Is Less Really More? Comparing the Climate and Productivity Impacts of a Shrinking Population [*]

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Abstract: A smaller human population would produce less carbon emissions, other things equal. This fact has led to the view that an important benefit of the present global decline in fertility will be reductions in long-run temperatures. Here we assess the magnitude and economic significance of this relationship. We find that it is quantitatively small and, therefore, insignificant relative to other well-documented effects of population growth. This conclusion follows from facts related to timing: Population sizes respond to growth rate increases with a many-decades lag, by which point per capita emissions are projected to have significantly declined. The additional warming from increased population growth is inconsequential when compared against the resulting productivity gains. Furthermore, even the *sign* of the population-warming relationship is ambiguous when aggregate net-negative emissions are accounted for. Alongside other benefits, increased population growth plausibly leads to *lower* long-run warming.

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1 Introduction

A smaller global population would produce fewer carbon emissions, holding all else fixed. This fact informs a widely held view that reductions in population growth can play an important role in mitigating the eventual damages from climate change (Bongaarts and O'Neill, 2018; Wynes and Nicholas, 2017; Conly, 2016). However, there are also well-documented benefits of large and growing populations via market size effects and business dynamism (Karahan et al., 2019; Peters and Walsh, 2021; Hopenhayn et al., 2022), increased provision of non-rival goods (Romer, 1990; Jones, 2022; Peters, 2022), and a less retiree-heavy age structure (Vollrath, 2020; Maestas et al., 2023).

Understanding which of these categories of population impacts on living standards—climate or productivity—is likely to dominate in the near and distant future is important: Two thirds of people now live in a country with below-replacement fertility and the global population is projected to begin shrinking within the next few decades (Vollset et al., 2020; United Nations, 2022). Various evaluations of a smaller population indicate that the costs and benefits have the potential to be large. For example: achieving 2°C (rather than 4°C) may avert more than 10 p.p. of GDP losses annually (see e.g., Burke et al., 2015; Howard and Sterner, 2017), and recent work in Jones (2022) suggests economic growth may end entirely under enduring population decline. Yet, there has been remarkably little dialogue between, on the one hand, research using integrated assessment models to understand the climate costs of human activity and, on the other, work studying the relationship between population and economic growth. How these forces compare and what this implies for future living standards thus remains an open and critical question.

In this paper, we quantitatively assess the climate and productivity impacts of a shrinking population. We begin with a simple analytical model to clarify how changes in population growth (a flow) pass through to long-run cumulative emissions (a stock), arriving at a closed-form relationship between these terms. This solution demonstrates exactly how this link is mediated by the rate of (per capita) decarbonization and helps to develop intuitions for the dynamic interactions at the core of our analysis. Calibrating the relevant parameters to possibilities for decarbonization paths yields the novel result that the pass-through from population growth to long-run warming is necessarily limited. This insight—about the response of cumulative emissions to future population size—is critical for understanding why even moderate productivity losses caused by a shrinking world might outstrip the climate benefits of smaller population sizes.

The simple model illustrates the key mechanism over the long run, but does not deliver detailed quantitative comparisons or consider medium-run dynamics of the decades ahead. To generate these assessments, our main numerical exercise builds on William Nordhaus' DICE model (Nordhaus, 2017), the most widely-used and studied climate-economy model. We innovate on this model by incorporating two key ideas related to population growth: (i) that people are the source of non-rival innovations and ideas that propel economic growth, and (ii) that some consumers are too young or too old to also be workers, so that changes in the age structure of the population can affect per capita production for a given population size. The innovation effects of population are calibrated to recent estimates of the elasticity of productivity gains with respect to research inputs (Bloom et al., 2020). Within this framework, we contrast per capita output under two paths for future population: a shrinking population that is consistent with consensus projections and alternatively a stable-population future.

Consistent with the intuition from the analytic model, the result from the integrated climate assessment highlights the strikingly small temperature response to changes in future population size. Immediate and persistent increases to fertility, even to unrealistically high levels, produce a difference of 0.05°C by 2200 relative to status-quo projections of global depopulation in our quantitative model. This is on a decarbonization trajectory where emissions remain positive for another century and eventual warming exceeds 4°C. Specifically, the larger population scenario we study has about 6 billion more people by 2200 who face warming of 4.25°C rather than 4.20°C. This finding is not built-in as an assumption: We do not specify that the rate of decarbonization increases with population size through increased innovation or a planner's reoptimization. We conservatively and mechanically hold fixed the time path of emissions-per-output-unit across the large population and small population scenarios.

In terms of productivity costs of a smaller population, the integrated model finds that increases in fertility, relative to the status quo population decline would yield benefits mainly because of the contribution to productivity of increased non-rival innovation that a larger population can sustain.

In contrast to conventional wisdom, but as anticipated by Weil (1999, 2023), the dependency ratio benefits are more limited, and are realized only after many decades. This is because the additional children in a higher-fertility scenario actually increase the dependency ratio and contribute to lower production in the short-run relative to the shrinking population. Overall, the climate costs of a larger future population according to standard climate damage functions are small compared to the competing economic effects, all measured on a common scale of per capita economic output.

This surprising conclusion follows from facts of timing: Both population size and cumulative concentrations of atmospheric greenhouse gases (GHGs)—the driver of global warming—are slow-moving stocks. Changes in population growth rates take many decades to generate significant changes in population sizes. Many decades from now, the remainder of humanity's emissions will be small relative to the existing stock of accumulated atmospheric GHGs, under even pessimistic assumptions for climate policy. Scaling up or down this small remainder does not importantly influence the long-run stock of atmospheric GHGs. This implies that in the long run the gains associated with a larger future population need not be large to dominate the tiny difference in temperature generated by the larger future population. However, the time path of these effects shows that there is an inter-generational trade-off: the net effect of the larger population scenario (which assumes near-term increases in fertility rates) leads to lower per capita output in the shorter run of the next few decades before the new, larger generations age into the workforce. The dynamics arising from differences in the age distribution are not in contradiction with our main result. Leaving aside the economic impacts of a larger and growing population, the climate cost of a larger population is still economically insignificant.

These results are robust to a wide range of model specifications. For example, climate damage functions that translate temperature changes into human harms are an area of uncertainty and active research in climate science (Burke et al., 2015; Moore and Diaz, 2015; Dietz et al., 2021, etc.). Increasing the scale or shape of the climate damage function lowers long-run incomes (and hence increases the social cost of carbon) in both population scenarios, but the function acts on a temperature difference too small to outpace the productivity benefits of a larger population for any assumptions on damages. Likewise, because the small temperature difference between population scenarios is driven by a small difference in cumulative emissions, the findings are not sensitive to use of a more sophisticated climate and atmospheric representation, which translate from emissions to temperatures. The same is true for other model dimensions that we vary. The most critical assumption is over the pace of decarbonization. Throughout our presentation of the main results, we demonstrate that even in worst-case futures with more than 6°C of warming, the *difference* in climate damages between population scenarios is small. This carries the important implication that climate policy and technology will succeed or fail independent of population trajectories, and suggests against describing population decline as an important component of climate action.

Finally, as an extension of the main exercises, we consider the scenario in which it is eventually possible to produce *negative* emissions at scale. Already, there exist activities for generating negative emissions. These include high-tech approaches (e.g., direct air capture) and low-tech approaches (e.g., planting trees and weathering—crushing rocks to capture CO_2 in sediment as bicarbonate). In a future with scalable versions of carbon-negative technologies, even the sign of the relationship between warming and population growth is ambiguous. A larger population produces more near-term emissions which warm the planet, but can then also produce more negative emissions into the indefinite future, which re-cool the planet. Considering net-negative aggregate emissions upsets (and even reverses) common intuitions about population and climate: For any fixed stock of cumulative historical emissions to date, capturing them from the atmosphere is a global public good that can be more cheaply produced on a per capita basis by a larger population than a smaller one. Therefore, even a dogmatic planner with an objective function that only values achieving some long-run temperature target may prefer the population scenario with higher levels of near-term population growth.

This paper contributes to an active and influential debate on the climate effects of population dynamics. Our first contribution is demonstrating that changes to future population growth have, at worst, small negative impacts for climate outcomes. This finding is in direct contrast with the dominant view in academic and public discussions. Within economics Kruse-Andersen (2019) and Gerlagh et al. (2023) find that population policy is a useful (or even necessary) complement to policy aimed at lessening global warming in part because these authors assume that population sizes can respond much more quickly than is realistic.[1] Casey and Galor (2017) reports a headline finding that a simulated reduction in fertility can reduce annual emissions by 35% by 2100. Our paper clarifies why the Casey and Galor (2017) estimate can be both correct and misleading as a guide to understanding the climate impacts of future population growth or decline: The climate impact of a 35% reduction in emissions by 2100 depends on the base emissions flow in that year and afterward. Understanding this nuance is especially important given that the pace of actual and projected decarbonization has substantially accelerated over just the past few years. And it underscores the usefulness of our analytic model, which highlights and separates the parameter describing per capita emissions as a time-dependent variable.

Our second contribution is to propose, for the first time, that a comparatively larger population could have positive climate impacts in the longer run. The sum total of all historical emissions presents a fixed-cost problem (i.e., not tied to current population size) from the perspective of a future generation employing a negative emissions technology. By relaxing the assumption that per capita emissions are bounded below by zero, we cast doubt on even the sign of the long-run population-warming relationship. This insight complements the few existing papers re-examining the importance of population growth for climate outcomes. Bretschger (2020) makes the theoretical point that the optimal path of fossil fuel use will be independent of population sizes, generating a null relationship in steady-state between population sizes and cumulative emissions. Our lesson is different, and extends to settings where the path of fossil fuel use is, in fact, sensitive to population sizes.[2]

Finally, we contribute to the long and ongoing debate on the relationship between population trajectories and per capita incomes by showing that common sources of economic benefits from

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[1] For example, Kruse-Andersen (2019) studies a high-population scenario with a working age population of 10B in 2100 (whereas the UN's 95% confidence interval for individuals aged 25-64 in 2100 extends to a maximum of 6.8B); Gerlagh et al. (2023) compare scenarios of total population that range from 8B to 12B by 2060 (the UN's 95% confidence interval for this year is 9.7B - 10.7B). Population forecasting is fairly mechanical on time-horizons of decades, so it would be very surprising to observe such large deviations from leading projections.

