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IS LESS REALLY MORE? COMPARING THE CLIMATE AND PRODUCTIVITY IMPACTS OF A SHRINKING POPULATION

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ABSTRACT

A smaller human population would emit less carbon, other things equal, but how large is the effect? Here we test the widely-shared view that an important benefit of the ongoing, global decline in fertility will be reductions in long-run temperatures. We contrast a baseline of global depopulation (the most likely future) with a counterfactual in which the world population continues to grow for two more centuries. Although the two population paths differ by billions of people in 2200, we find that the implied temperatures would differ by less than one tenth of a degree C—far too small to impact climate goals. Timing drives the result. Depopulation is coming within the 21st century, but not for decades. Fertility shifts take generations to meaningfully change population size, by which time per capita emissions are projected to have significantly declined, even under pessimistic policy assumptions. Meanwhile, a smaller population slows the non-rival innovation that powers improvements in long-run productivity and living standards, an effect we estimate to be quantitatively important. Once the possibility of large-scale net-negative emissions is accounted for, even the sign of the population-temperature link becomes ambiguous. Humans cause greenhouse gas emissions, but human depopulation, starting in a few decades, will not meet today's climate challenges.

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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 (Casey and Galor, 2017; Bongaarts and O'Neill, 2018; Wynes and Nicholas, 2017). However, there are also well-documented productivity 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 (Jones, 2022; Peters, 2022), and a less retiree-heavy age structure (Vollrath, 2020; Fernández-Villaverde et al., 2023; Maestas et al., 2023).

Understanding which of these categories of 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 (United Nations, 2022). Various evaluations of these competing channels indicate that the costs and benefits both have the potential to be large. For example: warming of 3–4°C may cause annual losses (in output, life, and overall wellbeing) valued in excess of 10 percent of GDP (see e.g., Howard and Sterner, 2017; Bilal and Känzig, 2024), and recent work by Jones (2022) suggests economic growth may end entirely under enduring population decline. But 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 decline to long-run warming is necessarily limited. This would not have been true a half century ago or more, but it is true from the vantage of a society that has already begun reducing per capita emissions. 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 even large changes in future population size. We find that immediate and persistent increases to fertility, even to unrealistically high levels, produce a difference of less than one-tenth of one degree Celsius by 2200 relative to status-quo projections of global depopulation. This is on a pessimistic decarbonization trajectory where emissions remain positive for another century and eventual warming exceeds 4°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, faster turnover of the capital stock, or a planner's reoptimization. Instead, we conservatively and mechanically hold fixed the same time path of emissions-per-output-unit across the large population and small population scenarios.

The integrated model finds that increases in fertility, relative to the status quo population decline, would benefit living standards mainly through 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 increase the near-term dependency ratio relative to the shrinking population. Overall, the additional climate costs resulting from 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 conclusion follows from facts of timing. The cumulative concentration of atmospheric greenhouse gases—the driver of global warming—is a stock determined by the entire history of emissions. Moreover, while the annual flow of emissions can in principle adjust quickly, the instantaneous global population size is itself a slow-moving stock. Changes in population growth rates take many decades to generate significant changes in population size. Even under pessimistic scenarios for decarbonization, only a small share of humanity's cumulative emissions will occur after the many decades it takes for fertility rate changes today to produce large population size changes. Scaling up or down this small remainder of emissions has only a small impact on the long-run stock of atmospheric GHGs. This implies that, in the long run, any form of gains associated with a larger future population need not be large to dominate the tiny difference in temperature generated by the larger future population.

Because our main results follow from these facts of timing rather than particular features of the climate or economic modeling, they are robust to a wide range of model specifications. For example, climate damage functions that translate temperature changes into harms are an area of uncertainty and active research in climate economics (Dell et al., 2012; Burke et al., 2015; Dietz et al., 2021; Bilal and Känzig, 2024; Cruz and Rossi-Hansberg, 2024, etc.). Our core results are robust to several alternative (more pessimistic) specifications for the damage function. This is because although increasing the scale or convexity of the climate damage function lowers long-run incomes (and hence increases the social cost of carbon), the population scenarios we compare produce a small difference in temperature on which any damage function acts. 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 translates from emissions to temperatures. The same is true for other model dimensions that we vary, including when disaggregating the analysis into a regional model that accommodates correlation between regional population growth and region-specific per capita emissions.

An assumption that is critical in this analysis is the pace of decarbonization. Along with our presentation of the main results, we demonstrate that, even in worst-case futures with more than 6°C of warming, the *incremental* effect of the larger population on warming and climate damages is relatively small. This carries the important implication that climate policy and technology will mostly succeed or fail independent of population trajectories, and tells against describing population decline as a useful complement to or component of climate policy.

These results do not imply that larger populations come at no cost. The time path of changes we estimate shows that there is an inter-generational trade-off: The net effect of the larger population scenario (which assumes exogenous near-term increases in fertility rates) leads to lower per capita output in the coming decades before the new, larger generations age into the workforce. Simply put, children are initially expensive.

Finally, as an extension of the main exercises, we consider the scenario in which it is eventually possible to produce *negative* emissions at scale. This possibility is ruled out in the main exercises, to isolate the effect of the additional emissions of a larger population over the period that net emissions remain positive. But already there exist activities that generate negative emissions. These include high-tech approaches (e.g., direct air capture) and low-tech approaches (e.g., reforestation). 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 population size has inertia and a larger population later could 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 carbon 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 depending on the expected arrival of negative emissions at scale.

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 negative impacts for climate outcomes that are small. This finding is in direct contrast with the dominant view in academic and public discussions. Within economics, too, the view that we rebut is mainstream. For example, Kruse-Andersen (2023a) and Gerlagh et al. (2023) conclude that policies aimed at reducing population growth could have significant effects on carbon accumulation this century, in part because these authors assume that population sizes can change much more quickly than is realistic.[1] Galor (2022) hypothesizes that reductions in fertility can provide additional time to transition to clean energy sources, a conjecture based on earlier work in Casey and Galor (2017) that 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 for understanding the climate impacts of future population growth or decline: The climate impact of a 35% reduction in the *annual flow* of emissions by 2100 depends on the base emissions flow in that year and afterward—and is unlikely to be more than a small fraction of the accumulated stock of atmospheric greenhouse gasses. Understanding this nuance is especially important given that the pace of actual and projected decarbonization has substantially accelerated over just the past few years (Hausfather and Peters, 2020; Arkolakis and Walsh, 2023). 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

[1] Kruse-Andersen (2023a) studies a high-population scenario with a working age population of just over 9B in 2100 (whereas the UN's 95% confidence interval for individuals aged 25-64 in 2100 extends to a maximum of about 5.8B, with potentially another 1.5B aged 15-24); 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.

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 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 affect living standards. Instead, this paper casts new light on the most widely cited channel by which a larger population is hypothesized to 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 rich numerical setting—the objective of Section 4—the goal here is to clarify the dynamic interactions that drive the main results in the simplest fashion. The key insight delivered by our model is that altering the population growth rate now will not meaningfully change the size of the population on a timeline relevant for impacting the

[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 'no policy' path and much less consequential for per capita income than other effects of population growth. See also Bradshaw and Brook (2014).

[3] Alongside the citations in the first paragraph, see recent work by Dasgupta et al. (2021), Henderson et al. (2025), Pindyck (2022) and others.

stock of GHGs and long-run warming. This is because of the background rate at which per-capita emissions intensities are declining relative to any plausible change in the rate of global population growth.

Global warming is determined by the stock of atmospheric GHGs. Therefore, we focus directly on the level to which this GHG stock converges to over the long-run. We denote this long-run stock as $\mathcal{E}_T$. For simplicity, we assume it is equal to the time-independent sum of all annual (flow) emissions, $E(t)$.[4] The present day is normalized to $t = 0$, such that $t < 0$ is the past.

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

The evolution of $E(t)$ can be decomposed into 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 as some fixed g and d. In this simplified setting with constant rates of growth, we ignore cases where $g > d$ because this leads to an unbounded GHG stock and long-run warming.

$$E(t) = N(t) \times \epsilon(t) \tag{2}$$

$$N(t) = N_0 e^{gt} \tag{3}$$

$$\epsilon(t) = \epsilon_0 e^{-dt}, \text{with } \ d > g \tag{4}$$

Throughout the paper we take the rate at which emission intensities fall as exogenous and independent of population sizes.[5] We do this for two reasons. First, our main result is to demonstrate that the pass through from additional population growth to additional warming is small. Thus, for conservatism and transparency we do not build-in additional

[4] A more realistic model would include depreciation of this stock over time 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.

[5] This has the implication that our model is precisely consistent with O'Neill et al.'s (2012) widely-cited estimate of a within-period unit elasticity: "CO_2 emissions from energy use respond almost proportionately to changes in population size."

channels by which a larger population could endogenously decarbonize faster than a smaller population via an innovation advantage or an advantage coming from the rate at which the capital stock turns over.[6] Our results would be strictly and straightforwardly stronger if such a channel exists. Second, and more substantively, these advantages will be limited on the time horizon relevant for climate change for the same reason that emissions differences are limited: Population sizes change too slowly. Relatively small increases in research capacity many decades from now will not be a first-order factor in reducing per capita emissions this century (see also Kruse-Andersen, 2023a).

