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CER-ETH – Center of Economic Research at ETH Zurich

Malthus in the Light of Climate Change

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Malthus in the Light of Climate Change

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Abstract

To reconsider the Malthusian predictions of natural limits to economic development, the paper develops a multi-sector growth model with exhaustible resource extraction, investments in physical and knowledge capital, climate change, and endogenous fertility. Economic growth is driven by endogenous innovations which increase in the availability and productivity of research labour. Poor substitution of natural resources triggers sectoral change. Climate change is the result of polluting resource use which is, like consumption and investments, based on the intertemporal optimization of the households. Highlighting the importance of bounded resource supply and of rational extraction decisions I show that climate change is independent of population growth in steady state and there is no causal relationship between climate and population during transition to steady state. The consumption per capita growth rate rises in the innovation rate and the output elasticities of labour and capital in the different sectors. Unlike climate policy, population policy is not warranted; it may be counterproductive because labour is crucial for the research sector.

Keywords: Population growth, climate change, endogenous innovation, sectoral change, fertility choice.

JEL Classification: Q43, O47, Q56, O41

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1 Introduction

1.1 Population and the Climate

Until two hundred years ago, population size was largely constrained by food supply. Technical revolutions in agriculture and industry relaxed this restriction, and a rapidly growing population could avoid the famines predicted by Thomas Malthus (1798). But industrialization entailed massive expansion in the use of fossil fuels, the source of the current climate problem. This warrants asking whether, and in which form, a “New Malthusianism” will arise. In it, the limited absorption capacity of the atmosphere would replace the agricultural sector as the constraint of a Malthusian world. In the past, greenhouse gas emissions correlated reasonably well with economic development. Failure to delink emissions from income will result in growing climate damages and large adverse environmental shocks. One could interpret these as an indirect and lagged response to population pressure in the 18th century.

In a static analysis, a positive link between population size and resource use causing greenhouse gas emissions can readily be established.² But the world is not static, it is dynamic and evolves rapidly. Applying dynamic theory reveals that counterforces to past trends of pollution, resource use, and population development are active and important.³ First, efficient markets adjust to limitations in natural resource supply. In his famous contribution, Harold Hotelling (1931) showed that increasing resource scarcity implies growing resource rents and, with constant or increasing extraction costs, rising resource prices over time. As a consequence, firms will adjust the input mix in production using more capital which affects investment and consumption growth, a central topic studied in the seminal paper of Partha Dasgupta and Geoffrey Heal (1974). These supply side conditions in an economy will constitute a central part of my analysis. Second, resource scarcity has an impact on innovation and knowledge creation. The principle of "induced innovation" of John Hicks (1932) suggests that innovative activities are fostered by scarcity and directed at economizing factors which become increasingly scarce.⁴ Remarkably, population den-

²Paul Ehrlich (1968) published an alarmist book called "The Population Bomb" foretelling a Malthusian catastrophe due to resource scarcity, a topic which was rephrased in Ehrlich and Ehrlich (1990) under the title "Population Explosion". The direct links between quantities, e.g. population size and resource use, emerge from basic decomposition analysis which disregards market mechanisms, economic dynamics, and optimizing behaviour of the agents.

³The nature and power of these forces are decisive for the possibility of decoupling of economic development from environmental pollution, which is a prerequisite for efficient climate policy.

⁴Recent progress in green technologies and renewable energy conversion was largely triggered by signals from markets and politics aiming at decarbonization.

sity can have a similar positive effect on innovation. Esther Boserup's (1965) research on agrarian societies concludes that agricultural methods depend on the size and density of the population; when the quantity of available food is low, productivity in food production grows by increasing workforce, better machinery and technology, and use of fertilizers.⁵ Third, and connected to innovation, is the importance of labour as an input. Julian Simon (1981) suggests that population is not the problem but the solution to resource scarcities and environmental problems, since people are able to innovate. Along the same line, Johnson (2001) argues that population growth helps because more people can contribute to the creation of new knowledge and knowledge creation becomes more specialized and diversified. This reasoning is prominently reflected in endogenous growth theory initiated by Paul Romer (1990) where innovation is the key to economic growth and a larger workforce allows to have a more powerful research sector. A fourth element of development is fertility behaviour. The current "demographic transition" will induce the growth rate of world population to decrease in the future. Following Gary Becker (1965), families choose fertility according to incentives; opportunity costs of child rearing are a key element for the decision. In the light of natural resource scarcity, the Brundtland report (1987) on development, population, and the environment identified economic development as a key mechanism to stopping Malthusian population growth curves. The fifth and final counterforce to ever increasing emissions is most critical: policy. To mitigate climate change we have to curb future use of fossil fuels drastically. Based on the recommendations of Arthur Cécile Pigou (1920), taxation of carbon would be an effective instrument. But the implementation of environmental taxes and other environmental policies has proven to be difficult in practice, especially in an international context. Also, resource owners may react to such policies by shifting resource extraction on the time axis thereby undermining policy targets, which has to be anticipated in the policy design.

Summarizing the counterforces to ever growing greenhouse gas emissions, the effects of resource scarcity, technical progress, growing education, demographic transition, and climate policy will be significant. But are they strong enough to avoid the "roundabout" Malthusian trap of climate change? Does population growth have adverse effects on the economy so that a "New Malthusianism" emerges in the light of climate change? The present paper provides answers to these questions by developing and exploiting a novel theory framework. It reframes the original Malthusian concern of natural scarcities in

⁵This effect has been interpreted as an application of the proverb "necessity is the mother of invention." Kremer (1993) confirms the positive impact of population size on innovation in the long run.

an up-to-date context and derives conclusions using recent achievements in resource and climate economics and macroeconomic theory.

1.2 Paper Contribution

While there are widespread concerns about negative effects of a fastly increasing world population on climate change, the present contribution offers a different reasoning which is based on optimal resource extraction as well as optimal savings and investments derived in an intertemporal framework. The paper examines endogenous growth of population and the economy in the light of climate change which relates to different strands of recent literature. Endogenous population growth and the associated emergence of new ideas driving the growth process are prominently studied in Jones (2001) and Connolly and Peretto (2003). Peretto and Valente (2015) analyze the links between natural resources, income, and population development by looking at endogenous growth through technological change, endogenous fertility, and population dynamics. In their approach, the natural resource is “land” i.e. resource scarcity is included in their model but resource input is fixed and non-polluting while the present approach deals with exhaustible resources, increasing scarcity, and stock pollution externalities. Substitution between labour and resources is crucial in Peretto and Valente (2015); poor input substitution can drive the economy towards demographic explosion or collapse.⁶ Peretto (2017) includes exhaustible resources and shows under which conditions an economy will experience a transition from resource-based to sustainable knowledge-based growth. Following this literature, my contribution also builds on endogenous innovation and endogenous fertility but adds exhaustible resource extraction as well as poor input substitution giving rise to structural change, aspects of real economies which are often considered important but are mostly disregarded in theory.⁷ The present paper introduces climate change by modeling the accumulation of a pollution stock which is caused by resource use and which harms existing capital stock in the economy. My contribution complements some recent literature on population development and its macroeconomic context. Lanz, Dietz, and Swanson (2017) present quantitative results on the role of Malthusian constraints in future population growth and find that the limited supply of land does not bind as a constraint for economic development because of sufficient capital investment and technological progress. In a dynamic climate-economy model with endoge-

⁶Inelastic energy demand also plays a dominant role for the results in Peretto (2009).

⁷Poor input substitution is discussed by Dasgupta and Heal (1974) in a one-sector model and included in multisector models by Bretschger (1998) and Bretschger and Smulders (2012) where climate change and population growth are not considered.

nous population, Dietz and Lanz (2018) show that climate induced damages in agriculture taken as a separate sector require significantly more stringent climate policy to achieve the agreed temperature targets. Madsen and Strulik (2018) derive that technological progress increased inequality before the fertility transition disabling the Malthusian mechanism and show under which conditions the impact of technology is reverted such that development of inequality is hump-shaped in the very long run.