[2] Alternatively, Budolfson and Spears (2021) shares our focus on the slowness of population changes, but makes a much weaker claim. They show that fertility reduction cannot be a "core" mitigation strategy by showing that 'no climate policy' scenarios still reach 6.4°C (as opposed to 7.1°C) under large declines in fertility rates. This leaves open the relevant questions of (1) what temperature reductions can be achieved on plausible decarbonization trajectories and (2) whether these reductions are economically significant. We show that they are much smaller than the 0.7°C difference found under their (now outdated) 'no policy' path and much less consequential for per capita income than other effects of population growth. See also our companion paper for the demography literature (Kuruc et al., 2023).

population growth have much larger effects than (marginal) climate damages. This literature is vast, encompassing many forces.[3] We do not aim to incorporate every channel by which increases in fertility could decrease living standards. Instead, this paper rules out a widely cited channel by which a larger population could reduce long-run living standards—climate harms. Our findings indicate that future exercises attempting to sort out the net effects of population growth can set aside the marginal climate damages as a second-order consideration.

2 An analytical demonstration of dynamic interactions between emissions and population

This section proposes a tractable analytical framework that links near-term changes in population growth to long-run changes in atmospheric GHGs. Rather than quantify this effect in a numerical setting—the objective of Section 4—the goal here is to clarify the dynamic interactions that drive the main results. The key insight is that altering the population growth rate now will not meaningfully change population size on a timeline relevant for impacting the stock of GHGs and long-run warming.

Global warming is determined by the stock of atmospheric GHGs. We denote this long-run stock as $\mathcal{E}$ and employ a simple atmospheric representation where this stock is equal to the time-independent sum of instantaneous emissions, $E(t)$. The present day is normalized to $t = 0$, such that $t < 0$ is the past.

$$\mathcal{E} = \int_{-\infty}^{\infty} E(t)dt \tag{1}$$

There is no time-subscript on $\mathcal{E}$ because it is a representation of where the stock of emissions converges as the flow of emissions converges to zero. This is what we refer to as the "long-run" stock of emissions, which in turn leads to some fixed level of long-run warming.[4]

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[3] Alongside the citations in the first paragraph, see recent work by Dasgupta et al. (2021), Henderson et al. (2022), Pindyck (2022) and others.

[4] A more realistic model would include depreciation of this stock because CO_2 does eventually dissipate from the atmosphere. However, its atmospheric half-life is longer than one century, so for the purposes of this exercise a zero rate of depreciation is a reasonable simplification. We defer detailed climate modeling to our integrated assessment that begins in Section 3.

The evolution of $E(t)$ follows from the evolution of population, $N(t)$, and per capita emissions, $\epsilon(t)$. The respective rates of change for population and per capita emissions are denoted g and d. We take these as independent of one another; for simplicity and conservatism a larger population does not endogenously change the rate of per capita decarbonization.

$$\begin{aligned} E(t) =& N(t) \times \epsilon(t) && (2) \\ N(t) =& N_0 e^{gt}, \text{with } \ g > 0 && (3) \\ \epsilon(t) =& \epsilon_0 e^{-dt}, \text{with } \ d > g && (4) \end{aligned}$$

Equations 2 – 4 imply the following path of exponential decay for aggregate emissions.

$$E(t) = E_0 e^{-(d-g)t} \tag{5}$$

Equation 5 implies a simple analytical relationship between g, d and all future emissions. Denoting the pre-determined stock due to historical emissions as $\mathcal{E}^h$, we have:

$$\begin{aligned} \mathcal{E} =& \mathcal{E}^h + \int_0^\infty E(t)dt \\ =& \mathcal{E}^h + \frac{E_0}{d-g}. && (6) \end{aligned}$$

Equation 6 makes clear that there are two forces limiting the pass-through from population growth rates to the stock of long-run cumulative emissions. First, there already exists a non-trivial concentration of GHGs. This will be important for intuitions that rely on proportionately scaling up or down the total stock. Second, population growth is only one of two channels which determine aggregate future emissions. Future emissions, of course, also depend on the evolution of per capita emissions. Formally, the derivative of $\mathcal{E}$ with respect to the population growth rate g is:

$$\frac{\partial \mathcal{E}}{\partial g} = \frac{E_0}{(d-g)^2}. \tag{7}$$

It will be helpful to contextualize this with numerical values. Assume that $(d - g) = .02$, which implies a half-life of aggregate (annual) emissions of 35 years by Equation 5. Under this assumption, annual emissions will be only halfway to net-zero by 2060. Cumulative future emissions would be equal to $\frac{1}{0.02} = 50$ times our current annual emissions. This is a fairly pessimistic emissions trajectory, especially in relation to international targets. It implicitly assumes many more years in which population will influence annual emissions.

And yet, it implies a small population growth effect on long-run warming. For example, consider an increase in g of 0.1 p.p., a non-trivial increase on its current base of 0.8%. According to Equation (7), this increases emissions by $2.5 \times E_0$.[5] In other words, a 12.5% increase in g leads to only a 5% increase in future emissions.[6] And what matters is $\mathcal{E}$, which will increase proportionally less than future emissions because of the pre-determined stock, $\mathcal{E}^h$. Empirically, the existing stock of historical emissions is also approximately 50 times more than current annual emissions.[7] Therefore, under the $(d-g) = 0.02$ assumption, $\mathcal{E}^h \approx \mathcal{E}^f$ (where $\mathcal{E}^f$ denotes all future emissions). The elasticity of $\mathcal{E}$ with respect to g is then about 0.2.

$$\frac{\partial ln(\mathcal{E})}{\partial ln(g)} = \underbrace{\frac{\mathcal{E}^f}{\mathcal{E}}}_{\approx 0.5} \times \underbrace{\frac{g}{d-g}}_{\approx 0.4} = 0.2 \tag{8}$$

It is worth better understanding the intuition behind this small value. It is the key feature underlying the paper's results. If we had naively assumed that N, rather than g, were immediately and permanently increased, the pass-through would be much larger. In fact, there would be a unit elasticity, rather than 0.4, between cumulative future emissions and population because there would simply be a 1% increase in emissions in each period under our assumptions. The difference arises from timing: an increase in g leads to a proportionally similar increase in N only after many decades. For example, a 1% increase in g from a base of 0.8% (to 0.808%) takes *125* years to result in a 1% increase in the population size.[8] Over these decades, emission intensities are declining. The

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[5] $\frac{E_0}{(d-g)^2} = 2500E_0$ for a one-unit increase, or $2.5E_0$ for an increase of 0.001.

[6] $2.5E_0/50E_0 = 0.05$.

[7] Current total CO_2 emissions are about 38 billion tonnes, whereas cumulative historical emissions are about 1.7 trillion tonnes (see `https://ourworldindata.org/grapher/cumulative-co-emissions`.

[8] For the time it takes to achieve a (counterfactual) 1% increase in the size of the population from a 1% increase in g, consider that $\frac{N_t'}{N_t} = \frac{N_0 e^{0.00808t}}{N_0 e^{0.008t}} \Rightarrow 1.01 = e^{.00008t} \Rightarrow t = \frac{.01}{.00008} = 125$.

population becomes significantly larger only *after* per capita emissions are much lower than their current level, limiting the ability for population size to influence the long-run stock of emissions.

This simple setting provides strong reason to believe that the emissions, and therefore warming, effects of increases in population growth will be small. A richer quantitative model is necessary for demonstrating exactly how small, and how the implications of these small increases compare with the economic effects of population growth. That is the task of the next two sections. To preview: The marginal warming from changes to population growth is insignificant relative to the productivity benefits.

3 Integrated assessment model of population, the economy, and climate

The prior section analytically demonstrated that the impact of population growth on warming is likely to be small. This section describes the rich model that we use to study the quantitative tradeoffs between climate costs and productivity benefits, and outlines the emissions and population paths that we consider.

3.1 The DICE model

We start with DICE (Nordhaus, 2017), the most widely known and well-studied climate-economy model. DICE is not explicitly designed to study the implications of population growth, but is built on top of a neoclassical growth model in which labor contributes to output (and output determines capital accumulation, emissions, and so on). The model is therefore already set up in a way that generates an emissions response to a change in the path of population. We build on this by incorporating (1) the productivity and (2) the impacts of population growth on the dependency ratio.