Equations 2 – 4 imply the following path of exponential decay for annual 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 of atmospheric GHGs from historical emissions as $\mathcal{E}^h$, we have:

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

Equation 6 makes clear that there are two forces limiting the pass-through from population growth rates to the stock of long-run atmospheric GHGs. First, there already exists a non-trivial concentration of GHGs, $\mathcal{E}^h$. This will be important for intuitions that rely on altering flows in order to affect the total stock. Second, population growth is only one of two channels which determine cumulative future emissions. Future emissions also depend on the evolution of annual per capita emissions, which as a matter of fact have evolved rapidly in recent decades and are forecast to continue to change as consequence

[6] In a larger future economy, a smaller share of the future capital stock will consist of capital that has already been built (and thus is more likely to be outfitted for fossil energy). For detailed discussion on the centrality of turning over the capital stock in mitigating GHGs see Mehrotra (2025).

of both industrial policy and technology. Formally, the derivative of $\mathcal{E}_T$ with respect to the population growth rate g is:

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

It will be helpful to contextualize this with a simple numerical example. Assume first that $g = -0.2\%$.[7] This rate of decay would result in the world depopulating from our current 8 billion to about 5.5 billion by 2200. If we further assume that $d = 1.8\%$,[8] then $(d-g) = .02$, which would imply it would take until about 2060 for annual global emissions to be halfway to net-zero. Under these assumptions, cumulative future emissions would be equal to $\frac{1}{0.02} = 50$ times current annual emissions, E_0. For context, the existing stock of emissions, $\mathcal{E}^h$, is also equal to approximately $50E_0$.[9] So if $(d-g) = .02$, then $\mathcal{E}_T \approx 2\mathcal{E}^h$. In other words, future cumulative emissions would equal historical cumulative emissions, so long-run cumulative emissions would be about twice historical cumulative emissions.[10]

Perhaps surprisingly, even under these assumptions, which imply a slow pace of decarbonization and therefore significant future emissions, the marginal impact of future population growth on long-run warming is small. For simplicity, suppose that the population were immediately stabilized with a long-run growth rate of $g' = 0\%$. Such an increase in population growth (from a negative rate to zero growth) would be implausibly large relative to the body of empirical evidence on policy interventions and birth rates: it is about three times larger than the upper-bound of what estimates suggest could be accomplished with a one-time government benefit at birth equal to 10% of a household's

[7]This is about the rate of population decline that would result over a long period in which the global average total fertility rate held at 1.9. For context, in 2023, the average total fertility rate in Africa was 4.0, in Latin America was 1.8, in the U.S. was 1.6, in Europe was 1.4, and in China was 1.0 (United Nations, 2024).

[8]For reference, the annual rate of per capita decline in carbon emissions in the U.S. from 2000 to 2020 was over 2%.

[9]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`).

[10]For further context, this central case would likely result in peak warming between 2.5-3°C. Current estimates of "committed warming" from existing atmospheric GHGs are between 1.2°-1.5° (Sherwood et al., 2022).

annual income (Stone, 2020; Zhou, 2023).[11] Indeed, it would be equivalent to rolling back more than 40% of the global fall in birth rates over the last two decades.[12] According to Equation 7, this increase in g that would stabilize the global population size results in $5E_0$ additional future emissions,[13] which is a 10% difference in cumulative future emissions, $\mathcal{E}^f$, relative to the depopulation path ($g = -0.2\%$) first considered. And what matters is $\mathcal{E}_T$, which will increase proportionally less than cumulative future emissions because of the pre-determined atmospheric stock, $\mathcal{E}^h$. As noted above, the existing atmospheric stock is roughly equal to the quantity of future emissions under this assumption, implying that the increase in the overall stock is only 5%.[14]

The quantitative analysis in the following sections will impose more realistic assumptions, but it is worth first understanding the intuition behind the small values in this simple model as 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 to cumulative emissions would be much larger. There would be a simple unit elasticity between cumulative future emissions and population increase because, in this stylized exercise, we have assumed a fixed path of per capita emissions. The difference arises from timing: an increase in g leads to a proportionally similar increase in N only after many decades. Birth rates that change instantaneously require generations to pass to significantly affect population size. In our numerical example, increasing g by 0.2 p.p. generates a 10% difference in the population size only after 50 years.[15] Over the course of

[11] The natural rate of population growth is approximately the birth rate minus the death rate. Holding fixed death rates, it takes a 0.2 p.p. increase in birth rates to raise population growth rates by 0.2 p.p. The 2021 global birth rate was 1.69% (Our World in Data, 2023). Raising this to 1.89% represents a 12% increase in births. Stone (2020) and Zhou (2023) bound the fertility increase from transfers of this size below 4.1% and 3.65%, respectively.

[12] Between 2001-2021 the crude birth rate fell from 2.15% to 1.69%, or by 0.46 p.p. (Our World in Data, 2023). An increase of 0.2 p.p. undoes 44% of this decline.

[13] $\frac{E_0}{(d-g)^2} = 2500E_0$ for a one-unit increase, or $5E_0$ for an increase of 0.002.

[14] In a significantly more pessimistic scenario, where the decay rate on annual emissions is only 1% per year, this same 0.2 p.p. increase in population growth rates has a larger level effect. But this is on a base of cumulative emissions that is also larger. Overall, even under this very slow pace of decarbonization there is only a 10% increase in the long-run stock of GHGs coming from this large population increase.

[15] For the time it takes to achieve a (counterfactual) 10% increase in the size of the population from a 1%

these decades, emission intensities are declining. The 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 predict 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.

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

The prior section demonstrated in a simple analytical model that the impact of population growth on warming could be small under various parameter assumptions, as long as humanity eventually decarbonizes. This section describes the quantitative model that assesses the same question using detailed population projections and a full integrated climate-economy model. It also describes how the model can be used to study the tradeoffs between climate costs and productivity benefits.

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 constructed in a way that generates an emissions response to a change in the path of population. We build on this by introducing into the model the effects of population growth on productivity and the dependency ratio. As described further

increase in g, consider that $\frac{N_t'}{N_t} = \frac{N_0 e^{(x+0.002)t}}{N_0 e^{xt}} \Rightarrow 1.1 = e^{.002t} \Rightarrow t \approx \frac{.1}{.002} = 50$.

below, to assess the robustness of our key results, we also relax and alter several features of the model, including by regionally disaggregating the analysis and by substituting the Finite Amplitude Impulse Response (FaIR) module to map from emissions to temperature changes.

The four core features that we take directly from DICE are: (a) the neoclassical model of economic growth where labor, (accumulated) capital, and productivity determine total output, (b) a forecast for the time path of the emissions-intensity of output (absent climate policy), (c) a representation of how annual greenhouse gas emissions influence the atmospheric stock and how that stock in turn influences the global temperature over time, and (d) a damage function that translates temperature changes to losses of GDP.

Formally, gross output, Y^G, is defined by a standard Cobb-Douglas production function which includes capital, labor, and total factor productivity (TFP), A. Consumption and investment makeup net output, Y^N, which is what is left of gross output after emission-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. As we show in Section 4.2, our core results are robust to the substitution of other damage functions. The key components from DICE are thus:

$$Y_t^G = A_t K_t^{\gamma} L_t^{1-\gamma} \tag{8}$$

$$Y_t^N = (1 - \Lambda_t)(1 - D_t) Y_t^G \tag{9}$$

$$D_t = \psi_1 T_t + \psi_2 T_t^2 \tag{10}$$

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, the standard climate policy variable in analyses using DICE, which determines cost Λ in Equation 9:

$$E_t = (1 - \mu_t)\sigma_t Y_t^G \tag{11}$$

$$\Lambda_t = \theta_1 \mu_t^{\theta_2} \tag{12}$$

For brevity, we omit description of the intermediate 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).[16]

3.2 Modifications

Our first major modification of DICE is to incorporate the innovation benefits of population. The original DICE model assumes that total factor 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 in aggregate (such as ideas and innovations), which increase per capita productivity.

Specifically, we employ a canonical semi-endogenous growth equation (Jones, 1995):

$$g_{A,t} = \frac{\Delta A_t}{A_t} = \alpha_t L_t^{\lambda} A_t^{-\beta} \tag{13}$$

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

[16]Furthermore, we verify that the atmospheric details of the model are not consequential for the main results: Robustness exercises that replace the DICE atmospheric module with a focal alternative representation of this process (National Academies, 2017) generate nearly identical results.

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. As in our simple model of Section 2, there is no link between TFP, A, and the emissions intensity of output, σ. For conservatism, both population scenarios that we study here (and describe further below) face the same exogenous path of σ_t.

Our 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 therefore omits any distinction between workers and people. 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 3.4. In Equation 8, 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 $1 - \frac{L}{N}$.[17] This accounting is important because, for example, a shrinking population is an aging population, with a greater share of retirees.

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

$$E_{land,m,t} = \frac{N_{m,t}}{N_{DICE,t}} \times E_{land,DICE,t}. \tag{14}$$

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.

[17]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.

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 versus a stable population, not which trajectories are more or less likely. Section 3.4 discusses the construction of these two exogenous population paths.

Parameter values for these DICE modules described above are taken directly from DICE where possible.[18] For the semi-endogenous growth parameters we introduce into the model, 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 to isolate the effects of population, not any modifications of DICE itself. We verify that 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 the National Academies (2017), and increase the emissions impact of population. We also relax DICE's simplified global set up and instead study a regional version of the model to understand the effects of heterogeneity in emission intensities. These analyses demonstrate that our results are robust across these modeling choices.

[18]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.

3.3 Decarbonization Paths

As made clear in Section 2, to study the climate costs of population paths, a stance must be taken on a decarbonization 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 (Hausfather and Peters, 2020; Ou et al., 2021; Arkolakis and Walsh, 2023). In our baseline case, we assume a path of mitigation rates calibrated to global emissions in 2030, 2050 and 2100 under the current policy trajectory estimate in Ou et al. (2021) (see Appendix Figure A2). 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 2). For conservatism, we also consider a "low ambition" policy environment, which yields end-of-century warming similar to common worst-case climate scenarios (Figure 4). In Figure 5 we additionally consider an alternative climate policy path that is much more ambitious than the baseline. (See also Section 4.2.)