In the context of natural resource use, literature has dealt with different population-related issues. Prskawetz et al. (1994) consider population growth in the context of renewable resources and study the emergence of Malthusian traps in a two-sector economy; the present paper adds to that analysis, among others, the elements of capital accumulation, exhaustibility of resources, and endogenous innovation. Schou (2002) analyzes endogenous fertility in a model with human capital formation and pollution externalities and discusses policy measures like a fertility tax supplementing the pollution tax. I abstain from deriving optimal policies because the social optimum in the context of endogenous population growth is not a well-defined concept (Blackorby et al. 2005, Ng 1986). Family altruism is the subject of Bréchet and Lambrecht (2009) where, in an overlapping-generations setup, it is shown that altruism can lead either to more preservation or to a bigger waste of natural resources. Their conclusion that the pressure on natural resource extraction is not necessarily reduced when population size is lower corresponds with the findings of this paper, which are derived from an infinite horizon approach with endogenous growth.⁸ The development of backstop technologies to alleviate the limits to economic growth is studied by Tsur and Zemel (2005) who find that resource scarcity induces additional research; I obtain the same mechanism but abstract from the emergence of backstop resources in order to maintain the challenge of population growth for the environment.

The paper develops a multisector model in which growth is driven by innovations allowing an increasing division of labour through an extension in goods varieties (Romer 1990). Resources are exhaustible and optimally extracted according to Hotelling (1931). Capital build-up as a substitute for fading resource input is based on Dasgupta and Heal (1974) and

⁸The paper topic relates to "unified growth theory," an encompassing development framework covering the interdependence of population, technical progress, education and fertility, explaining the transition from Malthusian stagnation to sustained growth (Galor and Weil 1999) and, even more general, the evolution of the human species (Galor and Moav 2002). Using an infinite-horizon framework I abstract from the tradeoff between children quality and quantity used in that literature but add the elements of exhaustible resource extraction, sectoral change, and environmental stock pollution to analyse transitional dynamics and long-run equilibria. Barbier (1999) provides a basic sustainability model and Smulders (2000) a valuable survey on endogenous growth in the context of exhaustible resources. Asheim et al. (2007) study resource use and growth with exogenous population growth.

applied to knowledge and physical capital. Following the suggestion of Christian Groth and Paul Schou (2002), natural resources are assumed to be an essential input in the research sector. In line with endogenous growth literature I assume positive knowledge spillovers from innovation to public knowledge which is a free input in subsequent research. I follow Charles Jones (1995) and Groth and Schou (2002) to posit that spillovers are less than proportional i.e. output elasticity of knowledge in the research sector is less than unity. Adding to this literature I assume a link between structural change and knowledge productivity.⁹ Growing resource price triggers a reallocation of labour from production to research which reflects induced innovation in the wake of Hicks (1932) and Boserup (1965). Put differently, increasing scarcity of resources induces higher efforts in innovative activities, where labour is an essential input, and drives sectoral change, which has been identified as a major topic in the sustainability debate by López, Anriquez and Gulati (2007). Population size becomes endogenous through fertility decisions following the traditional approach of Gary Becker (1965). As documented by the development in urban areas, fertility is adversely affected by increasing congestion with a growing population.¹⁰ I also follow Partha Dasgupta (1995) in assuming that households receive positive spillovers of economy-wide birth flow, reflecting the social context of family decisions. Climate change is represented by a pollution stock which negatively affects installed capital so that the output level is reduced at any moment of time. To mitigate climate change, the implementation of policies correcting for pollution externalities is warranted (Pigou 1920). The optimal Pigouvian tax has been derived under different conditions of climate effects, e.g. in the presence of spatial heterogeneity (Brock and Xepapadeas 2017). The present paper discusses the impact of climate policies on long-run development with endogenous population.

As a result I find that resource use and climate change are governed by optimal resource depletion paths which are themselves driven by resource supply and intertemporal optimization but are independent of population growth; climate damages harm the economy by a negative impact on capital stock and income level but do not alter fertility decisions. With endogenous population growth and climate change, long-run per capita consumption growth rates can be positive or negative, depending on the productivity in the research sector and on the impatience of agents determining resource extraction as well as investments in financial assets and offspring. A growing labour force helps the innovation sector to keep

⁹Proportional knowledge spillovers are assumed in Bretschger (2013) where population growth is included while climate change, physical capital, and a distinct sector for final goods are disregarded.

¹⁰Moreno-Cruz and Taylor (2018) present a model with endogenous number of agglomerations, their size, and population density in a spatial energy model with transportation costs.

developing new products which augments total factor productivity.

The paper concludes that a Malthusian view on climate change, i.e. the assumption that population growth is reduced by global warming or should actively be reduced to mitigate global warming, is not warranted. Applying dynamic theory it turns out that population growth is not a threat to the economy but rather supports development by fostering its core growth engine, research and development. I will show that specific modifications of the model setup lead to some qualifications of this quite strong result. But I will argue that the main model mechanisms firmly rely on first principles of intertemporal optimization and are thus robust to alternative modeling assumptions.

The remainder of the paper is organized as follows. In section 2 I develop the framework with the different production sectors and the non-market effects. Section 3 presents transitional dynamics. In section 4, I present the effects of climate change and the macro-economic characteristics of long-run equilibrium. Section 5 provides model extensions and a discussion of the robustness of the results. Section 6 concludes.

2 Model

2.1 Multisector Framework

I consider a world economy with four different sectors. This subsection develops supply and demand in the different markets while the specification of positive and negative externalities is added below. The first sector produces final output Y using labour L , physical capital K , and intermediate input varieties x_i , $i \in (0, N]$ as inputs, according to

$$Y_t = AL_{Y,t}^\alpha K_t^\beta \int_0^N x_{i,t}^{1-\alpha-\beta} di \quad (1)$$

where $0 < \alpha, \beta < 1$, t is the time index, $A > 0$ denotes total factor productivity, and L_Y labels use of input L in sector Y . According to Eq. (1), production relies on input quantities and on input diversification; both are important drivers of economic development. The gains from diversification depend on the mass of varieties N . With the chosen Cobb-Douglas specification, the three inputs labour, capital, and (aggregate) intermediates are essential i.e. output becomes nil if one of them is run to zero. I use broad definitions for resources and capital: the former includes all natural resources causing climate change and the latter also covers renewable energy capital like dams, solar panels, and wind turbines which are clearly stocks and assumed to be non-polluting.

In the second sector, intermediate firms, indexed by i , produce intermediate input x_i using labour L_{ix} and natural resources R_{ix} as inputs, which are combined in a CES production

function reading

$$x_{i,t} = [\lambda \cdot L_{ix,t}^{(\sigma-1)/\sigma} + (1 - \lambda) \cdot R_{ix,t}^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)} \quad (2)$$

where $0 < \lambda < 1$ is a distribution parameter. Accommodating the concern that substitution of natural inputs is difficult under realistic conditions I assume poor input substitution in this sector, i.e. $0 < \sigma < 1$.¹¹ In a symmetrical equilibrium, which I will adopt, firms i have identical cost functions so that for the quantity of intermediates we have $x_i = x$, $\forall i$, and $\int_0^N x_{i,t}^{1-\alpha-\beta} di = N_t x_t^{1-\alpha-\beta}$ in Eq. (1).¹² Intermediate goods are produced under monopolistic competition; in profit maximum prices p_x are a mark-up over marginal costs which is determined by the price elasticity of demand for intermediates and given by $1/(1 - \alpha - \beta) > 1$. The share of profits of intermediate goods sales then amounts to $0 < \alpha + \beta < 1$. I label the share of resources in intermediates production by m and resource price by p_R so that for each firm

$$m_t \equiv \frac{p_{R,t} R_{ix,t}}{(1 - \alpha - \beta) p_{x,t} x_t}. \quad (3)$$