The standard DICE model that we start from combines three features: (a) a neoclassical model of economic growth where labor, (accumulated) capital, and productivity determine production, (b) a reduced-form representation of greenhouse gas emissions, concentrations, and temperature consequences, and (c) a damage function that translates temperature changes to future losses of economic well-being. Formally, gross production, Y^G, is defined by a standard Cobb-Douglas production function which includes capital, labor, and total factor productivity (TFP), A. Net output, Y^N, which can be used for consumption and investment, is what is left of gross output after GHG mitigation costs, Λ, are paid and climate damages, D, are suffered. Damages are represented as losses to GDP, but are calibrated to include the monetary value of non-market harms (e.g., health and mortality effects). D is assumed to increase quadratically in temperature T (above pre-industrial levels), although we explore alternative specifications in robustness exercises.

$$Y_t^G = A_t K_t^\gamma L_t^{1-\gamma} \tag{9}$$

$$Y_t^N = (1-\Lambda_t)(1-D_t) A_t K_t^\gamma L_t^{1-\gamma} \tag{10}$$

$$D_t = \psi_1 T_t + \psi_2 T_t^2 \tag{11}$$

Industrial emissions, E_t, are a function of gross output, determined by the emissions-intensity of production, σ_t. These emissions can be abated at rate μ_t, which determines cost Λ in Equation (10).

$$E_t = (1-\mu_t)\sigma_t Y_t^G \tag{12}$$

$$\Lambda_t = \theta_1 \mu_t^{\theta_2} \tag{13}$$

For brevity, we omit description of the climate and atmospheric modules, which map the history of E_t (and non-industrial emissions) to T_t. They are discussed in detail elsewhere (see e.g., Nordhaus, 2017), and are not directly relevant for the economic lessons of this paper.[9]

We first modify DICE to incorporate the productivity benefits of population. The original DICE model assumes that productivity increases are exogenous. Instead, following the semi-endogenous growth literature (Jones, 1995, 2022), we allow for resources—namely, people—to contribute to economic growth. These models build on the insight by Romer (1990) that larger economies produce more non-rival goods on aggregate (such as ideas and innovations), which increase per capita productivity.

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[9] Furthermore, we verify that this module is not consequential for the main results: robustness exercises that substitute the DICE atmospheric module for a well-regarded alternative representation of this process does not influence the result.

Specifically, we employ a canonical semi-endogenous growth equation.

$$g_{A,t} = \frac{\Delta A_t}{A_t} = \alpha_t L_t^{\lambda} A_t^{-\beta}. \tag{14}$$

The rate of increase of A is increasing in the size of the labor force, L (not the population). Innovation and progress comes from economic activity—either through learning-by-doing or explicit research efforts—which scales with L. α_t is a scaling factor between the labor force and the production of ideas, determined by the share of the labor force participating in idea production as well as the productivity of this sector. λ allows for intra-period increasing or decreasing returns to research effort. $\beta > 0$ allows for the possibility that there are dynamic diminishing returns to knowledge accumulation. If proportional increases in productivity become more difficult to achieve as productivity increases, that would be reflected by a large value for β.

It is important to note that there is no link between TFP, A, and the emissions intensity of output, σ. This is for conservatism: our main finding is that the impact of population growth on total emissions is small, even without assuming that a larger population endogenously increases the speed of decarbonization.[10] Both population scenarios that we study here (and describe further below) face the same exogenous path of σ_t.

The second major modification of DICE is to include dependency ratio effects. Because DICE was not designed to explicitly study changes in population growth rates, the standard model assumes that workers scale linearly with the population and the distinction between workers and people is omitted. We decouple the total population from the work force based on the age structure in each period of the respective population scenarios described in Section 3.2. In Equation 9, L is the working-age population, which is not equal to the total consuming population, N, in our implementation. Accordingly, the working-age population ratio is $\frac{L}{N}$ and the dependency ratio is $1 - \frac{L}{N}$.[11]

As a final minor modification to DICE, we endogenize the emissions from changes in land

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[10] Furthermore, Kruse-Andersen (2019) finds that endogenous progress in decarbonization technologies will have a second-order effect on emissions relative to changes in population size.

[11] Modifying the labor input in this way implies an immediate and permanent decrease in L relative to DICE, where every person is assumed to be in the labor force. To avoid mechanically reducing total production from this redefinition, we add a constant scalar on labor productivity equal to $\frac{N_{2020}}{L_{2020}}$ to replicate year 2020 output.

use (E_{land}, e.g., from deforestation). These are exogenous in DICE, corresponding to its single exogenous path of population. We assume a unit-elasticity between population and land-use emissions, such that for population path m in time t:

$$E_{land,m,t} = \frac{N_{m,t}}{N_{DICE,t}} \times E_{land,DICE,t}. \tag{15}$$

If the population is $x\%$ larger in time t than it is in DICE for that period, land-use emissions will also be $x\%$ larger than in DICE for that period.

We do not explicitly model fertility decisions, or any other channel by which populations endogenously evolve. The analysis aims to understand the consequences of a shrinking population, which represents the demographic consensus, versus a stable population, not which trajectories are more or less likely. Section 3.2 discusses the construction of these two exogenous population paths.

Parameter values for these modules are taken directly from DICE where possible.[12] For the semi-endogenous growth parameters, we use $\lambda = 1$ and $\beta = 3.1$, based on Bloom et al. (2020). We calibrate α_t to exactly match DICE's exogenous path of TFP growth when the population trajectory from DICE is inputted. Our goal is to replicate the baseline DICE model as closely as possible in an effort to isolate the effects of population, not any modifications of DICE itself. When the DICE population is read into our model, the exact output from DICE is obtained for all variables (see Appendix Figure A1).

In summary, the modifications to DICE are as follows: (i) Technological progress increases in population size based on the endogenous growth literature; (ii) the distinction between total population and labor is explicitly represented, such that an economy with more children or retirees has lower GDP per capita, other things equal; and (iii) emissions from deforestation and other sources of land use scale with population. Alternative model specifications presented in Section 4.2 additionally modify the climate damages in DICE, replace DICE's climate module with the Finite Amplitude Impulse Response (FAIR) climate module in line with recommendations from

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[12] The version we modify is DICE2016—the latest version available at the time of research—which is publicly available on Nordhaus' website (`https://williamnordhaus.com/dicerice-models`) and has been translated to other software and coding languages that we build from (see `https://www.mimiframework.org/`). Since performing this research, DICE2023 has been released. Most of the modifications align with modifications we had independently made in the robustness checks of Section 4.2.

the National Academies (2017), and increase the emissions impact of population. These analyses demonstrate that our results are robust to these modeling choices.

To study the climate costs of population paths, a stance must be taken on a climate policy path. Advances in renewables technology and the implementation of (some) mitigation-inducing policy has rendered common "business as usual" emissions paths pessimistic relative to updated estimates of the world's likely emissions and warming trajectory (Ou et al., 2021). In our baseline case, we assume a path of mitigation rates calibrated to global emissions in 2030 and 2100 under the current policy trajectory estimate in Ou et al. (2021). This assumed "current policy" trajectory exhibits reductions of (net) emissions by the end of this century, but too slowly to meet international climate goals (see Figure 2a). For conservatism, we also consider a "low ambition" policy environment when presenting our main results, which yields end-of-century warming similar to common worst-case climate scenarios (Figure 2b). In Figure 3 we additionally consider an alternative climate policy path that is much more ambitious than the baseline. (See also Section 4.2.)

The comparative analyses between the two population scenarios hold policy—i.e., mitigation rates in each period—fixed and let the level of emissions differ based on the level of economic activity (which is in turn influenced by population size).

3.2 Population paths: *Depopulation* versus *Stabilization*

We compare two paths for the long-run global population: *Depopulation* and *Stabilization*. They are plotted in Figure 1. *Depopulation* represents demographers' central, consensus projection of the demographic future (United Nations, 2022; Basten et al., 2013; Raftery and Ševčíková, 2023): Fertility rates worldwide will converge to below-replacement levels (i.e., lower than 2.1 births per woman) and global population growth will become negative later this century. Quantitatively, we use and extend population projections by the United Nations (UN) World Population Prospects (United Nations, 2022). The path follows the UN Medium projection until 2100, when that projection ends. After 2100 we mechanically project continued (negative) population growth, guided by Basten et al. (2013) and Spears et al. (2023), the latter of which is a companion paper detailing the long-term decline scenario studied here. In this population path, the global total fertility rate converges to

1.66 births per woman, the current TFR in the United States, and a value that is on the higher end of developed economies as a whole.

In the *Stabilization* path, negative population growth is avoided and the population stabilizes. This purely hypothetical scenario is constructed by combining two existing UN scenarios: the Instant Replacement variant for High-income, Upper-middle-income, and Lower-middle-income countries, according to World Bank income groups, and the Medium variant for Low-income, and No-income-group-available countries (so these latter two country groups have the same path to 2100 in *Stabilization* and *Depopulation*).[13] The Instant Replacement variant is one in which fertility rates immediately increase to replacement rate (about 2.1 births). After 2100, when the UN projections end, fertility rates in richer countries remain at replacement rate, and fertility rates in Low-income and No-income-group countries converge to replacement if they have not already reached that level. In this scenario, the global population stabilizes in the long-run at about 13 billion people. The age pyramid stabilizes with about half of the population in working ages at any give time in later centuries. This is approximately the working-age proportion of the population that the UN projects for 2100 in High-income countries.

Our results are not contingent on the particular population paths that we compare here. The economic benefits of population far outweigh the climate damages even in a comparison between *Depopulation* and a much higher population projection, one which is well beyond the upper bound of the UN's 95% prediction interval for the demographic future (see Appendix Figure A3).

Figure 1 demonstrates the overall population pathways and highlights the distinction between stocks and flows that are important for understanding our results. Despite the immediate jump in fertility rates in the *Stabilization* path, and a population difference by 2200 of nearly 100%, it takes until the end of this century for the difference in population size between the two paths to exceed just 10%. The main result follows immediately from this (lack of) difference in population size during the time in which the world is expected to make progress towards net-zero emissions.

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[13] The distinction between countries by income level is purely functional for the construction of the *Stabilization* path. Country income level is correlated with fertility. The strategy described here brings below-replacement fertility countries (which happen to also be richer) up to replacement level, and allows above-replacement fertility countries (which happen to be poorer) to continue their UN-projected decline until 2100. In DICE, we input paths for the *global* labor force and population size, and do not disaggregate by country.

4 Results: Differences in emissions, temperature and per capita income from simulated differences in population growth

This section discusses our main results. Based on the model described in Section 3, we find that the emissions and temperature differences between the two population paths are quantitatively small. The economic benefits of population via increased innovation are large. The section concludes by demonstrating the robustness of this result to a host of alternative parameterizations and specifications.