Each comparative analysis between the two population scenarios holds decarbonization rates fixed, so the only source of emission differences will be the first-order effect that economic activity (including land use) is increasing in the size of the population. As noted in Section 2, alternatively allowing for endogenous channels by which the larger population can offset some of this first-order difference would only strengthen our main takeaway.[19]

3.4 Population paths: *Depopulation* versus *Stabilization*

We compare two paths for the long-run global population, which we call *Depopulation* and *Stabilization* for ease of reference. They are plotted in Figure 1. *Depopulation* repre-

[19] Aside from the possibility of increased progress on clean energy technology, we also have in mind here endogenous policy that responds to the anticipated increase in cumulative emissions and warming (Bretschger, 2020).

sents 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 (lower than two births per woman) and global population growth will become negative later this century. Quantitatively, we use and extend cohort-component based population projections by the United Nations (UN) World Population Prospects (United Nations, 2022). These projections disaggregate the population into 5-year age bins by country, where country-age-specific fertility estimates are applied to each group to determine the size of the following periods' cohort of newborns. This level of detail for the age-pyramids, and age-profile of reproductive rates, provides an accurate representation of the lag between changes in fertility rates and changes in the total population size.

Our implementation of the *Depopulation* path replicates the UN Medium projection exactly 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 2021 TFR in the United States, through the end of the model span.

In the *Stabilization* path, negative population growth is avoided and the population stabilizes, eventually neither growing nor shrinking. This purely hypothetical scenario is constructed with a simple augmentation of age-specific fertility rates: Starting immediately, we bound country-year TFRs below by the replacement rate (2.04 given our mortality and sex-ratio-at-birth assumptions). We do so by proportionately increasing each age-specific fertility rate in that country-year. For example, if a country is projected to have a TFR of 1.75 in 2030, we multiply each age group's fertility rate in that year by 1.17 ($= 2.04 \div 1.75$). This ensures that no country-year has a TFR below replacement. For country-years that are projected to have an above-replacement fertility rate, nothing is done.[20] After 2100,

[20]In DICE, we input paths for the *global* labor force and population size, and do not disaggregate by country. This method for constructing large increases in the global population is aimed at transparency, not realism.

when the UN projections end, fertility rates that have reached replacement remain there and fertility rates for countries that remain above replacement converge to replacement. In this scenario, the long-run global population stabilizes at about 13.5 billion people.[21] The age pyramid stabilizes with about half of the population in working ages at any give time in later centuries, in line with what the UN projects for 2100 in High-income countries.

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 that is nearly twice as large by 2200, it takes until 2080 for the difference in population size between the two paths to exceed even 10%. The main results follow from this (lack of) difference in population size during the time in which the world is expected to make progress towards net-zero emissions.

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

This section discusses our main results, first showing that the integrated assessment model of Section 3 generates emissions and temperature differences between the two population paths that are quantitatively small. It then assesses the economic impacts of productivity differences across the two population paths, which are large in comparison. The section concludes by demonstrating the robustness of these results to a host of alternative parameterizations and specifications, including a regionally disaggregated version of the model.

Any realistic stabilization scenario would result in slower rebounds in fertility rates and therefore a lower long-run population. In this way, we intend for our main results to be an upper-bound on the emissions impacts of stabilization. In Section 4.2 we revisit a regional model that takes seriously the possibility that the distribution of population changes may be important.

[21] Our results are not contingent on these particular population paths. The productivity 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 A4).

4.1 Main Results

Consider first Figure 2, which depicts the emissions and climate impacts of replacement-rate fertility under current policy estimates. Recall that *policy* here means only the time path of emissions per unit of GDP. The temperature in the two population scenarios is nearly indistinguishable on the scale plotted, following directly from the slow speed of population change relative to the decline in emissions intensities that we have already stressed. *Depopulation* reaches 4.17°C by 2200; *Stabilization* reaches 4.25°C.[22] While these are warming levels that are likely to result in substantial climate damages, the point we make here is that the expected damages are effectively invariant to the path of population. The difference in warming between them (0.08°C) is small. This 1.9% increase would, under a quadratic damage function, lead to a difference of less than 4% in annual climate damages in 2200. By that same point, the difference in population would be just over 6 billion people, a 90% difference.

Because the climate costs of a larger population are so small, even very modest benefits of population arising from endogenous innovation or dependency ratio improvements can dominate the harms. There are two reasons for this. First, a 90% increase in population by 2200 would require a long-run population-productivity elasticity of only about 0.04 to generate a similar 4% increase in the level of productivity. Second, increases in climate damages scale only a fraction of GDP. For example, if climate damages were 10% the size of total output, then a 4% increase in climate damages produces just a 0.4% decline in output available for consumption and investment. Increases in total factor productivity, or the labor force, would instead scale total output. So in fact, the long-run population-productivity elasticity would not even need to reach 0.01 for this 90% population increase to generate a 1% increase in GDP, a gain that would more than offset these additional climate damages.

[22]These temperature changes we find under a current policy scenario are large, compared to the focal 1.5°C target outlined in the Paris Agreement. That is because the current policy scenario we evaluate is not optimistic.

Evidence from the literature on population and productivity (Bloom et al., 2020; Peters, 2022; Ekerdt and Wu, 2023; Kruse-Andersen, 2023b) is consistent with a population-productivity elasticity of at least 0.3—about thirty times larger than the minimum needed for productivity gains to exceed climate damages in our baseline scenario in Figure 2. Figure 3a documents the relative increases in TFP and the share of the population in working ages for our larger population scenario. By 2100, TFP is roughly 3% 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. By 2200 TFP is more than 10% larger in *Stabilization* relative to *Depopulation*.

The dependency ratio impacts are more complex, tracing out non-monotonic effects. Initially, and for a prolonged period, the additional children worsen the dependency ratio, leading to lower GDP per capita, a finding anticipated by Marois et al. (2021), Vollrath (2020), Weil (1999, 2023) and others. Over the long run, however, the dependency ratio improves. *Stabilization* eventually generates an age profile advantage in which about 2.5 percentage points (about 5%) more of the population are workers, relative to *Depopulation*.[23]

4.2 Robustness

The magnitude of population's impact on climate is conditional on assumptions about decarbonization progress. Realistically accounting for the dynamic interaction between demographic change and decarbonization progress is a contribution of this paper relative to past work. But it also implies that if per capita emissions remain significant into the far future, the warming effects of near-term population growth could become large. To provide a sense for whether plausible, but extremely pessimistic, decarbonization paths could reverse our qualitative conclusions, Figure 4 considers a pathway that is in line with standard worst case scenarios (Hausfather and Peters, 2020; Ou et al., 2021). In this

[23] This analysis is not designed to make normative claims about changes in population growth. Therefore, we do not attempt to take a discounted sum of changes to per capita output over time. The positive research question that motivates the analysis is whether low fertility in 2025 and beyond can have an economically significant effect on long-run climate outcomes.

future, warming is approximately 4°C by the end of this century and 6°C by 2200, even with long-term population decline.

We find that in this extreme warming scenario the *marginal* contribution of population growth to warming remains small: 6.36°C versus 5.89°C (Figure 4a). For the same reasons as above, this 0.47°C difference continues to imply a small impact on per capita GDP-equivalent damages, relative to the innovation benefits. Panel (b) makes this explicit by plotting the net effect of larger populations in this pessimistic decarbonization scenario. It is positive in the long-run and qualitatively similar to the results in Figure 3b.

Alongside varying the emissions pathways, we gauge sensitivity to alternative implementations of the endogenous growth channel, and to addressing several well-studied limitations of DICE. Figure 5 presents the results of 192 robustness checks, each from a different set of modifications to the baseline model. Scenarios in Figure 5 span from ambitious futures in which temperature change comes close to meeting international targets and global living standards grow four-fold by 2100, to scenarios with end-of-century temperature change near 4°C and in which living standards *fall* over the following century. In all cases the *additional* warming caused by larger populations remains small and economically insignificant.

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 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 baseline and pessimistic policies considered in Figures 2 and 4. 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 zero to more than three decimal places because (net) per capita emissions fall to zero well before significant population change occurs. (See Appendix Figure A3 for a detailed depiction of this scenario and the difference in warming between population scenarios.)

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).[24,25]

Because FaIR may be of special interest to readers in the IAM community, we additionally replicate Figure 3 in Appendix Figure A5. 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. Our first alternative allows for the economic effects of tipping points, following recent work by Dietz et al. (2021) and adopting their parameters. As a reminder, our baseline model uses the standard specification for damages in DICE2016, which is quadratic in temperature but includes no tipping points (see Equation 10). Our second alternative considers much larger damages than DICE, estimated in an influential paper by Burke et al. (2015). A third

[24] 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.

[25] 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`.

alternative considers the possibility that temperature also influences economic growth rates, as in Dell et al. (2012) and Moore and Diaz (2015). We calibrate parameters such that a 1-degree increase in temperature reduces GDP growth by 1 percentage point per year, consistent with the largest negative impacts on GDP growth presented by Moore and Diaz. For each of the three alternatives we summarize here, full details are provided in Appendix A.

Each 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 2100 than it is today (see bottom left inset histogram in Figure 5). 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. In the baseline model, the industrial emissions come from economic production, not people, and so do not scale identically with population. There is a lag between births and labor force increases. Therefore, an additional child today, who does not contribute to productive capacity, does not immediately increase emissions in the model.[26]

To avoid the possibility of understating population's effects on emissions, we mechanically increase the emissions elasticity of population to exactly one in each period. (See Appendix A). Overall, this does not change the quantity of emissions enough to make a qualitative difference to long-run warming.