The share of labour in intermediates production then is $1 - m$. Profit optimization of intermediate firms yields relative input demand in the intermediate sector from which I obtain the resource share as a function of relative prices

$$\frac{m_t}{1 - m_t} = \left(\frac{\lambda}{1 - \lambda} \right)^{\sigma} \left(\frac{p_{R,t}}{w_t} \right)^{1-\sigma}, \quad (4)$$

where w denotes the labour wage. The use of natural resources reduces resource stocks in the ground S so that

$$\dot{S}_t = -R_t, \quad (5)$$

where a dot denotes the derivative with respect to time, S_0 is given and $S_t \geq 0$ for all t ; extraction costs are disregarded.¹³ Physical capital K , as introduced in Eq. (1), is accumulated by households devoting part of final output to investments. It is characteristic for climate damages to have an impact on the economy by adversely affecting physical capital such as buildings, roads, and infrastructure.¹⁴ In the model, capital K is hit by climate damages destroying a part $0 < D_t < 1$ of existing stock in each point in time so

¹¹In empirical studies, the elasticity of substitution between natural resources and other inputs is mostly estimated to be less than unity, see e.g. Christopoulos and Tsionas (2002).

¹²As already noted in Romer (1990) it shows that in Eq. (1) we assume constant returns to scale for the rival inputs while knowledge is a public good which can be fully used by all the agents so that overall production in Eq. (1) exhibits increasing returns to scale.

¹³The assumption can be justified by noting that extraction costs are still low in many important countries and will not be high enough in the future to solve the climate problem without policy intervention.

¹⁴An alternative would be to assume a negative impact of climate change on total factor productivity which has the same effect of reducing the output level and would thus not change the results.

that net capital accumulation is the difference between gross investments I and depreciation DK

$$\dot{K}_t = I_t - D_t K_t = Y_t - C_t - D_t K_t \quad (6)$$

where C denotes aggregate consumption; climate damage D_t depends on pollution stock P_t with $D_t = h_t P_t$ where h_t will be specified in the next subsection. Capital and knowledge accumulation have to compensate for increasing resource scarcity and climate damages if production should be increasing or at least remain constant over time.

For the third sector, I follow the seminal contribution to endogenous growth literature of Paul Romer (1990) where the mass of goods varieties N is raised by endogenous research activities. Innovation is a sectoral output with skilled labour¹⁵ and knowledge as inputs used to invent new blueprints or patents for the production of additional input varieties. Specifically, each intermediate firm needs one new blueprint in order to start production; profits in the intermediate sector are used to pay the costs of blueprint development. Free market entry in the intermediate sector guarantees that the value of a firm equals the costs of blueprint development in equilibrium. Following Romer (1990) I assume positive knowledge spillovers from innovation to public knowledge which is a free input in subsequent research. It has been argued by Charles Jones (1995) and, in the resource context, by Christian Groth and Paul Schou (2002) that in reality spillovers are lower than what is assumed in the Romer approach i.e. they are less than proportional to existing knowledge. These authors suggest that innovators profit from the existing knowledge pool at a decreasing rate, an assumption which I adopt here. Also, I add exhaustible resources as an essential input in the research sector to show the consequences of resource scarcity in innovative activities as these are important for growth.¹⁶ With H denoting skilled labor and \dot{N} additional input varieties I obtain

$$\dot{N}_t = H_t^\gamma R_{N,t}^{1-\gamma} N_t^{q_t} \quad (7)$$

with $0 < \gamma, q_t \leq 1$. Spillover intensity q_t will be specified in the next subsection; the case $q_t = q = 1$ reflects proportional spillovers applied in standard endogenous growth literature. Labour can be transformed into skilled labour by continuous on-the-job-training which requires part of total worktime. When labour devoted to research is L_N , skilled

¹⁵I distinguish between skilled and unskilled labour because it is generally assumed that research work requires some (costly) education or training and that only a part of the labour force is able to work in the research lab.

¹⁶The reader who thinks that essential resource input in research is a too cautious assumption can easily check that all the results below go through when assuming it is not an (essential) input by setting the output elasticity γ equal to unity.

labour becomes $H = \kappa \cdot L_N$ with $0 \leq \kappa < 1$. The innovation rate g is then given by¹⁷

$$\frac{\dot{N}_t}{N_t} \equiv g_t = (\kappa L_{N,t})^\gamma R_{N,t}^{1-\gamma} N_t^{q_t-1}. \quad (8)$$

Following Eq. (8) $g > 0$ can only be realized when fading resource input in the research sector, R_N , and shrinking impact of knowledge spillovers, N_t^{q-1} , is sufficiently compensated by an increase in skilled labour, κL_N . I assume there is a maximum share of population which can be used for skilled work so that the ratio of labour used in the research sector to total labor, $\omega \equiv L_N/L$, is bounded from above at level $\bar{\omega}$.

The fourth sector is the household sector, where population size L is determined by the fertility decisions. Family members obtain utility from individual consumption c and the mass of family birth flow b

$$U(t) = \int_t^\infty e^{-\rho(\tau-t)} [\log c_\tau + \phi \max(\log b_\tau, 0)] d\tau \quad (9)$$

where ρ is equal to the pure time preference rate plus the probability of death and $\phi > 0$ is the elasticity of instantaneous utility with respect to the (net) birth flow. Birth flow increases with family labour effort, denoted by L_B , and is given by

$$b_t = B_t L_{B,t}^\varepsilon \quad (10)$$

where $0 < \varepsilon < 1$ is the elasticity of labour in child rearing and B is household productivity; the specification of B is given in the next subsection. Each individual is endowed with one unit of labour, which can be either offered to the (formal) labor market or be used for child-rearing. The two equilibria on input markets read

$$L_t = L_{Y,t} + L_{X,t} + L_{N,t} + L_{B,t} \quad (11)$$

$$R_t = R_{X,t} + R_{N,t}. \quad (12)$$

The clearing of final goods markets requires

$$Y_t/L_t - I_t/L_t = c_t. \quad (13)$$

2.2 Non-market effects

Environmental economics deals with negative pollution externalities in the economy, endogenous growth theory highlights positive knowledge spillovers, and population theory

¹⁷Here $-1 < q_t - 1 \leq 0$ reflects the drag of knowledge stock on the innovation rate; the higher is q_t , the smaller the drag.

includes externalities in fertility decisions. Hence, given the paper topic, non-market effects i.e. negative and positive externalities are a crucial part of the analysis, which is developed in this subsection.

Pollution stock in the atmosphere P grows with the extraction and use of fossil fuels i.e. natural resources R . I do not include natural pollution decay for simplicity.¹⁸ Then, the increase of pollution stock in each period is a linear function of resource use

$$\dot{P}_t = \theta R_t, \quad (14)$$

where $\theta > 0$. Pollution stock harms capital stock through damage intensity h_t , see the explanation following Eq. (6); I use the specification

$$h_t = \frac{\eta}{S_0 - S_t}, \quad (15)$$

implying that climate impact intensity h_t grows with parameter $\eta > 0$ and decreases with extracted resource quantity.¹⁹ It is conceivable and generally assumed that knowledge capital survives climate shocks and does not suffer from congestion. Hence, I do not include negative feedbacks of climate change or population density in the research sector.

Household productivity B depends on two effects. First it is harmed by congestion, caused by a growing population, a result of the competition for limited factors such as land, fresh water, and city infrastructure.²⁰ Second, I follow Partha Dasgupta (1995, p. 1993) in assuming that households receive positive spillovers from economy-wide birth flow which is in analogy to the knowledge spillovers in Eq. (7). Specifically, families receive incentives for having offspring by social relationships,²¹ learn from child-rearing of other families, and have higher productivity with good child care institutions. Taken together I have

$$B_t = L_t^{-\xi} \bar{b}, \quad (16)$$

¹⁸The largest part of greenhouse gas emissions stays in the atmosphere for a very long time period and natural sinks are also affected by warming; the linear relationship between emissions and climate change is confirmed by Matthews et al. (2009) and Knutti (2013) and also used in Brock and Xepapadeas (2016) and Bretschger and Karydas (2018).