4.1 Main Results

The main result—plotted in panel (d) of Figure 2—is that the stabilized population yields higher per capita consumption for future generations, net of climate damages. This plot shows the ratio of per capita income under *Stabilization* relative to *Depopulation* under two climate policy scenarios. The long-run net benefits of population stabilization become large—a 16% increase in per capita income by 2200—under our implementation of current climate policy.

These results follow from the slow speed of population change relative to the decline in emissions intensities that we have already stressed. The top panels of Figure 2, which depict the emissions and climate impacts of population stabilization, demonstrate this point quantitatively. Under the current policy trajectory (panel (a)), the temperature in the two population scenarios is nearly indistinguishable on the scale plotted. Numerically, *Depopulation* reaches 4.19°C while *Stabilization* reaches 4.24°. The 1.2% difference in warming would, under a quadratic damage function, lead to a difference of less than 3% in annual climate damages two centuries from now, when the difference in population would be nearly 6 billion people (an 87% increase).

Because of this timing, the climate costs of a larger population are very small, and even very modest benefits of population arising from endogenous innovation or dependency ratio effects can dominate the harms. There are two reasons for this. First, an 87% increase in population by 2200 would require a population-productivity elasticity of only about 0.03 to generate a similar 3% increase in productivity. Second, climate damages are only a fraction of GDP. A 3% increase in climate damages that are, for example, 20% the size of total output produces just a 0.6% decline in net output. Increases in total factor productivity, or the labor force, would apply to total output. So in fact, the long-run population-productivity elasticity would not even need to be 0.01 to exceed climate damages.

Based on our calibration, which relies on evidence from the literature on population and productivity (Bloom et al., 2020; Peters, 2022; Ekerdt and Wu, 2023), the population-productivity elasticity is much larger than 0.01. Specifically, panel (c) documents the relative increases in TFP and the share of the population in working ages in a world with a larger versus smaller population. By 2100, TFP is roughly 2% larger in *Stabilization*. This relatively small effect by the end of the century is because TFP is also a cumulative stock, and population size increases slowly. However, unlike emissions, standard models give no reason to expect the TFP-population relationship to decline over time. By 2200, for example, TFP is more than 10% larger in *Stabilization* relative to *Depopulation*.

The dependency ratio has non-monotonic effects, as shown in panel (c). Initially, and for a prolonged period, the additional children worsen the dependency ratio, a finding anticipated by Marois et al. (2021) and Weil (1999, 2023). Over the long run, however, it improves. *Stabilization* eventually reaches a dependency ratio in which about 2.5 percentage points (about 5%) more of the population are workers, relative to *Depopulation*. The quantitatively small and delayed improvement in dependency ratios casts doubt on the efficacy of policies that aim to reduce dependency ratios in the short run by increasing fertility rates.

This analysis is not designed to make normative claims about population policy—there are of course many costs and benefits to parents and (potential) children that are not modeled. And our modeling of these dependency effects are relatively simplistic. Therefore, we do not attempt to take a discounted sum of changes to per capita consumption. The (positive) point we wish to make is that it is incorrect to believe that low fertility in 2023 and beyond can improve climate outcomes in a way that is economically relevant.

Finally, and as displayed in Figures 2b,d, our results do not rely on assuming rates of decarbonization that some observers would argue is too optimistic as a baseline. In even our high-warming scenario in which emissions have not reached net-zero even by 2200, most of the population size increase occurs at a time of significantly less emissions per person than today. Although overall warming in this scenario exceeds 6°C, the *difference* in warming between *Stabilization* and *Depopulation* is relatively small in 2200: 6.26°C versus 5.90°C. This is a 6.1% increase in warming, or a 12% increase in expected annual climate damages. This increase is still too small to exceed the economic benefits of a larger population under leading calibrations of innovation benefits.

4.2 Robustness

Our baseline model combines consensus demographic projections with standard components of integrated assessment models and macroeconomic growth models. Therefore, we inherit the well-studied advantages and limitations of these components. To gauge sensitivity to these, in Figure 4 we present the results of 192 robustness checks, each from a different set of modifications to the baseline model. Scenarios in Figure 4 span from ambitious futures in which temperature change comes close to meeting international targets and global living standards grow nearly tenfold by 2200, to scenarios with temperature change as extreme as the IPCC's worst-case RCP8.5 scenario and in which living standards *fall* over the following centuries. In all cases the *additional* warming caused by larger populations remains small: Policy choices leading to catastrophic climate outcomes continue to do so regardless of population size, and policy choices successful in constraining temperatures are not meaningfully bolstered by a smaller population.

These 192 modifications come from interacting changes to climate policy, the climate and atmospheric module, the climate damage function, parameter values in the semi-endogenous growth equation, the driver of increased TFP growth in the semi-endogenous growth equation, and the elasticity of emissions with respect to policy.

$$\underbrace{\substack{\text{Climate}\\\text{Policy}}}_{3} \times \underbrace{\substack{\text{Climate}\\\text{Representation}}}_{2} \times \underbrace{\substack{\text{Climate}\\\text{Damages}}}_{4} \times \underbrace{\substack{\text{Population} \rightarrow \text{TFP}\\\text{Pass Through}}}_{2} \times \underbrace{\substack{\text{Source of}\\\text{TFP Growth}}}_{2} \times \underbrace{\substack{\text{Population}\\\text{Emissions Elasticity}}}_{2} = 192$$

Each modification is described below.

Climate Policy. Three climate policy scenarios are considered. The first two have already been detailed as the "current" and "low amibition" policies considered in Figure 2. For completeness we also include a more optimistic path, one in which 2°C end-of-century warming is only just breached. In this path, temperature differences between *Stabilization* and *Depopulation* are even smaller than the other cases because aggregate emissions fall to zero well before the end of the century.

Climate Representation. The DICE climate representation was designed to integrate simply within a macroeconomic model. In recent years there have been numerous attempts to produce more realistic, but still tractable, climate representations. The Finite Amplitude Impulse Response (FAIR) is one such model that has been recommended in a National Academies' report on better practices in integrated assessment modeling (National Academies, 2017).[14,15]

Because FAIR may be of special interest to readers in the IAM community, we additionally replicate Figure 2 in Appendix Figure A2. FAIR implies *less* warming for a fixed set of emissions, and our core results are robust to this modification.

Climate Damages. It is well-known that the damage function is consequential for estimating the social cost of carbon. Therefore, we consider three alternative specifications for damage functions, all of which are more pessimistic than the DICE damage function. As a reminder, our baseline model uses the standard specification for damages in DICE2016, which is quadratic in temperature (see Equation 11).

A modification that allows for the economic effects of tipping points is straightforward due to recent work by Dietz et al. (2021). Dietz et al. present a reduced-form, additive modification of standard quadratic damage functions with coefficients ξ_1, ξ_2:

$$D_t = (\psi_1 + \xi_1)T_t + (\psi_2 + \xi_2)T_t^2. \tag{16}$$

We use the coefficients reported in Figure 5 of Dietz et al. (2021).

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[14] In fact, since writing this paper, a 2023 update to DICE was released that has incorporated key equations from FAIR in its updated climate module.

[15] We use an implementation of FAIR that was coded into the Julia programming language, where the rest of our model is run. Details are available at: `https://github.com/anthofflab/MimiFAIR.jl`.

A second alternative considers much larger damages than DICE, estimated in an influential paper by Burke et al. (2015). The damage estimates constructed there come from a non-linear model disaggregated to the country level. DICE is specified at a coarser level of aggregation, so we implement the reduced-form version presented in Figure 5d of Burke et al., linking global temperatures to global losses of GDP.[16]

A third alternative considers the possibility that temperature also influences economic growth rates, as in Moore and Diaz (2015). In Moore and Diaz (2015), the model is disaggregated to multiple regions making exact replication infeasible. We instead implement their functional form at the global level and employ coefficients on the higher end of their proposed range in an effort to be conservative (against our findings). Specifically, the rate of TFP growth becomes:

$$g_{A,t} = \alpha_t L_t A_t^{-\beta} - \varepsilon \tilde{T}. \tag{17}$$

We calibrate ε such that a 1-degree increase in $\tilde{T}$ reduces GDP growth by 1 percentage point per year, consistent with the largest negative impacts on GDP growth presented by Moore and Diaz. Also following their implementation, we use what they call "effective temperature," $\tilde{T}$, to allow for adaptation. The idea is to subtract a function of past temperatures such that the long-run effect of a fixed level of warming tends back to zero.[17]

All of these damage function modifications substantially increase the economic costs of global warming under both population paths. Indeed, some of these model specifications have climate damages so severe that per capita output is lower in 2200 than it is today (see Figure 4d). But because the differences in temperature are small across the two population paths, large damages per degree do not translate into large damage differences across population scenarios.

Population Emissions Intensity. To avoid the possibility of understating the population effects of

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[16] We translate the graphical depiction to numerical values using data extraction software. We then estimate a cubic function, $D = \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3$ for the corresponding damage function.

[17] We numerically implement this in a slightly different way than Diaz and Moore owing to differences in model construction, but we retain that warming (i) passes through to $\tilde{T}$ one-to-one in the immediate-term and (ii) has a near-zero effect on growth rates after 30 years at that level. Specifically, Moore and Diaz define $\tilde{T}_t = \sum_{j=1850}^{j=t} (T_j - T_{j-1}) e^{-a(t-j)}$ such that if warming is fixed at some level in the long-run $\tilde{T} \to 0$. For simplicity, and because our version of DICE does not track temperatures back to 1850, we instead subtract a rolling average of the prior 30 years. This is chosen to match Moore and Diaz's calibration where the effective temperature from a one-time temperature shock is near-zero after 30 years.

emissions, we mechanically increase the emissions elasticity of population to exactly one in each period. In DICE, the industrial emissions we study come from economic production, not people.