Population $\rightarrow$ 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 then calibrate α_t to replicate DICE's TFP path.

To ensure that our findings do not rely on an overly optimistic calibration of how

[26]Emissions increase once the child ages into the workforce. The consumption of a marginal individual who does not contribute to output is implicitly assumed to be substituting for some economic activity that would have otherwise taken place. This is consistent with the standard neoclassical structure of DICE and other medium- to long-run models of economic growth.

much more TFP a larger population can eventually generate, we make ideas "harder to find" by increasing β.[27] Specifically, we increase β from 3.1 to 4.5. This is a quantitatively meaningful change: TFP grows nearly 6-fold by 2200 with $\beta = 3.1$, but only doubles with $\beta = 4.5$ in our baseline model. Because it greatly shrinks the total growth of TFP, it closes the gap in TFP between population scenarios. However, even these smaller differences in TFP are enough for the larger population to eventually have higher per capita income 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 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*.

$$g_{A,t} = \alpha_t^Y Y_t^N A_t^{-\beta}. \tag{15}$$

Equation 15 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.[28] Even a specification where capital was the *only* input to idea-creation would carry the

[27] The long-run effect of a 1% increase in population is governed by the ratio of λ to β, so this is quantitatively similar to scaling λ down by the same factor.

[28] This is 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.

implication that larger populations support larger capital stocks, which then support more TFP growth.

Figure 5 demonstrates that none of these modifications change the takeaways of the paper. Long-run per capita GDP net of climate damages is higher in the larger population for all 192 model combinations because the difference in warming is small in all 192 combinations. Focusing on the model variants that do not consider worst-case emissions trajectories, the mass of the distribution of temperature differences between population scenarios lies almost entirely under 0.1°C,[29] emphasizing that this small effect is driven by timing rather than DICE-specific simplifications.

Regional Model. Separately, and as detailed in Appendix B, we build an alternative version of our baseline model which is sensitive to regional differences in population growth and emissions. The reason that this disaggregation could be important is that locations with low fertility are the locations projected to have higher emission intensities over the coming decades. If we are considering the possibility that low-fertility countries see increases in birth rates, that will be different than a uniformly distributed population increase: Additional births in the United States will generate a different quantity of additional emissions than additional births in Uganda.

For this regional exercise we disaggregate the world into 11 regions, with emission intensities calibrated to match current and projected shares of global industrial emissions. The regional population scenarios come from the same country-level projections that are used to construct the global population scenarios: Country-year fertility rates are bounded below at the replacement rate to generate *Stabilization*, and *Depopulation* is the UN Medium projection for each country until 2100 (after which point each country's fertility rate converges to 1.66). This has very different effects on population sizes for each

[29]As a further example, in a prior version of the companion working paper ("Population Decline: Too Small and Too Slow to Influence Climate Change"), we found this temperature difference to be .06 when constructing the *Stabilization* population path to climb slower and when turning off the dependency and productivity effects that have a second-order effect on emissions. For policy pathways leading to a less than 4-5 degree C temperature increase under *Depopulation*, it is difficult *not* to generate an incremental temperature effect of the larger population on the order of 0.05-0.15.

region. Sub-Sahara Africa, with few countries projected to reach the binding constraint of replacement-rate fertility before 2100, has virtually the same population path until then under *Stabilization* and *Depopulation*. China, on the other hand, experiences a counterfactual more-than-doubling of population by 2100 (see Appendix Figure A6). Interacting this fast increase with China's relatively high per capita emissions is useful for understanding how regional heterogeneity in emissions could matter for our core results.

Figure 6 presents the results of the regional model. It shows that assigning such large population differences disproportionately to regions that have above average per capita emissions generates overall warming effects that are similar to those produced in the global version of the model. Rather than 4.25°C of warming that the global model predicts under *Stabilization*, warming reaches 4.29°C in this scenario where additional people are not uniformly distributed across the world. From the 4.17°C under the baseline *Depopulation* scenario, this remains a less than 3% increase in warming above pre-industrial levels.[30]

5 Negative emissions generate an ambiguous relationship between population growth and 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 near-term 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 global public good. This is because removal of any fixed

[30]We do not modify the economic side of the model to account for regional differences, so we restrict our focus to the warming difference. That would require taking stances on *where* knowledge is produced, and how it is transmitted across countries. Nonetheless, in this regionally disaggregated exercise, differential population growth between the *Depopulation* and *Stabilization* scenarios is disproportionately concentrated in high-income regions (East Asia, Europe, China, North America, Oceania, etc.), whereas poorer regions, where birth rates are already high, experience less population difference between the scenarios. For that reason, the effect of this population increase on TFP growth in a regional model of TFP impacts would, under most assumptions, be larger than the effect assuming a global representative agent as we do in our main specification.

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 rate increases—leading to impacts on population levels only after a generations-long lag—may enable a more rapid reduction in the atmospheric GHG stock.

Futures with 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 include significant net-negative emissions in the second half of this century[31] and the United States' first industrial direct air capture facility recently opened.[32] The uncertainty appears to be around *when*, not whether, the world will produce negative emissions at scale. If net annual per capita emissions become negative, then the long-run population-warming relationship will almost certainly become negative, over a long enough future.

To see this, 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 atmospheric stock of GHGs in the larger population future is equal to the stock in

[31]See https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options.
[32]See https://www.nytimes.com/2023/11/09/climate/direct-air-capture-carbon.html.

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.

While this may be true in the limit, the argument does not tell us whether this result could arise on decision-relevant time horizons. To benchmark this, we use the timeline of net negative emissions in the original DICE model. We then compare the two population paths to evaluate how long after the introduction of net negative emissions it would be before the larger population would achieve the same level of warming as the smaller population.

In DICE's default settings, annual emissions become net-negative only beginning in 2150. After 2150 their quantity is governed by a cost-curve that maps incentives for negative emissions (i.e., a price on carbon), and a path for these prices. For this demonstration, the 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 prior to 2300. The same path of carbon prices is assumed in both *Stabilization* and *Depopulation*, in order to isolate the effect of population size.

Figure 7a plots the emissions paths of the two populations. Until 2150, this is an exact replication of the emissions paths in Figure 2. 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.[33] 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 tempera-

[33] The larger population could produce more negative emissions even if we eliminated the productivity benefits of population growth and assumed the two populations were equally wealthy on a per capita level. The first-order issue is one of scale.

tures are slightly higher, exactly as in Figure 2, 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 become possible to the point that the temperatures are equal.

Of course, the timing of net-negative emissions is subject to many uncertain 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 this set of accessible projections and assumptions provided by DICE, the time it takes for the larger population to have better climate outcomes is on the order of 50, rather than 500, years from the time net-negative emissions are realized. Moreover, the qualitative point will hold regardless of the details: population growth influences long-run populations, and humanity's long-run climate challenge is likely to be collectively financing the removal of existing emissions.

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 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 small when compared against well-studied productivity benefits of near-term increases in population growth. So population reduction is not a substitute for decarbonization policies. Moreover, reductions in fertility do not *complement* other efforts towards decarbonization. Decarbonization efforts reduce per capita emissions, reducing the marginal impact of declining populations and rendering future population sizes less important—or altogether unimportant, once net emissions per person reach zero.

There are at least two ways that future research could push beyond our paper. First, although climate change is the most widely discussed potential environment impact of population size, it is not the only one. A larger population would have environmental effects 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).

Second, productivity growth is not 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).

In general, as societies prepare for the concurrent challenges of reducing emissions and confronting sustained low fertility, it is useful to understand that these objectives are not at odds in a quantitatively meaningful way.