¹⁹This reflects that impact intensity is decreasing with a transition from very dirty fossils like coal to less dirty fuels like oil and gas; the assumption does not prevent total climate damage to be convex in pollution stock, which is the main requirement for a climate damage function, see the further explanations in Section 4.1.

²⁰Urbanization and economic development started simultaneously while the advances in urbanization have sharply reduced fertility. Schultz (1985) shows the causal effects empirically; Sato and Yamamoto (2005) introduce congestion diseconomies to derive declines in the total fertility rate and demographic transition. Dasgupta (1969, p. 296) writes that a strong "source of externality" affecting the individual is the "degree of congestion in his community." I adopt this by positing a negative impact of congestion on fertility.

²¹Dasgupta (1995, p. 1893) explains that households make similar choices because of imitative behavior and status seeking.

where $-\xi < 0$ measures the congestion effect of total population and \bar{b} denotes average birth flow. To assign sufficient weight to the congestion effect I will assume $\xi > \varepsilon$. Family members choose the optimum level of L_B , while total population L and average birth flow \bar{b} are endogenous on an aggregate level but exogenously given for the individuals. I define the share of labour devoted to child-rearing, L_B/L , as χ and set $\bar{\chi}$ as a maximum share individuals are willing to devote to family work.

2.3 Household optimization

Individuals maximize utility by optimizing over private consumption; the induced positive spillovers from innovation, negative externalities of pollution, and the non-market effects on fertility of the other households are not taken into account. Each agent owns a share $(p_Y K)/L$ of the value of capital stock and a share $(p_N N)/L$ of intermediate firms' value, where p_N is the market value of a blueprint or patent, so that individual financial wealth, denoted by v , becomes $v = (p_Y K + p_N N)/L$. Also, each agent owns a share $s = S/L$ of the resource stock, sells $u = R/L$ units of extracted resource to intermediate firms, receiving a royalty which equals the resource price p_R . Then, the dynamic budget constraint for each family member is written as (hats denote growth rates)

$$\dot{v}_t = (r_t - \hat{L}_t)v_t + p_{R,t}u_t + (1 - \chi_t)w_t - p_{Y,t}c_t \quad (17)$$

where r is the interest rate on financial wealth, while Eq. (5) implies the dynamic resource constraint

$$\dot{s}_t = -u_t - \hat{L}_t s_t. \quad (18)$$

The individual problem consists of maximizing Eq. (9) subject to Eqs. (17) and (18), with c , b , and u as control variables, and v and s as state variables. From intertemporal optimization, see the Appendix, I obtain first order conditions for the decentralized economy which can be solved to obtain expression for consumption growth according to

$$\hat{p}_{Y,t} + \hat{c}_t = r_t - \hat{L}_t - \rho, \quad (19)$$

which is a standard Keynes-Ramsey rule, and for resource price growth

$$\hat{p}_{R,t} = r_t, \quad (20)$$

which is the standard Hotelling rule. These well known relationships of capital resource models are supplemented by an equation for population growth reading

$$\hat{L}_t = \varepsilon(r_t - \hat{w}_t - \rho)/\xi. \quad (21)$$

The result of Eq. (21) says that population growth is positively affected by child-rearing productivity and a high interest rate reflecting the value of investments in family size but harmed by wage growth, impatience, and congestion, revealing the impact of opportunity costs of child rearing, preference for the present, and population density as in the big cities. The equilibria on capital markets are stated in Appendix C.

3 Transitional dynamics

In the model, development is driven by the change in input quantities, sectoral allocation of inputs, and the gains from diversification.²² Positive learning externalities support innovation, negative pollution externalities harm capital stock. Sectoral change is driven by the growth of natural resource prices affecting the intermediate sector and research. Taking growth rates of the resource share in the intermediate sector, given in Eq. (4), yields

$$\frac{\hat{m}_t}{1 - m_t} = (1 - \sigma)(r_t - \hat{w}_t), \quad (22)$$

where I made use of Eq. (20).

Lemma 1 *Given poor input substitution, sectoral change in the intermediate sector implies the resource share in intermediates' production to converge to unity i.e.*

$$\lim_{t \rightarrow \infty} m_t \rightarrow 1. \quad (23)$$

Proof. With poor input substitution ($\sigma < 1$) the resource share m_t grows with the difference between interest rate and wage growth, $r_t - \hat{w}_t$, see Eq. (22). Taking growth rates of the transversality condition Eq. (A.7) and using the price indices for the stocks reveals that the difference $r_t - \hat{w}_t$ is unambiguously positive so that m_t converges to unity in the steady state. ■

Generally, positive knowledge spillovers rise in the stability of existing knowledge networks and are comparatively weak in an economy with a large share of dirty firms and sectors.²³ I assume spillover elasticity q_t in Eq. (8) to be smaller than unity and to be adversely affected by the speed of change in the intermediates sector, reflected in the growth

²²To focus the analysis on the long run, which is requested by the issue of climate change, I present transitional dynamics in a concise way explaining the model parts which are necessary to understand the characteristics of the steady state.

²³Using patent citation analysis Dechezlepretre et al. (2017) find significantly higher levels of spillovers from clean technologies compared to brown activities.

of share m , which is \hat{m} , and the importance of polluting resources for intermediates goods production, which grow with share m . The two effects can thus be captured by writing

$$q_t = 1 - \zeta \frac{\hat{m}_t}{1 - m_t}, \quad (24)$$

where $\zeta \geq 0$ measures the intensity of the drag on knowledge productivity. Resource and pollution dynamics are characterized by decreasing resource stock, $\dot{S}_t < 0$, and rising pollution stock, $\dot{P}_t > 0$, as long as $R_t > 0$ which always holds in equilibrium. Physical capital converges to the steady-state pattern like in the standard Ramsey model because output elasticity of capital is below unity in final goods production, i.e. $\beta < 1$ in Eq. (1).

For the limiting values of input use I state

Lemma 2 *Growth rates of sectoral input use are negative, $\hat{R}_x, \hat{R}_N < 0$, and converge to a negative constant, $-\rho$. Labour shares in the household and the research sector converge to the following values in the steady state*

$$\lim_{t \rightarrow \infty} (L_{B,t}/L_t) \rightarrow \bar{\chi}, \quad (25)$$

$$\lim_{t \rightarrow \infty} (L_{N,t}/L_t) \rightarrow \bar{\omega}. \quad (26)$$

Proof. See Appendix C. ■

4 Long-run steady state

I characterize the long run in three steps. In the first subsection I derive the results for climate change and its relationship to population growth. Next I focus on the long-run innovation rate and on growth of consumption per capita and then combine the different perspectives.