Furthermore, and consistent with medium- to long-run neoclassical growth models, all working-age people work and all available capital is employed in each model period. Therefore, an additional child today, who does not contribute to GDP, does not immediately increase emissions in the model. Emissions increase once the child ages into the workforce. This child's consumption is implicitly assumed to be substituting for some economic activity that would have otherwise taken place.

We relax this assumption to show that it is not crucial to our results. In particular, beyond scaling land-use emissions to population as we do in every model interaction, we redefine industrial emissions as

$$E_{Ind,t} = (1 - \mu_t) \times \sigma_t^N \times N_t, \tag{18}$$

where σ^N corresponds to emissions per capita, rather than emissions per unit of output (also recall that μ is the mitigation rate). This functional form ensures that if in period t *Stabilization* has a population 10% larger than *Depopulation*, emissions will also be 10% larger. We calibrate σ^N to again replicate DICE2016's baseline implementation to avoid this redefinition changing the baseline outcome; i.e., we fit the equation $\sigma_t^N \times N_{t,DICE} = \sigma_t \times Y_{t,DICE}$ for DICE's population and output.

Population → TFP Pass-Through. In the baseline model we calibrate λ, β in $g_{A,t} = \alpha_t L_t^{\lambda} A_t^{-\beta}$ to reflect leading empirical estimates (Bloom et al., 2020). We calibrate α_t to replicate DICE's TFP path.

To ensure that our findings do not rely on an overly optimistic calibration of how much more TFP a larger population can eventually generate, we make ideas "harder to find" by increasing β.[18] Specifically, we increase β from 3.1 to 4.5. For context, TFP grows by 3.5-times by 2200 with $\beta = 3.1$, but only 1.5-times with $\beta = 4.5$ in our baseline model. Because it greatly shrinks the total growth of TFP, it closes the absolute gap in TFP. However, even these smaller differences in TFP are enough for the larger population to eventually have higher per capita consumption net of climate damages.

Source of TFP Growth. So far, we have stressed the importance of people for the idea generation that produces TFP improvements. However, this is not always how endogenous growth models

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[18] The long-run effect of a 1% increase in population is governed by the ratio of λ to β (see e.g., Eden and Kuruc, 2022), so this is quantitatively similar to scaling λ down by this same factor.

are specified. For example, Dietz and Stern (2015) implement the Romer (1986) endogenous growth model where economic capital is the key variable that scales innovation efforts. We implement a similar version of the innovation equation where TFP growth scales with total output—not people, *per se*.

$$g_{A,t} = \alpha_t^Y Y_t^N A_t^{-\beta}. \tag{19}$$

Equation 19 recognizes that people need research labs, computers, and other productive economic capital to produce knowledge. Other things equal, a larger economy—meaning here the combination of people and other resources—can generate more new knowledge. Notice that this formulation is such that Y^N, output net of climate damages, determines growth. Therefore, like in Dietz and Stern (2015), climate damages influence growth rates indirectly by damaging the inputs to economic growth, making this similar to our third damage function modification.

This ends up mattering very little to the main results for two reasons. First, people are a primary input to Y^N, so net output is also substantially larger in *Stabilization* over the long run, due to the population increase. Second, capital in the economy increases with the size of the labor force. This is straightforward, as we are discussing aggregate capital, not per-worker capital. In fact, even a specification where capital was the *only* input to idea-creation would carry the implication that larger populations support larger capital stocks, which then support more TFP growth.

5 Negative emissions generate an ambiguous relationship between near-term population growth and long-run climate outcomes

Our exercises in Sections 2 and 4 place a lower-bound on emissions at zero in order to isolate the potential increase in warming that population growth can generate. This section turns to a more novel possibility: the relationship between long-run levels of warming and contemporaneous population growth rates may be *negative*. If scalable technologies come to exist by which GHGs can be removed from the atmosphere, a larger population will be able to produce more of this public good. This is because removal of any fixed volume of atmospheric greenhouse gases will be a *fixed cost* from the perspective of a future generation. Therefore, for a larger population with a larger aggregate economy, the cost of removing a fixed volume of GHGs would be lower per capita and represent a smaller proportion of total output. Near-term population growth may enable a more rapid reduction in the atmospheric GHG stock.

Futures with aggregate net-negative emissions are not particularly speculative. It is already understood how CO_2 can be captured from the atmosphere; whether these activities scale is primarily a matter of resource allocation. Indeed, the DICE model by default assumes that emissions eventually become net-negative. And DICE is not alone. Almost all of the pathways in a recent IPCC report on reaching 1.5°C included significant net-negative emissions in the second half of this century.[19] The uncertainty appears to be around *when* annual per capita emissions will become negative, not *whether* they will. If so, it can be easily shown that the long-run population-warming relationship that we consider here will also eventually become negative.

Consider a simple setting that relies on the following assumptions:

1. There is some t_{neg} after which negative emissions exceed positive emissions, independent of population size;
2. A larger population produces $\nu > 0$ tonnes more of these net-negative emissions per year; and
3. The larger population reaches time t_{neg} with $\Theta > 0$ more tonnes of CO_2 in the atmosphere.

In this setting, there will be some $t' > t_{neg}$ such that $\Theta = \nu(t' - t_{neg})$. This equality implies that the stock of GHGs in the larger population future is equal to the stock in the smaller population future at time t'. Then, because the larger population continues to withdraw more GHGs beyond t', the stock will be lower for all $t > t'$. Therefore, long-run warming will be lower in the larger population world.

Using our modified DICE model, we estimate how long it might take for the larger population to achieve the same level of warming as the smaller population. Specifically, and like in DICE's baseline, aggregate emissions become net-negative only after 2150. After 2150 their quantity is governed by a cost-curve that maps incentives for negative emissions (i.e., a price on carbon) and

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[19] See `https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options`.

a path for these prices. For our demonstration, a path of carbon prices is chosen such that the larger population future eventually generates -17 $GtCO_2$ annually, the maximum level of negative emissions that the baseline version of DICE produces. The same path of carbon prices is assumed in both *Stabilization* and *Depopulation*, in order to isolate the effect of population size.

Figure 5(a) plots the emissions paths of the two populations. Until 2150, this is an exact replication of the emissions paths in Figure 2a. After 2150, more negative emissions are produced under the same policy incentives in *Stabilization* relative to *Depopulation* because the global economy is much larger by that time. Recall from Figure 1 that the population alone is more than 80% larger by 2200. The difference in output is greater still, because per-capita productivity is greater in the stabilized world.[20] Just as a larger economy produces more non-rival bads, other things equal, it also produces more non-rival goods.

Panel (b) plots warming in the two population scenarios: In *Stabilization*, peak temperatures are slightly higher, exactly as in Figure 2a, but the long-run temperature is substantially *lower* due to the increased resources for negative emissions. In this specification, it takes approximately 60 years from the point that negative emissions becomes possible to the point that the temperatures are equal.

Of course, the timing of net-negative emissions is subject to many details regarding future technologies and policies. And it will not, in general, be true that climate policy is invariant to population size. It is notable, though, that under these simple assumptions, the time it takes for the larger population to have better climate outcomes is on the order of 50, not 500, years from the time net-negative emissions are realized. This means that near-term population growth may have long-run environmental benefits rather than trade-offs.

6 Discussion and Conclusion

Global fertility is unprecedentedly low and is continuing to fall. This has prompted concern over an aging and shrinking workforce, but also optimism about environmental benefits. Foremost

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[20] The larger population can produce more negative emissions even if we eliminated the economic benefits of population growth and assumed the two populations were equally wealthy on a per capita level.

among the supposed environmental benefits are reduced greenhouse gas emissions and lower levels of long-run warming. This paper shows that this optimism greatly overstates the potential climate benefits of further declines in fertility: Feasible emissions reductions resulting from changes in population dynamics are negligible when compared against well-studied economic benefits of near-term increases in population growth.

While the most widely discussed, climate change is not the only potential benefit arising from a smaller future population. A larger population would have environmental impacts beyond climate change, including on biodiversity, non-human animals, and non-carbon air and water pollution. Our main analysis does not aim to address these. Additionally, we do not account for the possibility that it would be less costly for a population to invest in the human capital of a smaller generation of children, as is described in the macroeconomics of fertility literature (see e.g., Galor, 2022).

Nor is productivity growth the only potential welfare benefit of a larger population. In our analysis, we present results in per capita terms, and give no advantage to a larger population future for the reason that more people get to exist. Ignoring this pathway ignores potentially one of the major social welfare benefits of increased fertility (see e.g., Klenow et al., 2023).

The analysis also omits regional heterogeneity. We consider a marginal increase in *global* fertility rates, which need not be correlated with where population growth is projected to come from in the coming decades. For example, most future population growth will take place in Africa. That would be true in *Stabilization* and *Depopulation* and does not imply anything about where the marginal population growth we study comes from. Our exercise is one that imagines a representative agent of the global population having a slightly larger family to isolate the effect of population size. That population size changes are slow and predictable relative to the urgency of emissions reduction is a fact that will apply at finer levels of geographic aggregation. Like the other modeling variants examined in Figure 4, substituting a regional model would not alter these core results.

We conclude by noting that, despite the novelty of this point relative to conventional wisdom, analogies to other environmental problems make the takeaway less surprising. No one suggests, for example, to address high levels of particulate matter air pollution or open defection by reducing fertility rates. Nor was that how countries have made progress on these negative externalities in the past. The same ought to be true of climate change: to meet any reasonable international targets, progress must be made well before changes in fertility rates can influence cumulative emissions. Correspondingly, climate change should not be first-order concern in discussions on the costs and benefits of fertility rates.