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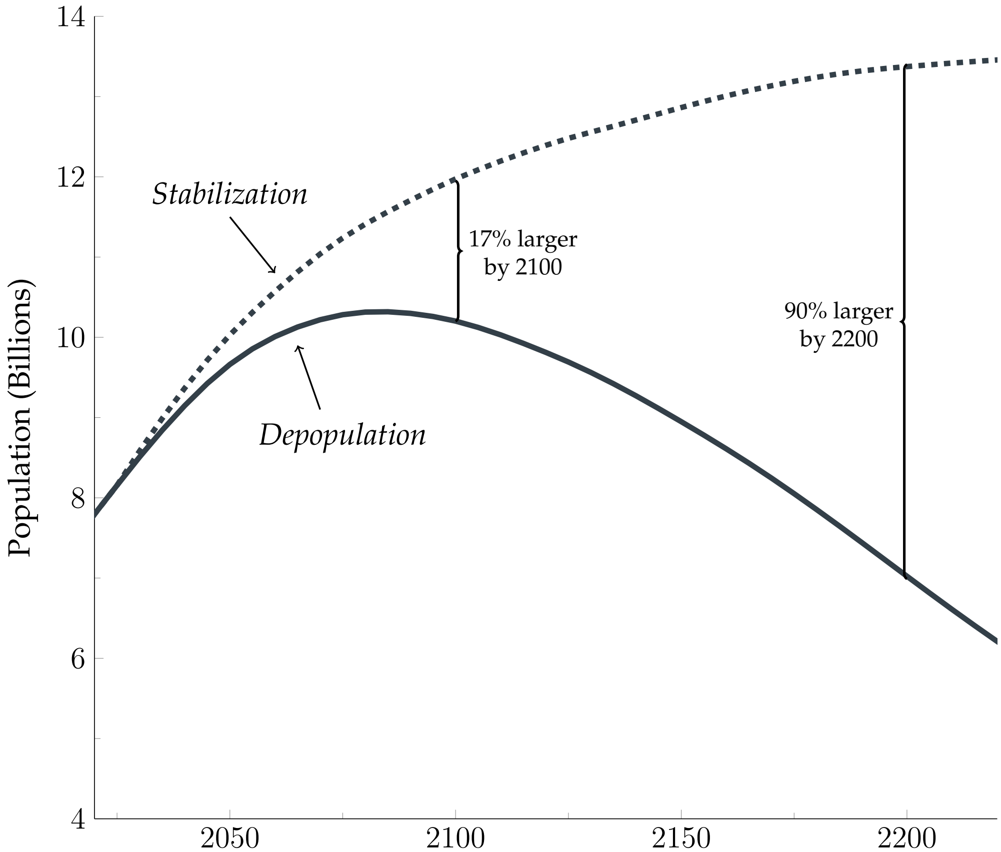
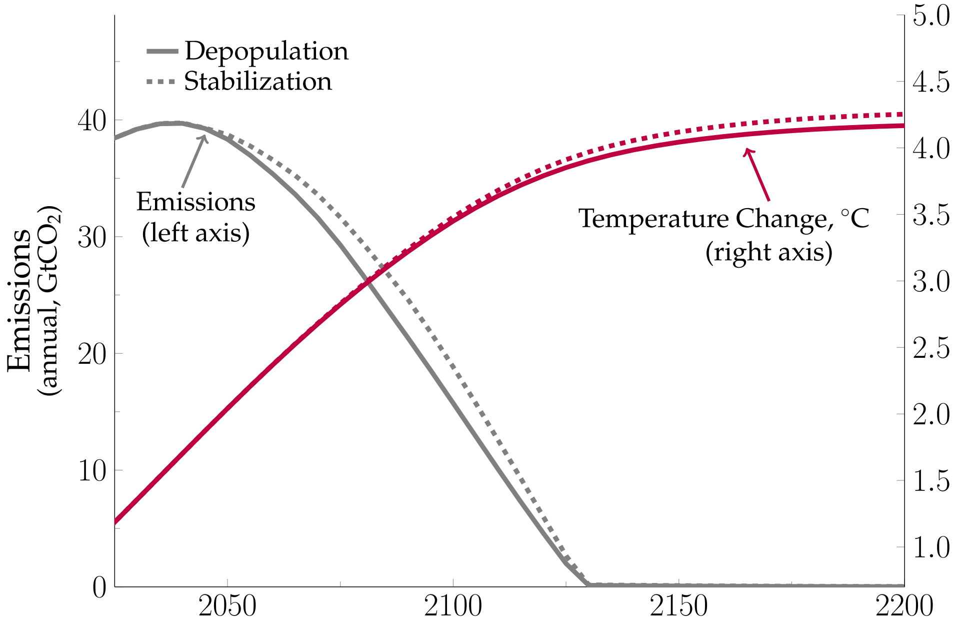
Figures

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



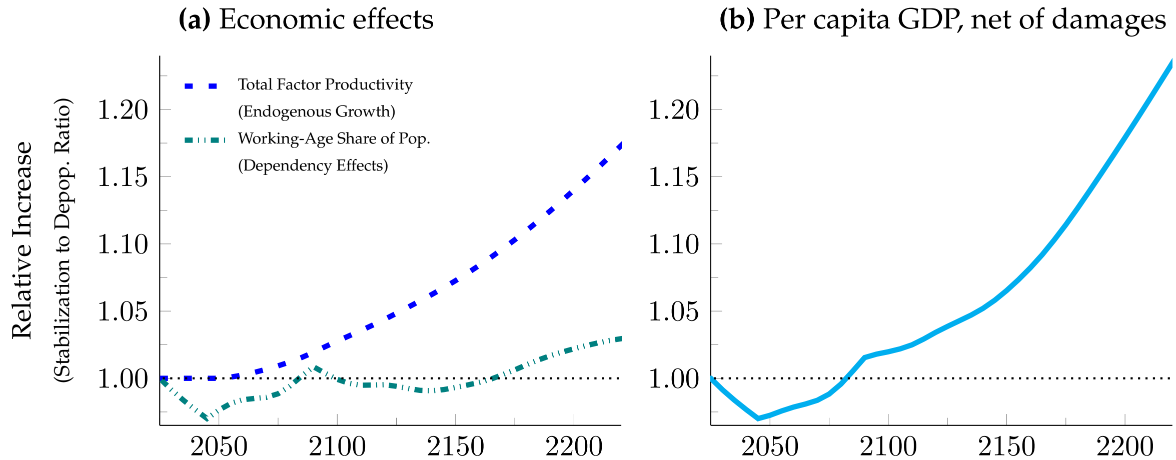
Notes: *Depopulation* and *Stabilization* population paths (inputs to the evaluation in later sections) are derived from United Nations (UN) World Population Prospects 2022 projections. UN projections are available until 2100. *Depopulation* follows UN Medium until then, after which it is extended to match demographic facts for low-fertility populations (United Nations, 2022; Basten et al., 2013). *Stabilization* avoids global population decline by immediately (and indefinitely) bounding country-year fertility rates from below at the replacement rate.

Figure 2: Long-run warming is similar between population scenarios



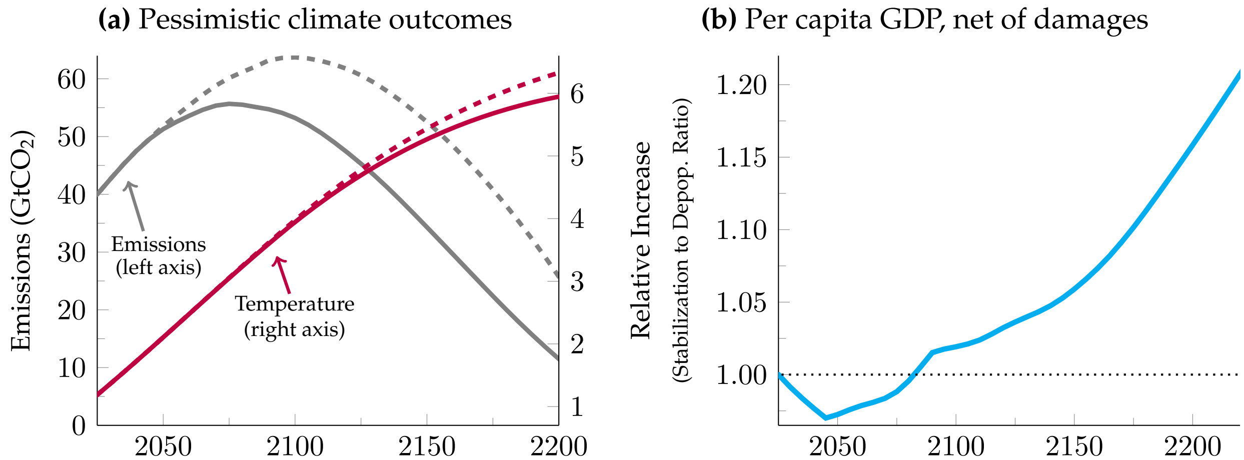
Notes: Emissions (left-axis) and temperature above pre-industrial (right axis) in each of the two population paths described in Section 3.4 when read through the climate-economy model. Annual emissions in each year approximately scale with the population—for example, emissions are approximately 15% higher in 2100, just as population is—but are a small share of remaining cumulative emissions by the time population change becomes significant.

Figure 3: Economic effects of population stabilization exceed climate costs



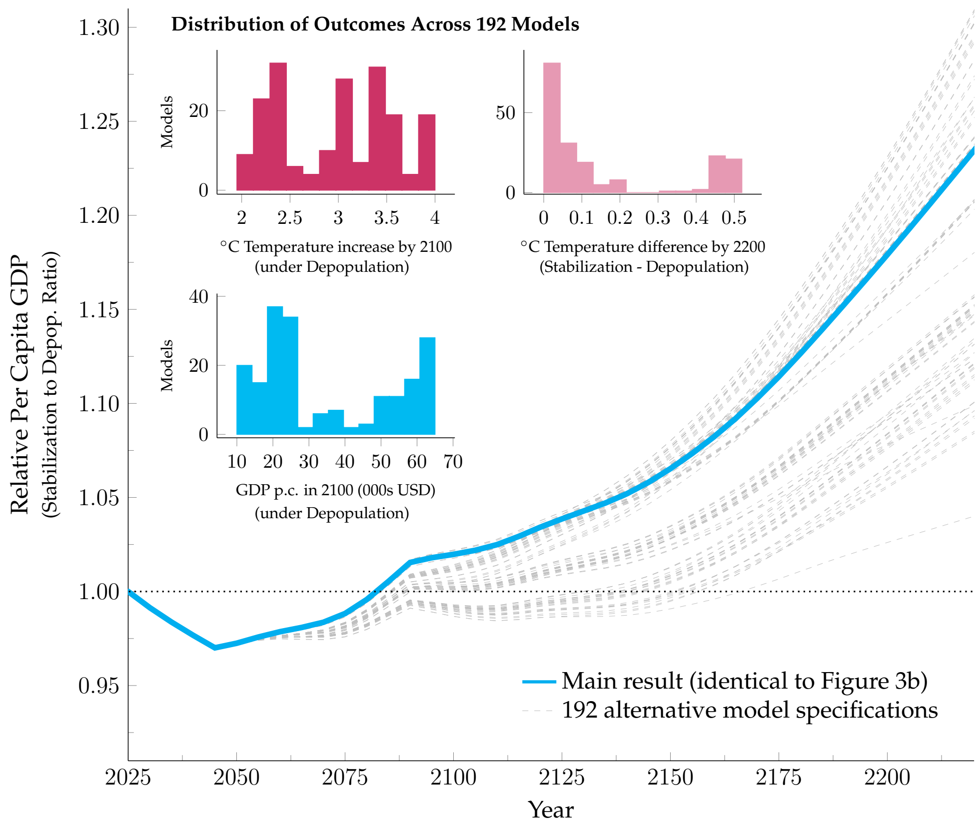
Notes: Panel (a) plots the increases in total factor productivity and working-age share under *Stabilization* relative to *Depopulation* as ratios. These are invariant to the assumed climate policy. Panel (b) plots the increase in average living standards (measured on scale of per capita income, net of climate damages) in *Stabilization* relative to *Depopulation*. This main outcome holds under a wide range of variations on baseline assumptions (see Figure 5).