4.1 Climate and Population

Based on the present framework I find for the assessment of population growth in the light of climate change the following

Proposition 1 *In the steady state, climate change is determined by pollution stock $P_\infty = \theta S_0$ which is independent of population growth; during transition, climate change and population growth are both driven by the interest rate r but there is no causal relationship between the two variables; climate damages are a constant fraction $0 < \theta\eta < 1$ of capital which is independent of population growth.*

Proof. See Appendix D. ■

Resource extraction causing climate change and population growth are both endogenous variables in the model. In the long run, profit maximising resource owners extract total available resource stock in order not to forgo profit opportunities, see the transversality condition of the optimization problem in Eq. (A.8).²⁴ In the steady state, the (negative) growth rate of resource extraction, which causes pollution due to Eq. (14), is determined by the discount rate (Lemma 2) and is thus independent of population growth. During transition to the steady state, resource use is determined by an optimal depletion path which is based on the first-order conditions of the intertemporal decision problem in Eqs. (A.4) - (A.6) in Appendix A. This leads to Eq.(20) fixing the time profile of resource prices as a function of interest rate r , given total resource stock. At each point in time, the resource price determines resource quantity which is equally shared among the current population. If r is raised, Eq.(20) yields a *steeper* resource price profile but Eq. (A.8) requires a *lower* initial resource price level such that profits for resource owners are maximized. Resource extraction is preponed, i.e. it is higher in the beginning entailing higher emissions and lower at a later stage causing less emissions. Conversely, based on Eq.(21), population growth increases *ceteris paribus* with the interest rate throughout, reflecting that fertility is an investment in offspring whose return is compared to the return to capital investments.²⁵ This reveals that the positive correlation of earlier pollution and higher population growth resulting from higher r does not reflect a causal relationship; at a later stage, the correlation is reversed: the economy experiences still higher population growth but lower extraction rates and associated emission flows. Higher population growth \hat{L} is obtained *ceteris paribus* when labour productivity in child rearing increases (rising ε) or congestion costs become lower (decreasing ξ), see Eq. (21). I will establish below that this also raises the per capita consumption growth rate, which with Eq. (20) says that the interest rate is increasing. This is a case where initial emissions are higher but later emissions are lower because the resource extraction profiles before and after the parameter changes in ε and/or ξ necessarily intersect when resource stock is given. These findings are robust against changes in the elasticity of substitution between resources and other inputs. Even in the extreme case of perfect substitution of natural resources, like in the case of a so-called "backstop" technology,

²⁴This makes clear that a climate policy which is effective with intertemporally optimizing resource owners has to limit resource stock S_0 which is available for extraction to a level \hat{S}_0 where stock \hat{P}_∞ with $\hat{P}_\infty = \theta \hat{S}_0$ would be compatible with the agreed temperature target.

²⁵Naturally, initial population size remains unchanged when r increases.

resource owners would still have the incentive to extract the whole resource stock before the backstop arrives.

On a balanced growth path,²⁶ capital stock K grows with output i.e. it grows exponentially while $D = \eta\theta$ is a constant so that total damages (DK) are a convex function of time. Conversely, Eq.(20) enforces declining resource use over time so that P is a concave function of time. Consequently, climate damages DK are convex in pollution stock P . By reducing a constant part of capital stock climate change affects the output level (and hence welfare) but not the economy's growth rate which is driven by the innovation rate, to which I turn in the next subsection.

The results suggest that population policy is not an accurate means to combat climate change but they do in no way challenge the welfare-improving effects of stringent climate policy. Due to the negative externalities of natural resource use, such a policy is unambiguously warranted to increase social welfare. Given the profit maximization of resource owners and the lack of natural decay, the only way to implement an effective climate policy in the present setup is to limit total resource stock which is available for extraction. This limited stock should correspond to a pollution level which is compatible with the temperature targets of international climate policy. I will get back to this point in the next Section.

4.2 Innovation

Knowledge stock grows with innovation and does not depreciate by assumption. Given final and intermediate goods production in Eq. (1) and (2), it is straightforward to see that, in the absence of innovative activities (constant N), output per capita will decrease in the long run because physical capital accumulation runs into decreasing returns ($\beta < 1$) and intermediate input shrinks because of fading resource input ($\hat{R} < 0$, see Lemma 2) and labour reallocation. Hence, innovation growth must necessarily be positive for positive consumption growth per capita. But it does not guarantee positive consumption growth, which requires that innovation growth is strong enough to offset the drag of resource use, which is shown in the next subsection. The steady-state value for the innovation rate is determined in the following

²⁶The emergence of balanced growth and its determination are shown in the next subsection.

Proposition 2 *The long-run innovation rate is given by*

$$g_{\infty} = \max \left[\frac{\varepsilon/\xi + \gamma - 1}{\zeta(1 - \sigma)}, 0 \right] \quad (27)$$

i.e. the innovation rate is high when labour is productive in household (high ε) and in research (high γ), congestion is low (small ξ), spillover reduction is low (small ζ), and the elasticity of substitution, σ , is high.

Proof. See Appendix E. ■

The necessary condition for a positive innovation growth rate in the long run reads $\gamma + \varepsilon/\xi \geq 1$. Hence the contribution of labour to innovation and to reproduction must be jointly sufficient to cope with congestion and to overcome the rising scarcity of natural resources. Provided that exhaustible resources are not an input in research ($\gamma = 1$) the innovation rate is unambiguously positive. A higher elasticity of substitution σ is good for innovation growth but, unlike in traditional capital resource models, its size is limited here by considering poor input substitution i.e. taking $0 < \sigma < 1$. Finally, a small reduction of spillovers by sectoral change, low ζ , fosters the growth rate of innovations.

High ε and low ξ are favourable for population growth, see Eq. (21), and at the same time - following Proposition 1 - good for innovation growth. Conversely, low population growth turns out to be a curse because it limits innovation and therefore development. The first important lesson about long-run growth is that labour productivity is driving both population and innovation growth. Resource scarcity is a major challenge because it affects the innovation negatively through the ever growing resource prices. Climate change has no effect on the innovation rate because labour and knowledge are not affected by climate damages, which I will further discuss below. Hence the growth machine of the world economy is active even with unfavourable climate conditions, provided that labour productivities are sufficiently high so that households keep investing in offspring and/or in innovations.

Corollary *With a constant innovation rate the economy grows along a balanced growth path in the steady state.*

Proof. Using Eq. (1) a balanced growth path is characterized by constant but possibly different and not necessarily positive growth rates of Y , C , K and N . Appendix C shows

that resource price growth and sectoral labour shares are constant in the long run so that the growth rates of Y , C , and K become equal. The difference between the growth rate of N and that of Y , C , and K is determined by the drag of resource use in final goods production which converges to a constant in the long run. ■

Balanced growth in a multisector model with endogenous innovations, physical capital accumulation, and resource extraction is also analyzed in Groth (2007) but there endogenous population and the transition phase of the present model are disregarded. Using the balanced growth equation $\hat{K}_t = \hat{Y}_t = \hat{C}_t$ and rearranging Eqs. (6) and (15) so that capital growth is given by

$$\hat{K}_t = \frac{Y_t - C_t}{K_t} - \theta\eta \quad (28)$$

shows that, given the steady state growth rate \hat{K} , the ratio of gross physical capital investment $Y - C$ to capital K is increasing in climate damage intensity $\theta\eta$ so that with rising damage intensity less output is left for consumption. This is a level and not a growth effect which does not diminish its importance for the economy because it is substantial.

4.3 Consumption growth

To obtain steady-state consumption growth, the development of labour, capital, and intermediate goods has to be calculated. The innovation rate derived above determines the development of the mass of goods variety N . In steady state growth, physical capital grows at the same rate as consumption, i.e. $\hat{C} = \hat{K} = \hat{c} + \hat{L}$. I write $\lim_{t \rightarrow \infty} q_t = q$ for the sake of brevity. As a result I state the following

Proposition 3 *The long-run consumption per capita growth rate is given by*

$$\hat{c}_\infty = \frac{1}{1 - \beta} \left\{ \left[1 - \frac{(1 - \alpha - \beta)(1 - q)}{\gamma} \right] g - \left[\frac{1 - \alpha - \beta}{\gamma} \right] \rho \right\} \quad (29)$$

so that the consumption per capita growth rate increases in the innovation rate g , see Proposition 1, and is high when the output elasticities of labour and capital in final goods production (α, β) and of labour in research (γ) are high and the discount rate ρ is low.