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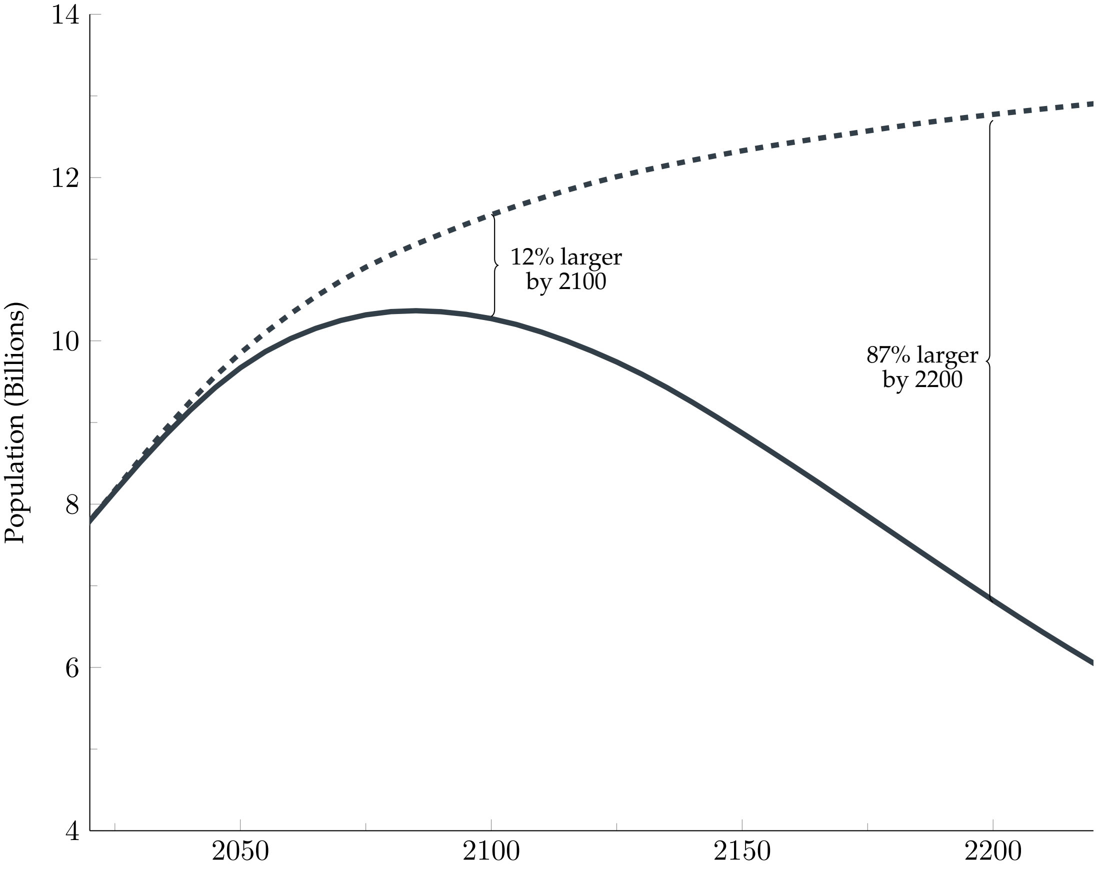
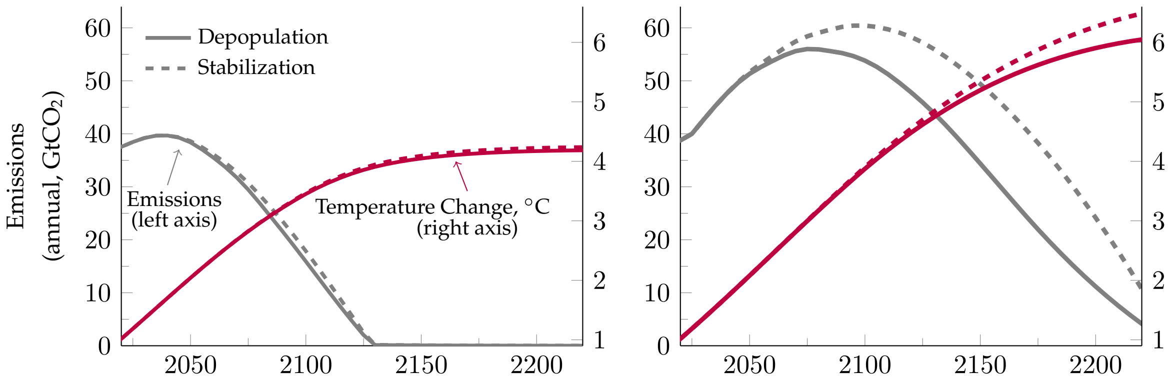
Figure 1: Two Population Paths: *Depopulation* and *Stabilization*



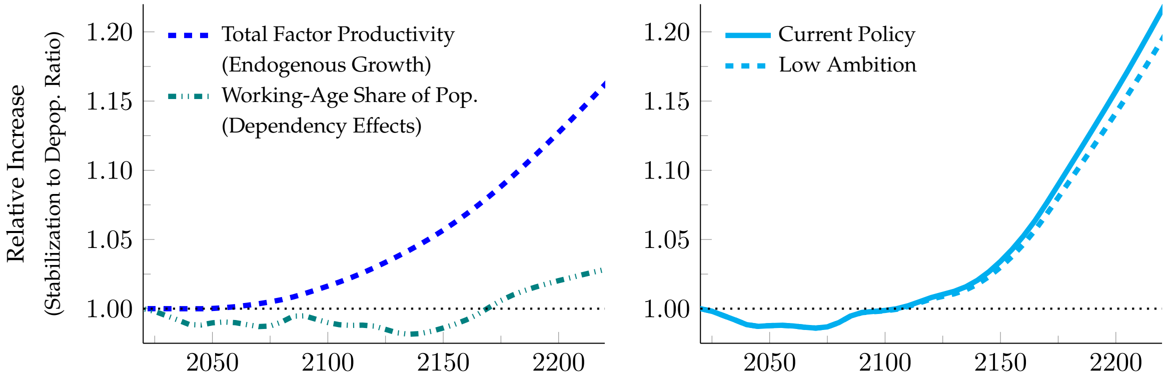
Notes: *Depopulation* and *Stabilization* population paths (inputs to the evaluation in Figs. 2 and 4) are derived from United Nations (UN) World Population Prospects 2022 projections. UN projections are available until 2100. *Depopulation* follows UN Medium. *Stabilization* combines Medium for Low-income countries and Instant Replacement for High-income, Upper-middle-income and Lower-middle-income countries. Population projections after 2100 are extended to match demographic facts for low-fertility populations (United Nations, 2022; Basten et al., 2013). See Section 3.2.

Figure 2: Net of climate harms, average living standards are higher under *Stabilization* than *Depopulation*

(a) Climate Outcomes (Current Policy) (b) Climate Outcomes (Low Ambition)

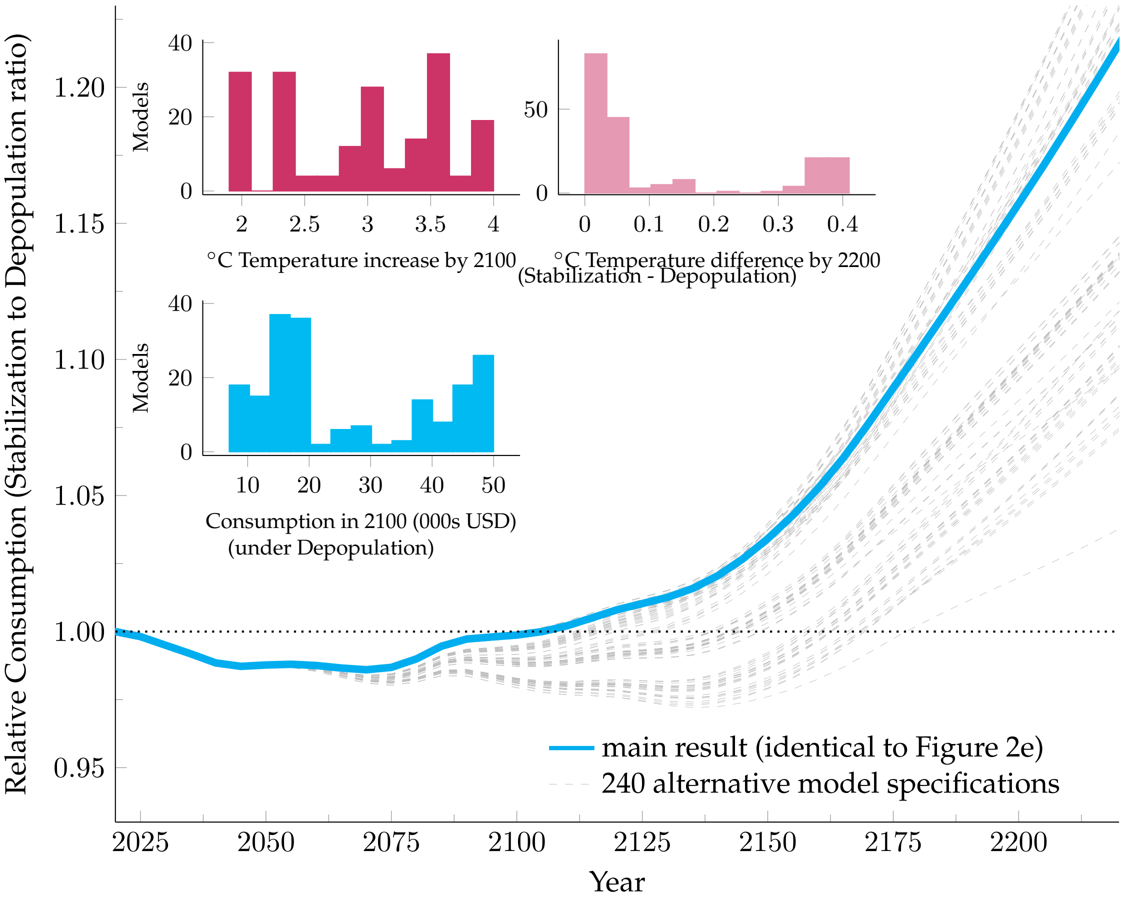


(c) Economic Effects (d) Consumption (net of climate damages)