Figure 4: Main results are robust to using more pessimistic decarbonization paths



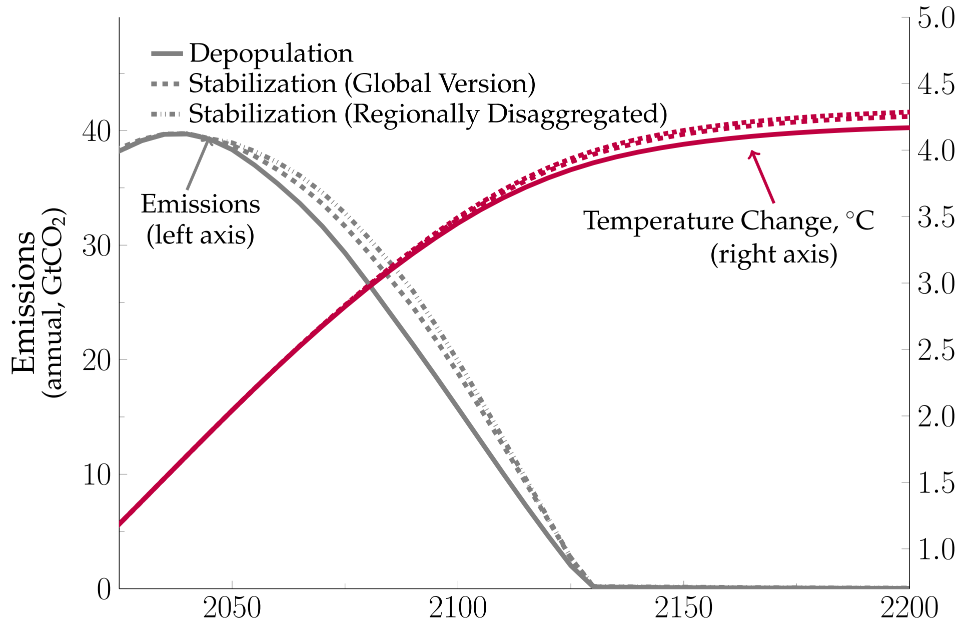
Notes: These figures plot identical exercises to those that generated Figure 2 and Figure 3b, respectively, with a more pessimistic assumption for the time it takes to decarbonize.

Figure 5: 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). The three inset histograms plot, for these 192 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 GDP per capita under the *Depopulation* scenario (bottom). The histograms illustrate that these alternative models are substantially different, despite their convergent finding that net living standards are higher under *Stabilization* compared to *Depopulation*.

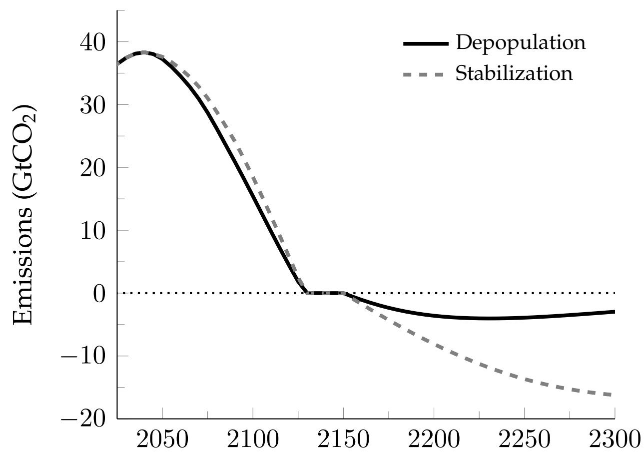
Figure 6: Regional Model: Long-run warming is similar between populations



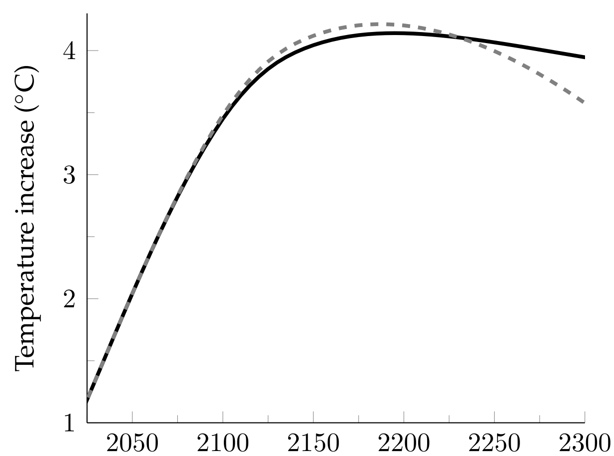
Notes: Replication of Figure 2 with an additional line for both emissions and temperature paths in an alternative version of the model that is regionally disaggregated. Details of the 11-region model are contained in Appendix B. Allowing for potential correlations between population change and emission-intensities leaves temperature increase essentially indistinguishable from the baseline global version of the model. (See Appendix Figures A6 and A7 for population and emissions differences for each region).

Figure 7: 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: A replication of the exercise that determines emissions and temperature effects in Figure 2, but that allows emissions to become net-negative after 2150 (the year in which the 2016 revision of DICE assumes negative emissions begin). In the main analysis and all specifications in Figure 5, we constrain the model such that annual GHG emissions can never fall below zero. The plots illustrate that with negative emissions technologies, there is the potential for climate *benefits* of a larger long-run population.

Appendix for Online Publication

A Details of modifications in Section 4.2

Damage Functions

Dietz et al. present a reduced-form, additive modification of standard quadratic damage functions with coefficients ξ_1, ξ_2. Note that a damage function with tipping points can still take a smooth quadratic form because there is *ex-ante* uncertainty about where such tipping points lie. Increases in temperature can continuously increase the probability of reaching a tipping point, even if the *ex-post* damage function has a discontinuity.

$$D_t = (\psi_1 + \xi_1)T_t + (\psi_2 + \xi_2)T_t^2$$

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

Our second alternative considers much larger damages than DICE, estimated in an influential paper by Burke et al. (2015). These damage estimates 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. We translate the graphical depiction to numerical values using data extraction software and estimate a cubic function, $D = \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3$, for the corresponding damage function.

Our third alternative considers the possibility that temperature also influences economic growth rates, as in Dell et al. (2012) and Moore and Diaz (2015). Moore and Diaz (2015) implement this in a regional integrated assessment model, making exact replication infeasible in our global setting. 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:

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

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. Subtracting a function of past temperatures allows for the long-run effect of a fixed level of warming to be reduced over time, in their specification back to zero. Our numerical implementation is slightly different 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, the $\tilde{T} \to 0$. In other words, there is no effect in the long-run of one-time increase in global temperatures. For simplicity, we instead subtract a rolling average of the prior 30 years. In Moore and Diaz's calibration, $\tilde{T}$ is nearly zero after 30 years following a one-time shock, so our simplification captures similar transition dynamics.

Population Emissions Elasticity

Beyond scaling land-use emissions to population as we do in every model interaction, to avoid understating the effect of population on emissions, we redefine industrial emissions as

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

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 outcomes; 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. This prevents this redefinition from substantively changing anything about the baseline cases we build from.

B Details of Regional Model

The regional model we employ is a disaggregation of the same exercise performed with the global model. The feature that this version may capture with more accuracy is that the *marginal* person resulting from a higher-fertility future may be different than the *average* person. If policies or norms that increase fertility arise in lower-fertility countries, this would be different than a uniform increase across all populations.

To study whether this correlation is significant enough to make a qualitative difference in our model, we split the world into 11 representative regions: North America, Latin America, the EU, Eastern Europe + West Asia, Middle East + North Africa, Sub Sahara Africa, South Asia, Southeast Asia, China, East Asia, Oceania. The baseline emissions pathways are calibrated to again match projections in Ou et al. (2021). Supplementary Table S9 in Ou et al. (2021) contains estimates of disaggregated projected emissions for a variety of countries/regions in the years 2030, 2050 and 2100 under the same *Current Policy* scenario that we use for our baseline global emissions. Just as for our global model, we need emissions pathways for each year, so we need a method for interpolating between years. Our approach is to compute the share of global industrial emissions each of these 11 regions accounts for in present day as well as in 2100, and then to (linearly) interpolate their shares.[34] For example, South Asia represents approximately 9% of global industrial emissions at present, and is projected to represent 45% by 2100 according to the Current Policy Scenario in Ou et al. (2021). We assume that there is a linear progression in the percentage points of global emissions made up by South Asia. Multiplying global emissions from our baseline scenario in each period by the regional shares of global emissions, provides a baseline value for total emissions by region-year.

With an estimate of emissions per region-year, we can calibrate the implied regional policy variables (i.e., the regional mitigation rate) that would produce this level of emissions. Specifically, for each region we have:

$$E_{t,r}^{IND} = \underbrace{\sigma_{r,t}(1-\mu_{t,r})}_{\text{emission-intensity of } Y} \; Y_{r,t}^{G}.$$

It is the product of σ, the technological parameter on emission-intensity of output, and μ, the policy variable, that is pinned down by an estimate of $E_{t,r}^{IIND}$ (once we have the model-implied $Y_{r,t}^{G}$ for each period). However, it is only this product that matters for our main exercise, so it is not problematic that we cannot separately calibrate changes in σ and μ. Our quantitative experiment asks how emissions increase through the channel of popu-

[34]Linear interpolation of percentage points ensures that each year 100% of emissions are accounted for.

lation increasing economic activity for a fixed policy/emissions-technology environment. This scalar is calibrated for the *Depopulation* scenario, such that our regional model and global model produce identical global emissions pathways under this "business-as-usual" population path.