Proof. See Appendix F. ■

For the innovation rate g the comments from above apply. If there is no drag of sectoral change on spillovers, $q = 1$, the impact of innovation rate on consumption growth is unam-

biguously positive, with $q < 1$ it is reduced but does not become zero or negative.²⁷ High output elasticities of labour and capital in final goods production, α and β , are supporting growth because these inputs are growing and counteracting the fading resource input in intermediates' production. In the same way, a high research productivity of labour in research γ is good for growth because labour input is growing while the other input, resources, is declining. High impatience i.e. a high discount rate ρ discourages investments, as usual in growth theory, and leads to more rapid resource extraction. Consumption growth does not exhibit a scale effect i.e. the growth rate is independent of population size, despite the fact that knowledge spillovers are caused by total knowledge stock. The reason is that fading resource use moderates the effect of labour size on innovative activities.

It is worth noting that the framework allows deriving a relatively simple and intuitive growth equation despite the high degree of model complexity. Positive economic growth is feasible with high labour and capital productivity but not achieved under market conditions when labour and capital productivity are low and the discount rate is high. There are no specific limits to growth from climate change, resource scarcity, or population growth except when these variables affect the discount rate, which is discussed in the next section.

5 Discussion and applications

5.1 Model discussion

The model results are driven by some main mechanisms, which are briefly reflected and discussed here. First, climate change affects physical capital but not the research sector which, in the present model, is what Rebelo (1991, p. 515) calls the "core sector" for growth. As a consequence, climate change has no growth effect but a level effect, which still may have a large negative impact on welfare. It is a standard finding in dynamic macroeconomics that endogenous growth can be obtained by constant returns to reproducible factors in the core sector. Here the result stems from a different mechanism because endogenous innovation growth relies on growth of one input, labour, which has to be strong enough to counteract the less-than-proportional contribution of existing knowledge and the negative growth of the other input, natural resources. Second, the intertemporally optimal resource extraction plans imply that market participants are forward looking and that resources are equally shared when families and total population are growing. Rational decisions and

²⁷The parameter constellation $(1 - \alpha - \beta)(1 - q) > \gamma$ would yield a negative impact of innovation on consumption growth but this case can be safely dismissed as the labour share in research, γ , is close to unity while the resource share in final goods production, $1 - \alpha - \beta$, is below 10 percent and $0 < q < 1$.

rational expectations are the usual assumptions in dynamic theory, in particular in growth theory, but they could be too optimistic under political conditions harming the functioning of resource markets. Third, poor input substitution is not hindering growth but rather favourable for development because it induces reallocation of labour to the dynamic research sector. That growth is driven by labour input in innovation follows new growth theory based on Romer (1990) and reflects the idea of the "ultimate resource" put forward by Simon (1981). Fourth, the induced impact of resource scarcity on innovation efforts reflects the ideas of Hicks (1932) and Boserup (1965) where scarcity induces dynamic processes. Remarkably, resource scarcity also affects fertility choices because it is the resource based pressure on wage growth which keeps family investing in offspring.

According to the results there is no guarantee that development be sustainable i.e. the consumption growth rate be zero or positive in the long run. This is a common result in macroeconomics but the context of population growth and climate change suggest having a closer look at the various growth conditions, which is done in the following.

5.2 Model extensions

It is known that the utility discount rate is a crucial parameter in climate economics. When society is not sufficiently patient, resource extraction starts on a high level while investments in financial wealth and offspring are low which unambiguously reduces the growth rate and may turn consumption growth negative. Under unfavourable circumstances, consumption level may fall continuously so that survival of humankind becomes impossible. This may happen when consumption goes below a subsistence level which is defined by minimal nutrition for sustaining population size. Such level is not formally introduced in the above-used felicity function but can easily be added as a first model extension through setting a level \underline{c} below which utility becomes 0. This would not change the main model mechanism because per capita consumption growth does not negatively depend on population growth. However, climate change is a negative externality harming consumption level and welfare by destroying physical capital. Hence, with climate change and under unfavourable conditions consumption level may reach \underline{c} earlier than without climate change which would call for more stringent climate policies to avoid a starving population. A subsidy to research would be an efficient instrument to foster the innovation rate inducing higher consumption growth.

As a second model extension, one may consider climate change adversely affecting the stocks of labour and knowledge. It is known that climate shocks and extreme weather

events may cause losses of human life which would have an impact on the growth rate in our economy. Casualties after climate shocks may become substantial on a local or regional scale but are not expected to have a major impact on the global growth rate. The relative importance is higher in less developed countries while the loss of physical capital does equally apply to all the countries and thus also to the developed countries, which are the main innovators on a global scale. A negative impact of global warming on knowledge capital is not very plausible, this is why it has not been included in the present modelling. But in principle one could add a (small) depreciation rate for knowledge capital as for physical capital and reconsider the model results. Further considerations are to assume an impact of climate change on risk aversion, so-called "risk vulnerability." This could affect the growth rate of the economy but its derivation requires a stochastic framework, see Bretschger and Vinogradova (2018). Finally, a (positive or negative) effect of population growth on diffusion intensity ζ , see Eq. (24), could be postulated but this does not appear to be a very plausible mechanism.

In a third model extension one could inquire further how population growth may have an impact on one of the model parameters determining consumption growth. A possible impact channel is effective through resource use. The term population "pressure" expresses the tendency of a fastly growing population to overuse natural resources. Increasing population size may lead to more rapacious resource extraction. Aggregated over time, total resource stock limits resource extraction but "pressure" could be interpreted in a way that resource extraction becomes rapacious and is preponed, which implies the use of a higher societal discount rate. This then is critical for consumption growth: higher discounting may revert a positively growing economy to a shrinking economy, which again would have to be countered by efficient growth policy i.e. subsidies to research. It is also unfavourable for climate change in a first phase because faster resource extraction at an early stage entails faster pollution accumulation in a first phase. Hence, a link between population growth and devastating climate change may emerge when population growth raises the discount rate such that consumption per capita recedes. A further impact of population "pressure" could be growing exploration activity in the resource sector to raise the stock of available resources; in case of a success this would aggravate the climate problem. Further impacts of population growth on the convexity of the climate damage function and research productivity could be additionally considered but empirical evidence does not appear to support them. The availability of a so-called backstop technology i.e. a perfect substitute

for exhaustible resources at constant prices would alter the outcome in the sense that the resource drag on innovation and consumption growth would be entirely avoided which made unbounded economic growth feasible like in modern endogenous growth theory. Population growth would then actually stop because wages are no longer negatively affected by natural resource scarcity. Current development shows the rising power of renewable energies which we include in the capital stock of our model but it does not suggest a speedy emergence of a backstop e.g. in the form of nuclear fusion.

A further issue not covered in the present model warrants specific attention: heterogeneity among the different countries. Two issues are worth special mentioning. First, with internationally unequal resource scarcity and regionally asymmetric climate damages, there are not only region-specific incentives for having population growth but also strong incentives for international displacement of population i.e. environmental migration. Second, with innovations depending on the availability of skilled labour, the education system and its capacity to educate the labour force (represented by κ in Eq. 8) becomes crucial for development. Given the huge international differences in education systems another source of unequal access to sustainable development becomes evident. These issues constitute important questions for further research in the field.

5.3 Policies

Given the problems of determining a social optimum with endogenous population size, the analysis in this paper is focused on decentralised equilibrium. As climate change is an externality, which in the present model is evident as households do not consider pollution externalities when deciding on resource extraction, appropriate climate policy improves social welfare. With the decentralized Hotelling approach, resource taxation may shift resource extraction over time but does not induce resource stocks to be less than fully exploited, for the reasons already explained after proposition 1. Following Eqs. (5) and (14), the only way to mitigate climate change is to establish a pollution cap translating into a cap for total resource extraction. This can be effectuated by a supply side policy which is decommissioning part of the resource stock.²⁸ In the model calculations, it would reduce the available resource stock S_0 but would not change our results about the "Malthusian perspective" of climate change as given in the propositions. Given a reduced resource stock the growth process would continue in the way described by the model, with resource use

²⁸See Bretschger and Karydas (2018) for further explanations; an alternative policy is to limit demand for resources by supporting the development of a substitute.

approaching but never reaching zero in finite time. The appearance of a backstop technology would be a demand side effect changing resource use but, when resource extraction costs remain unimportant resource owners would still aim at selling the whole stock so that again a supply side policy would be needed to limit climate change.