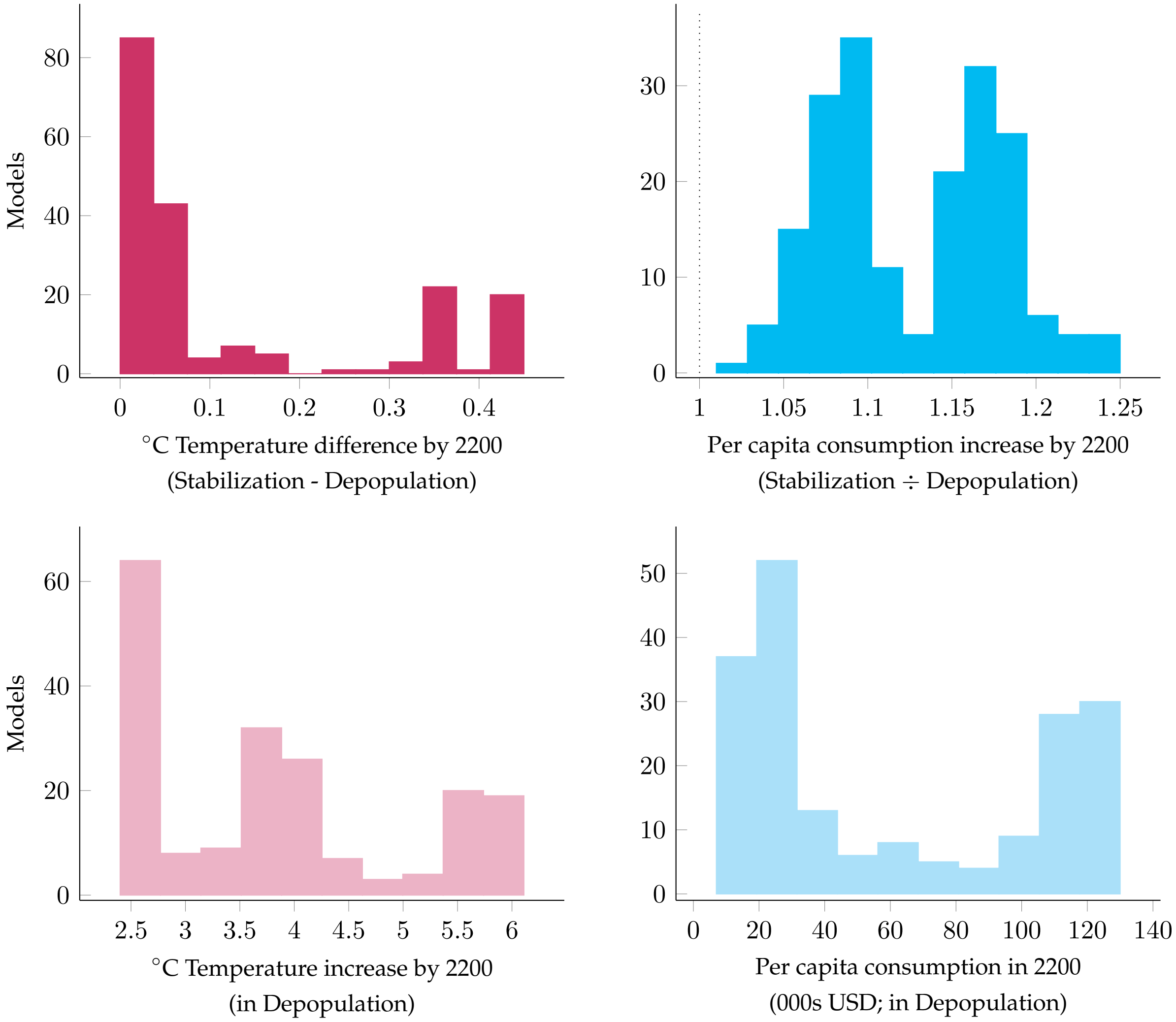
Notes: Left column depicts computations under a "current policy" scenario (Ou et al., 2021); right column assumes "low ambition" for future climate action (see Section 3.2). Mitigation rates are common for both population paths within each column. (Top row) Emissions (left-axis) and temperature above pre-industrial (right axis) are shown in each population path and for each climate policy scenario. (Middle row) Increases in total factor productivity and working-age share under *Stabilization* relative to *Depopulation* are plotted as ratios. (Bottom row) Increases in average living standards (measured on scale of per capita consumption) between *Stabilization* relative to *Depopulation* are plotted as ratios for three versions of the model: (1) the full model with innovation benefits for endogenous growth, the demographic structure for dependency effects, and population-emissions harms (solid); (2) innovation benefits and population-emissions harms, with no demographic dependency effects (dash); and (3) demographic dependency effects and population-emissions harms, with no innovation benefits of endogenous growth (dash-dot). Results hold under a wide range of variations on baseline assumptions (Figure 3).

Figure 3: Net economic benefits of *Stabilization* are robust across 192 alternative sets of assumptions and model specifications, even though models vary widely



Notes: Alternative specifications are generated by crossing each of the six model dimensions indicated: climate policy (3 variants); climate modules (2 variants); climate damages (4 variants); amount of TFP growth (2 variants); source of TFP growth (2 variants); and emissions intensity of population (2 variants). See Section 4.2 for details on each variant. The three inset histograms plot, for these 240 model specifications, the distributions of: year-2100 temperature change from pre-industrial under the *Depopulation* scenario (left); year-2200 temperature *difference* between *Stabilization* and *Depopulation* (right); and year-2100 consumption per capita under the *Depopulation* scenario (bottom). The histograms illustrate that these 240 alternative models are substantially different, despite their convergent finding that net living standards are higher under *Stabilization* compared to *Depopulation*.

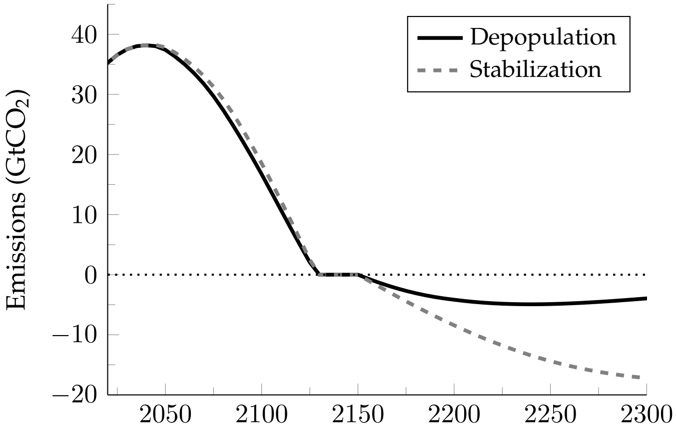
Figure 4: Net economic benefits of *Stabilization* are robust across 192 alternative sets of assumptions and model specifications, even though models vary widely



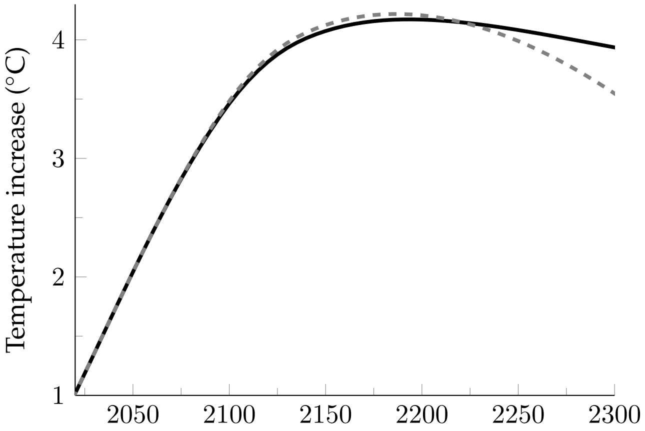
Notes: Distributional outcomes across 192 model specifications for key variables. Alternative specifications are generated by crossing each of the six model dimensions indicated: climate policy (3 variants); climate modules (2 variants); climate damages (4 variants); amount of TFP growth (2 variants); source of TFP growth (2 variants); and emissions intensity of population (2 variants). See Section 4.2 for details on each variant. Panel (a) depicts the increase in temperatures in Stabilization relative to Depopulation. Panel (b) depicts the per capita consumption gains (all of which are positive) in Stabilization by 2200. Panels (c) and (d) depicts the distribution of level outcomes in Depopulation across model variants in an effort to demonstrate that they are in fact substantial alterations.

Figure 5: Larger populations can have climate *benefits* if emissions become negative

(a) A larger population produces more positive and negative emissions...