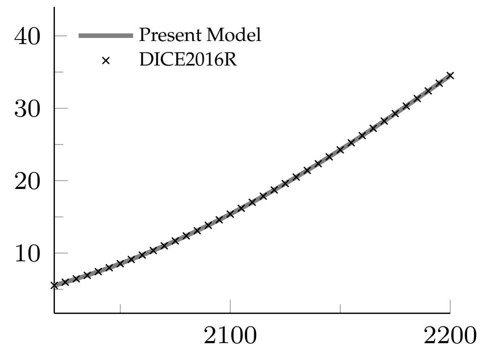
Because we are using the same country-year population paths in this regional exercise as we did in the global exercise, the exact same global population differences are obtained. What differs in this regional exercise is that *where* the additional people in *Stabilization* scenario exist is taken seriously: We have assume that all below-replacement countries immediately have their fertility rates increased to replacement rate (2.04 in our implementation). This has different effects on different regions, as can be seen in Figure A6. Sub Sahara Africa has few countries projected to be below replacement rate over the coming decades, resulting in the population being almost exactly identical in these two scenarios. (That changes after 2100, when countries begin converging to either the replacement- or below-replacement (1.66) common long-run fertility rates). China, on the other hand, is projected to see its population shrink to just 43% of its current size by 2100. Artificially bounding China's fertility rate below by the replacement rate makes a tremendous difference to it's projections over the course of the century.

Figure A7 shows how this change in population, coupled with our assumptions on the baseline emissions trajectories, passes through to differences in regional emissions. Not surprisingly, regions see increases in emissions that closely track their population increases. Finally, Figure A8 depicts how these differences aggregate up in the way presented in the main text. As shown in Section 4.2, and replicated here, total warming is very similar when projected from a regional model rather than our global set up.

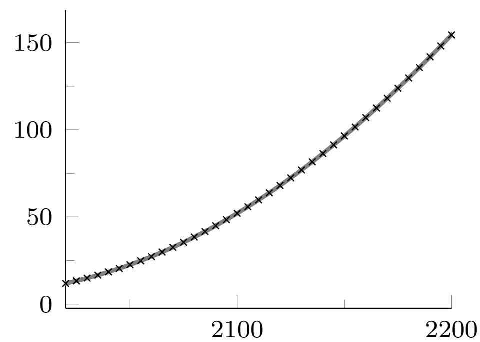
Appendix Figures

Figure A1: Our modified model reproduces DICE's output with DICE's population

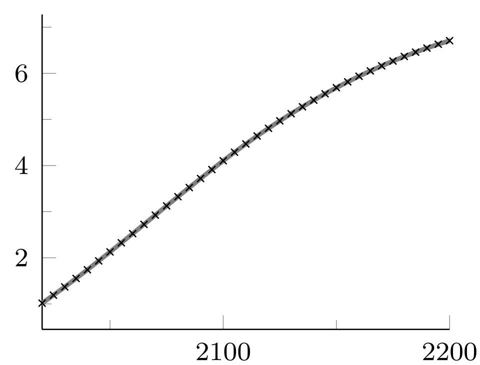
(a) TFP



(b) Per Cap. Consumption

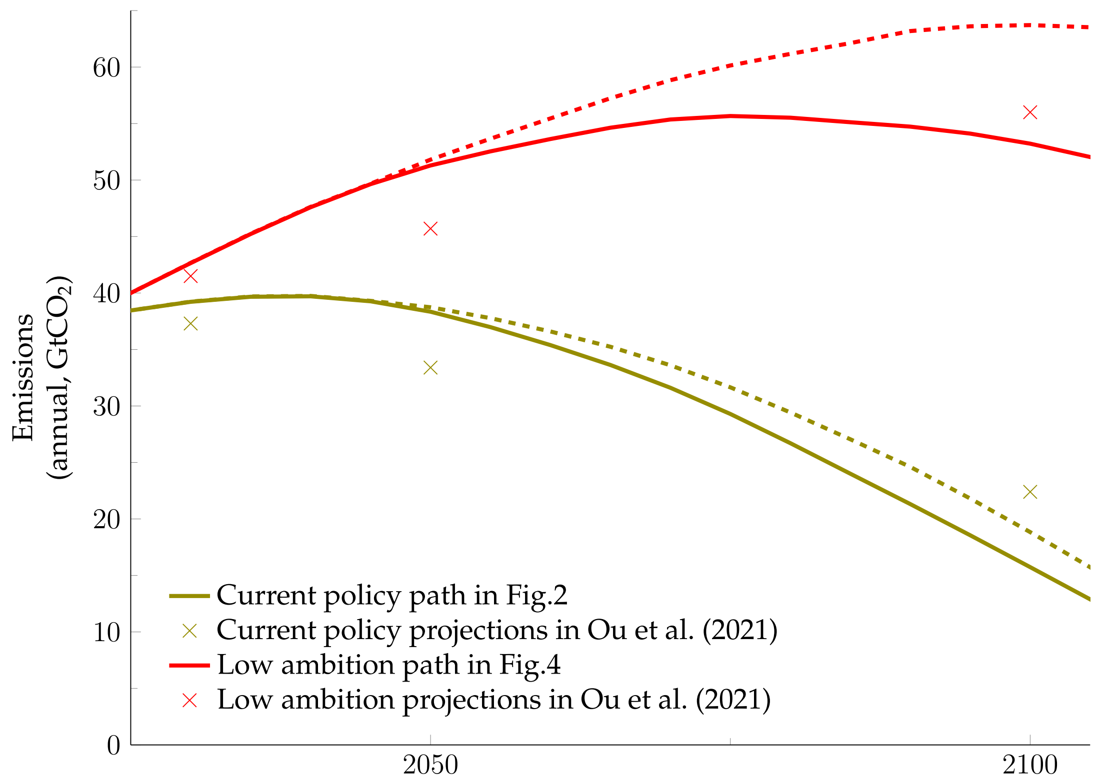


(c) BAU Temperature



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`.

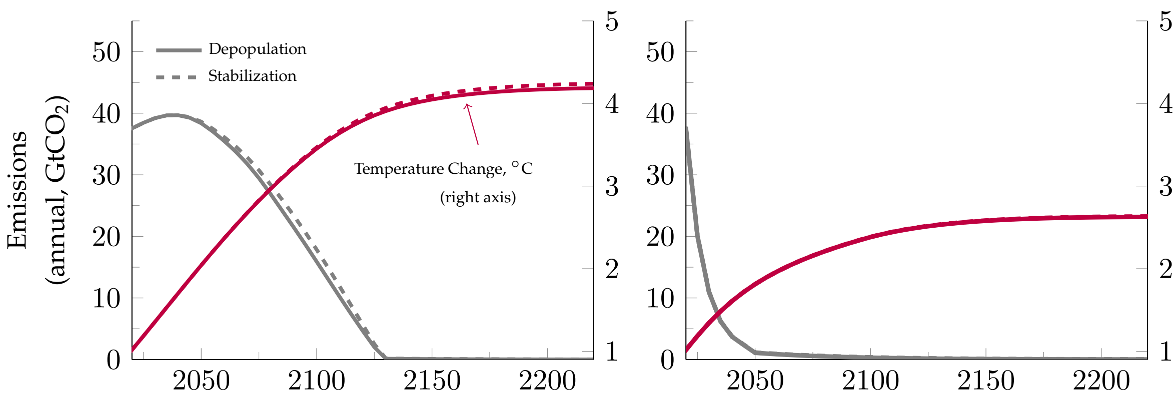
Figure A2: Industrial emissions in Figure 2 are calibrated to independent projections



Notes: The industrial emissions pathways in our model plotted against the projected industrial emissions in Ou et al. (2021) (from their Table S8). To calibrate our emissions pathway, we use a single variable—a fixed z p.p. increase in mitigation rates, μ_t, each five-year period (until an upper bound of 100% mitigation). DICE assumes a background rate of technological progress (σ_t) that increases over time, providing the accelerating decline towards the end of the century. With $z = 4$ p.p. per five-year time period, emissions initially decline less quickly in our model than is projected by Ou et al. (2021). By about 2080, the decline in our scenario is slightly more rapid. Note that the shape of an accelerating decline is consistent with other leading projections (see e.g., Hausfather and Peters, 2020, who uses International Energy Association projections with a similar time-profile to our path).