As a result of the paper, there is no support for population policies, even when including the effects of man-made greenhouse gas emissions on the global ecosystems. Such policies would even be critical because they may harm the research sector, the central growth machine in an innovation-driven economy. Climate policy is improving welfare but not harming the growth process of the economy. It is needed to speed up the decarbonization process which would be too slow and not sufficiently strong if only the Hotelling forces were at work.

6 Conclusions

The paper has addressed the Malthusian concerns that population growth may significantly add to global problems in the context of climate change. Notably, it has dealt with the question whether population growth harms the economy in the future by accentuating the pollution of the atmosphere and whether population growth is bounded by climate change, taking into account the consequences of global warming. As a main result I have found that, also in the context of climate change, specific concerns about population growth are not warranted. The model shows that, in steady state, climate change remains independent of population growth and, during transition, climate change and population growth may move in the same direction for a certain period of time but there is no causal relationship between the two variables. The economy is driven by innovations which emerge at high rate when labour is productive (in research and child rearing), congestion effects of a dense population are low, knowledge diffusion is efficient, and the elasticity of substitution between labour and resources is high. The long-run consumption per capita growth rate increases in the innovation rate, in the output elasticities of labour and capital in final goods production and of labour in research. A low discount rate supports consumption growth and lowers resource price growth. Population policy is not warranted to mitigate climate change, it can even be counterproductive because labour is the crucial input in the research sector.

There are related global problems which are not included in the present model because they go beyond the scope of the used framework. In fact, the model is already very rich and further issues may primarily be raised because the task to address one "big" problem induces

thinking about the other global issues as well. Specifically, income inequality, poverty, unemployment, North South division, ageing, environmental migration, uncertainty, and scarcity of local public goods are all clearly relevant in general and potentially also in a Malthusian context but they all would deserve a more specific analysis which goes beyond the scope of the present contribution.

The paper builds on several central assumptions, specifically on the dynamics of optimal resource extraction and capital accumulation, leading to conclusions which contradict the static view on resource use depending on population size and other scale variables. It would be challenging to see whether results are confirmed or could be extended when including specific further issues like ageing, environmental migration, and uncertainty. Also, it would be rewarding to include in a further step income inequalities and poverty into the analysis and to extend the part on climate policies. This is left for future research.

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7 Appendix

7.1 Appendix A: Optimization

The current-value Hamiltonian for the household problem is

$$H = \log c + \phi \log b + \mu_v \left[(r - \hat{L})v + p_R q + (1 - \chi)w - p_Y c \right] - \mu_q (q + \hat{L} s), \quad (\text{A.1})$$

where μ_v and μ_q denote the costate variables. The following first-order and transversality conditions provide the necessary conditions for an interior solution

$$1/c = p_Y \mu_v, \quad (\text{A.2})$$

$$\phi/b = \chi w b^{(1-\varepsilon)/\varepsilon} \mu_v / \xi, \quad (\text{A.3})$$

$$\mu_v p_R = \mu_q, \quad (\text{A.4})$$

$$\dot{\mu}_v = (\rho - r + \hat{L})\mu_v, \quad (\text{A.5})$$

$$\dot{\mu}_q = (\rho + \hat{L})\mu_q, \quad (\text{A.6})$$

$$\lim_{\tau \rightarrow \infty} \mu_v(\tau) v(\tau) e^{-\rho(\tau-t)} = 0, \quad (\text{A.7})$$

$$\lim_{\tau \rightarrow \infty} \mu_q(\tau) s(\tau) e^{-\rho(\tau-t)} = 0, \quad (\text{A.8})$$

and by the constraints Eqs. (17) and (18). Combining the FOCs yields Eqs. (19), (20) and (21) in the main text.

7.2 Appendix B: Capital markets

At each point in time, return on the market for new blueprints is given by the profit for blueprints or patents, a share $\alpha + \beta$ of intermediate goods sales, plus the change in the asset value \dot{p}_N , which in equilibrium must equal the return on a risk-free asset in the same amount p_N , with return r , so that

$$(\alpha + \beta)p_x x + \dot{p}_N = r p_N. \quad (\text{A.9})$$

Return on the market for physical capital is given by the value marginal product of physical capital $p_Y(\partial Y/\partial K) = \beta p_Y Y/K$ minus the share of capital lost due to climate change $p_Y \theta \eta$, plus the value change, \dot{p}_Y , so that in equilibrium

$$\frac{\beta p_Y Y}{K} - p_Y \theta \eta + \dot{p}_Y = r p_Y \quad (\text{A.10})$$

and with Eq. (1) yielding $p_x x = (1 - \alpha - \beta)p_Y Y/N$

$$r = \frac{(\alpha + \beta)(1 - \alpha - \beta)p_Y Y}{p_N N} + \hat{p}_N = \frac{\beta Y}{K} - \theta\eta + \hat{p}_Y, \quad (\text{A.11})$$

which is a no arbitrage condition for the two types of capital investments.

7.3 Appendix C: Input dynamics

Combining Eqs. (10) and (16) and using average birth flow on the aggregate level ($b = \bar{b}$) yields

$$L_t^\xi = L_{B,t}^\varepsilon. \quad (\text{A.12})$$

Taking growth rates and recalling that $\xi > \varepsilon$ I find for $\hat{L}_t > 0$ that

$$\lim_{t \rightarrow t'} (L_{B,t}/L_t) \rightarrow \bar{\chi}. \quad (\text{A.13})$$

where $t' \in (0, \infty)$. In steady state, resource share in intermediate production m is unity (Lemma 1) and labour share $1 - m$ and thus labour input become zero. Labour is used in final goods production where, by virtue of Eq. (1), it receives a constant share α of total revenues in the final goods sector. Labour is also used in research where, given Eq. (1) and Eq. (7), it receives a share $\gamma(\alpha + \beta)$ of total revenues in the final goods sector $p_{Y,t}Y_t$. From this we see that the ratio of the marginal product of labour in final goods production relative to research is below unity when $\alpha/\gamma(\alpha + \beta) < 1$ which I posit because γ is close to unity. Labour is reallocated to research up to the limiting value for the labour share from the main text, formally

$$\lim_{t \rightarrow t''} (L_{N,t}/L_t) \rightarrow \bar{\omega}. \quad (\text{A.14})$$

where $t'' \in (0, \infty)$. As regards resource extraction, given Eq. (7) we have $\hat{p}_{R,t} + \hat{R}_{N,t} = \hat{w}_t + \hat{L}_{N,t}$ at any moment of time. Using Eqs. (A.13) and (A.14) so that $\hat{L}_{N,t} = \hat{L}_{B,t}$ (for $t > t', t''$) and combining this with Eq. (21) yields $\hat{R}_{N,t} = -\rho$ (for $t > t', t''$). In the steady state, where labour share is zero in intermediate production, $p_{R,\infty}R_{x,\infty} = p_{x,\infty}x_\infty$ which, given Eq. (1), is a share $1 - \alpha - \beta$ of total revenues in the final goods sector $p_{Y,\infty}Y_\infty$. Taking growth rates and using Eq. (20) yields $\hat{R}_{x,\infty} = -\rho$ provided that prices of final output p_Y are normalized to unity (final output is the numeraire) which is a standard procedure. Accordingly, the steady state (de)growth rate of resource use is equalized in the two sectors.