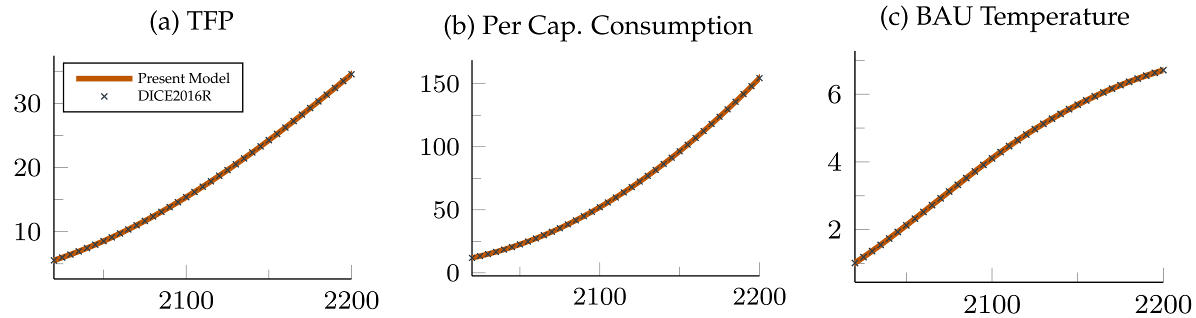
(b) ...which can reverse the initial temperature increase



Notes: This figure plots a replication of the emissions and temperature effects in Figure 2a under an assumption that restores the possibility of negative emissions. Negative emissions were included in the 2016 revision of DICE, but in the main analysis and all specifications in Figs. 2 and 3, we constrain the model such that annual GHG emissions can never fall below zero. Here, we allow negative emissions beginning in 2150. The plots illustrate that if negative emissions technologies exist, there are potentially large climate *benefits* of a larger long-run population.

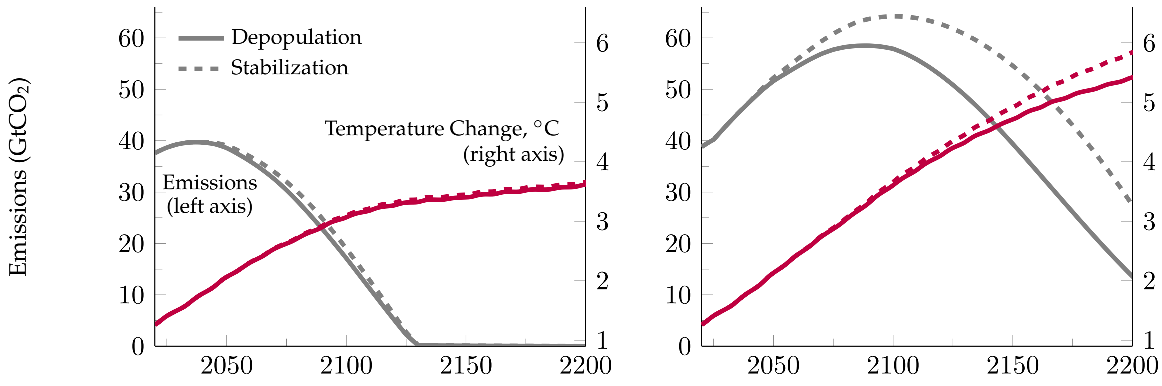
Appendix

Figure A1: Modified model with DICE population reproduces DICE's output

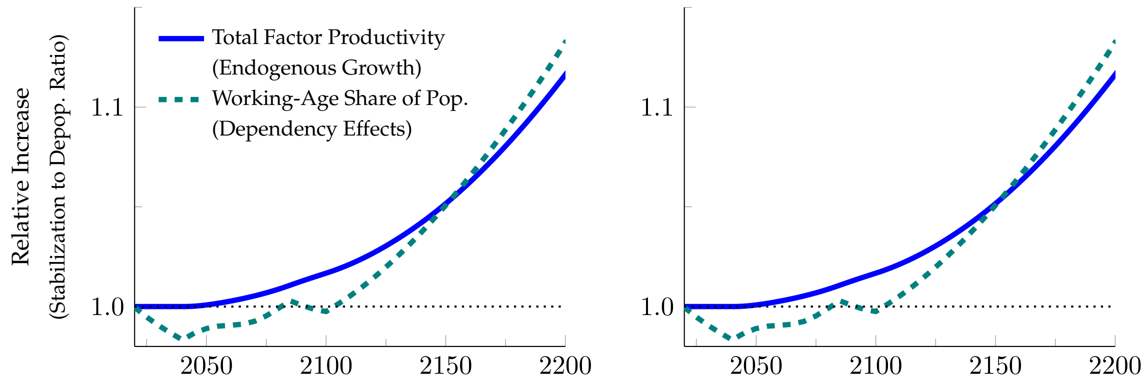


Notes: Verification that the modified version of DICE—with endogenized TFP and land-use emissions—exactly replicates DICE2016R when the original DICE population and policy trajectory is assumed. The output from DICE2016R is available at `https://williamnordhaus.com/dicerice-models`.

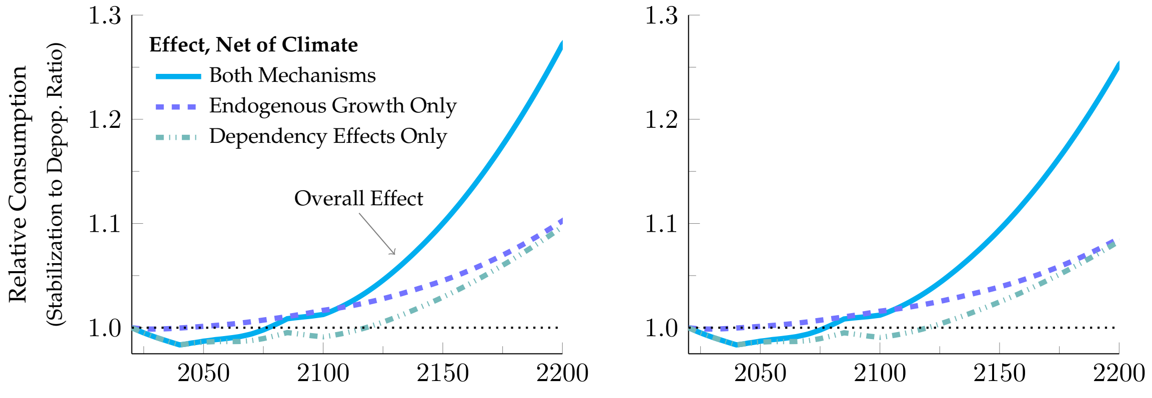
Figure A2: Replication of Figure 2 using FAIR climate module


(a) Emissions and Temperature (Current Policy)

(b) Emissions and Temperature (Low Ambition)


(c) Economic Benefits (Current Policy)

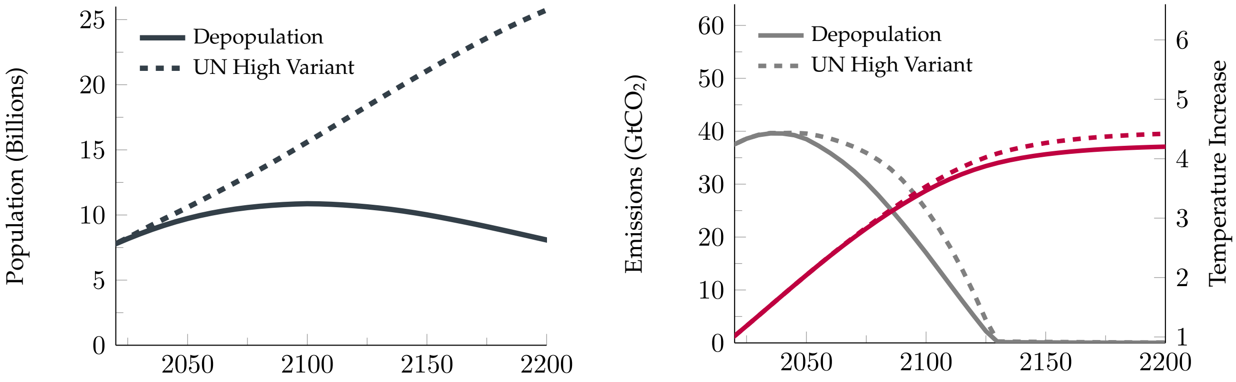
(d) Economic Benefits (Low Ambition)


(e) Living Standards (Current Policy)

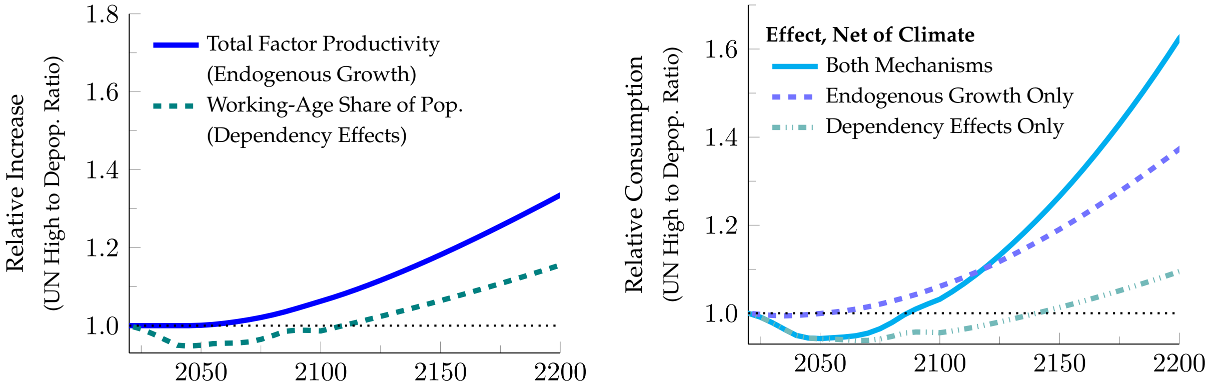
(f) Living Standards (Low Ambition)

Notes: A replication of Figure 2 in which the climate representation has been replaced by the FAIR model.

Figure A3: Benefits of population remain large when comparing UN High population projection with *Depopulation*


(a) Population Differences

(b) Emissions and Temperature


(c) Economic Benefits

(d) Living Standards

Notes: A replication of Figure 2 where an extension of the UN High variant, rather than *Stabilization*, is compared with *Depopulation*. Uses “current policy” mitigation pathways in both population scenarios.