P) - z)(F_K\,(K,\theta P) - \delta + \mu + \theta) = P^{\varphi} C.
\end{aligned}$$

Total differentiation yields

$$\begin{pmatrix}
1 & \delta - F_K & (z - F_E)\theta \\
F_K - \delta - \rho & F_{KK}C - \mu\,(\rho + \mu) & \theta F_{KE} C \\
-P^{\varphi} & \begin{matrix}(F_K - \delta + \mu + \theta)F_{KE} \ldots \\ \ldots + (F_E - z)F_{KK}\end{matrix} & \begin{matrix}(F_K - \delta + \mu + \theta)\theta F_{EE} \ldots \\ \ldots + (F_E - z)\theta F_{KE} - \varphi P^{\varphi - 1}\end{matrix}
\end{pmatrix}
\begin{pmatrix} dC \\ dK \\ dP \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ (\rho + 2\mu)K \\ -(F_E - z) \end{pmatrix} d\mu.$$

Although the majority of terms in the determinant, Δ, of the Jacobian matrix on the left-hand side are positive, its sign is ambiguous. Thus, the comparative statics are indeterminate:

$$\frac{dP}{d\mu} = \frac{1}{\Delta}\left(F_E - z\right)\left(\mu\left(\rho+\mu\right) - F_{KK}C + \left(F_K-\delta\right)\left(F_K-\delta-\rho\right)\right)$$
$$-\frac{1}{\Delta}\left(\rho+2\mu\right)K((F_K-\delta+\mu+\theta)F_{KE} + (F_E-z)F_{KK} - (F_K-\delta)P^{\varphi}).$$

The first part shows that the direct effect of mortality on emissions is positive if $\Delta > 0$. The indirect effect, coming from the turnover term in the consumption-growth condition, is always ambiguous.

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