7.4 Appendix D: Proof of Proposition 1

Transversality condition Eq. (A.8) induces resource owners to extract total resource stock, i.e. we have $\int_0^\infty R_t = S_0$. Given Eqs. (14) and (5), maximum pollution stock and thus long-run climate change depend on aggregate resource stock S_0 which is predetermined and independent of population size or population growth. During transition to the steady state, growth of resource extraction approximates a negative constant which is independent of population development, see Appendix C. Resource extraction follows an individually optimal depletion path which is based on a disinvestment decision determined by Eqs. (A.4) - (A.6) (see Appendix A) and the price equation Eq. (20); at each point in time this determines resource demand in the intermediates sector and thus pollution growth. Like resource extraction, population growth is an endogenous variable based on fertility choice which is an investment decision driven by its return. Disinvestment in resource stock and investments in offspring are compared to investing in an alternative asset, which is a bond yielding nominal interest rate r . In the expression Eq.(21) we see that higher return (higher r) and moderate wage growth (lower \hat{w}) increase the population growth rate. But it does not emerge from the model that there is a causal relationship between population growth and resource use. The easiest way to confirm this is to change both investment decisions simultaneously assuming a higher return on the alternative asset r . While this increases population growth via Eq.(21) it does not increase emissions at all times, which is not possible due to the resource stock constraint Eq.(5), invoking Eqs. (A.4) - (A.6), and (20); we find it only accelerates emissions in a first phase while reducing them compared to a lower interest rate at a later stage. When we assume family productivity ε to increase and/or congestion in child rearing ξ to decrease, the two effects raise \hat{L} , see Eq. (21), so that the industrial sectors have more labour input available. New blueprints are crafted under the conditions of a Cobb-Douglas production function, see Eq. (7) so that the output and the substitution effects of higher labour input cancel, resource demand will be unchanged. In the intermediates sector, see Eq. (2), when assuming that input substitution is poor ($0 < \sigma < 1$), the output effect dominates the substitution effect so that resource demand increases *ceteris paribus*, which raises emissions. However, given that total resource supply is fixed, the relatively higher demand in the present has to be compensated by lower demand in the future. Accordingly, the existence of a causal link between population growth and climate change cannot be confirmed with the present model setup, which incorporates optimal intertemporal resource extraction. Using $P_t = \theta(S_0 - S_t)$, setting $P_0 = 0$, and

combining Eqs. (14) and (15) I get

$$D_t = \eta\theta = D$$

so that $D_t = D$ is a constant. Capital stock is reduced by climate damages at a constant rate. Due to decreasing returns to capital in final goods production, capital growth rate is driven by the innovation growth rate (given in proposition 2) like in the basic Ramsey model. Population growth is not reduced by polluting resource use but rather supported because resource scarcity induces labour outflow from the intermediates sector which makes child rearing more attractive, see Eqn. (11) and (10) while pollution is an externality which is not considered on the level of the individual household decision.

7.5 Appendix E: Proof of Proposition 2

Cost minimization in the research sector, see Eq. (8), yields

$$\frac{R_{N,t}}{\kappa L_{N,t}} = \left(\frac{w_t}{p_{R,t}} \right) \left(\frac{1-\gamma}{\gamma} \right). \quad (\text{A.15})$$

I rewrite Eq. (8) as

$$g_t = \kappa L_{N,t} \left(\frac{R_{N,t}}{\kappa L_{N,t}} \right)^{1-\gamma} N_t^{q_t-1} = \kappa \tilde{\gamma} L_{N,t} \left(\frac{w_t}{p_{R,t}} \right)^{1-\gamma} N_t^{q_t-1}, \quad (\text{A.16})$$

where $\tilde{\gamma} = \left(\frac{1-\gamma}{\gamma} \right)^{1-\gamma}$. Using Eq. (4) I express relative input prices as

$$\frac{w_t}{p_{R,t}} = \left(\frac{m_t}{1-m_t} \right)^{-\frac{1}{1-\sigma}} \left(\frac{\lambda}{1-\lambda} \right)^{\frac{\sigma}{1-\sigma}}, \quad (\text{A.17})$$

so that the innovation rate becomes

$$g_t = \kappa \tilde{\gamma} \tilde{\lambda} L_{N,t} \left(\frac{m_t}{1-m_t} \right)^{-\frac{1-\gamma}{1-\sigma}} N_t^{q_t-1}, \quad (\text{A.18})$$

where $\tilde{\lambda} = \left(\frac{\lambda}{1-\lambda} \right)^{\frac{\sigma(1-\gamma)}{1-\sigma}}$. Rewriting Eq. (21) as

$$\hat{L}_t = \frac{\varepsilon}{\xi} (r_t - \hat{w}_t) - \varepsilon \rho / \xi. \quad (\text{A.19})$$

and using Eq. (22) yields

$$\hat{L}_t = \frac{\varepsilon}{\xi(1-\sigma)} \left(\frac{\hat{m}_t}{1-m_t} \right) - \varepsilon \rho / \xi. \quad (\text{A.20})$$

Integrating over time gives for the steady state

$$L_\infty = \varphi \left[\frac{m_\infty}{1 - m_\infty} \right]^{\frac{\epsilon}{\xi(1-\sigma)}} \quad (\text{A.21})$$

where φ is an integration constant i.e. $\varphi = \varphi(L_0)$. Using Eq. (A.14) i.e. $L_{N,\infty} = \bar{\omega}L_\infty$ and inserting in Eq. (A.18) yields the steady-state innovation rate as

$$g_\infty = \varphi \kappa \tilde{\gamma} \tilde{\lambda} \bar{\omega} \left[\frac{m_\infty}{1 - m_\infty} \right]^\Omega N_\infty^{q-1} \quad (\text{A.22})$$

where $\Omega = (\epsilon/\xi + \gamma - 1)/(1 - \sigma)$. Constant innovation rate, $\hat{g}_\infty = 0$, says with Eq. (24) that

$$\frac{\Omega \hat{m}_\infty}{1 - m_\infty} = \frac{\zeta \hat{m}_\infty}{1 - m_\infty} g_\infty \quad (\text{A.23})$$

so that

$$\Omega = \zeta g_\infty \quad (\text{A.24})$$

from which immediately follows the result in Proposition 2.

7.6 Appendix F: Proof of Proposition 3

On a balanced growth path we have $\hat{Y} = \hat{K} = \hat{c} + \hat{L}$ and $\hat{L}_Y = \hat{L}$; the innovation rate g is constant and given by Eq. (27) and intermediates good production x asymptotically shrinks the rate of R_x which is $-\rho$, see Appendix B. Then I obtain by taking log differentials of Eq. (1) and using Eq. (27)

$$\hat{c}_t + \hat{L}_t = \alpha \hat{L}_t + \beta (\hat{c}_t + \hat{L}_t) + g - (1 - \alpha - \beta)\rho \quad (\text{A.25})$$

$$\hat{c}_t = \frac{1}{1 - \beta} \left[g - (1 - \alpha - \beta) \hat{L}_t - (1 - \alpha - \beta)\rho \right] \quad (\text{A.26})$$

Furthermore, using $\hat{L}_{N,t} = \hat{L}_t$, $R_{x,\infty} = -\rho$, $q_\infty = q$ and the fact that innovation rate is constant in steady state as given in Eq. (27) as well as Eq. (8) yields

$$\begin{aligned} 0 &= \gamma \hat{L}_t - (1 - \gamma)\rho - (1 - q)g \\ \hat{L}_\infty &= \frac{1}{\gamma} [(1 - \gamma)\rho + (1 - q)g] \end{aligned}$$

so that

$$\begin{aligned} \hat{c}_t &= \frac{1}{1 - \beta} \left[g - \frac{1}{\gamma} (1 - \alpha - \beta) [(1 - \gamma)\rho + (1 - q)g] - (1 - \alpha - \beta)\rho \right] \\ &= \frac{1}{1 - \beta} \left[g - \frac{1}{\gamma} (1 - \alpha - \beta) (1 - q)g - \frac{1}{\gamma} (1 - \alpha - \beta) (1 - \gamma)\rho - (1 - \alpha - \beta)\rho \right] \end{aligned}$$

giving the result of Proposition 3.

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