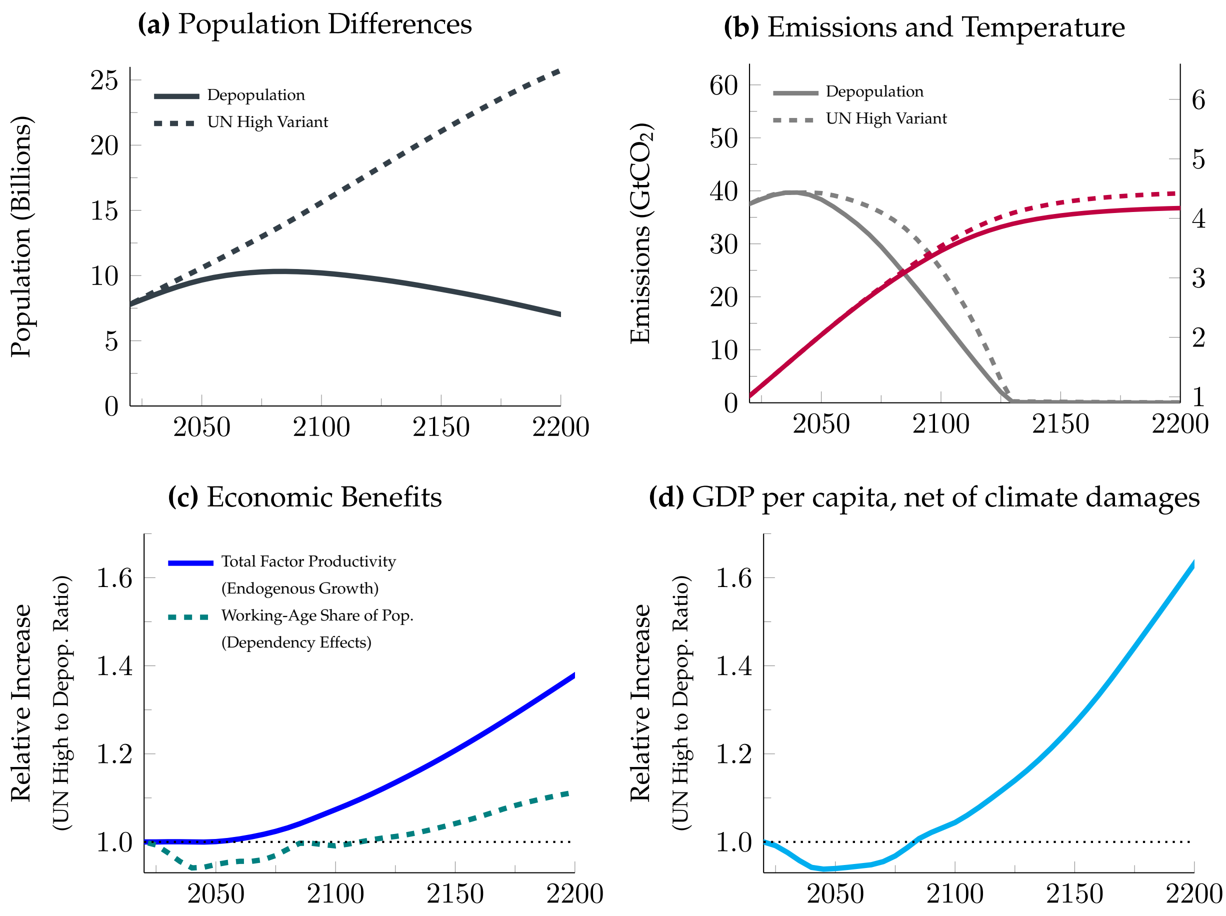
Figure A3: Depiction of optimistic policy scenario used in Figure 5

(a) Current Policy (Same as Fig. 2) **(b)** Rapid Decarbonization



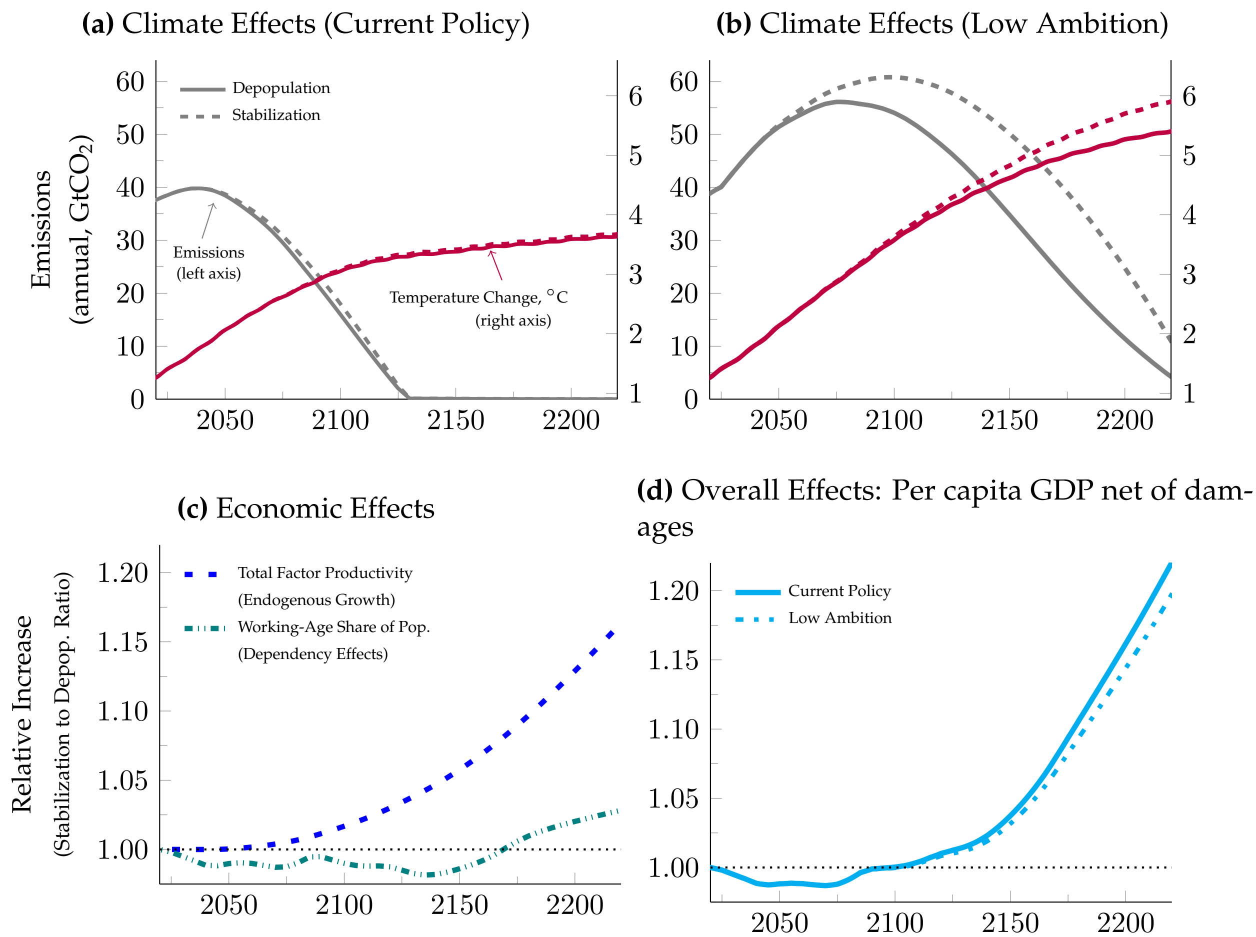
Notes: Emissions and warming under our "ambitious" climate policy, where emissions fall close to net-zero by around 2050. Current policy plotted in left panel for reference. This panel is identical to Figure 2. This alternative scenario is extremely ambitious relative to projections of future emissions. The point is to formally demonstrate that *if* emissions reductions are rapid, there is no distinction in warming between larger and smaller populations. As a corollary for policymakers and others interested in achieving rapid decarbonization: population change will not make any difference in whether ambitious temperature targets are met.

Figure A4: Benefits of population remain large when comparing UN High population projection with *Depopulation*



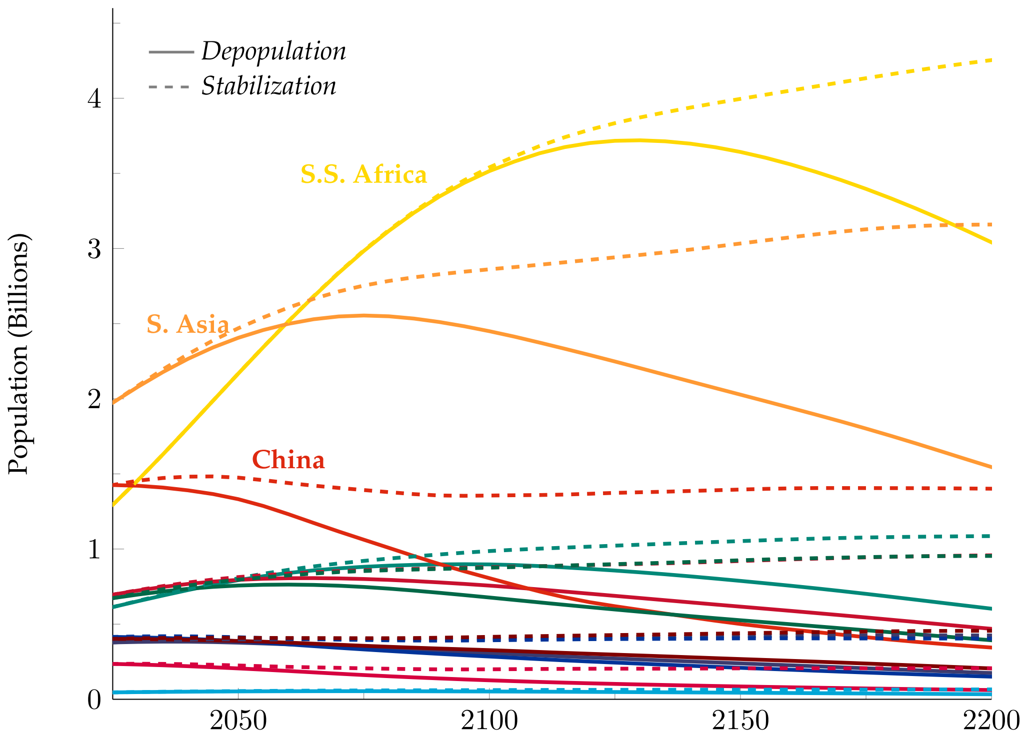
Notes: A replication of our results where an extension of the UN High variant, rather than *Stabilization*, is compared with *Depopulation*. Uses "current policy" mitigation pathways in both population scenarios.

Figure A5: Replication of our results using FaIR climate module



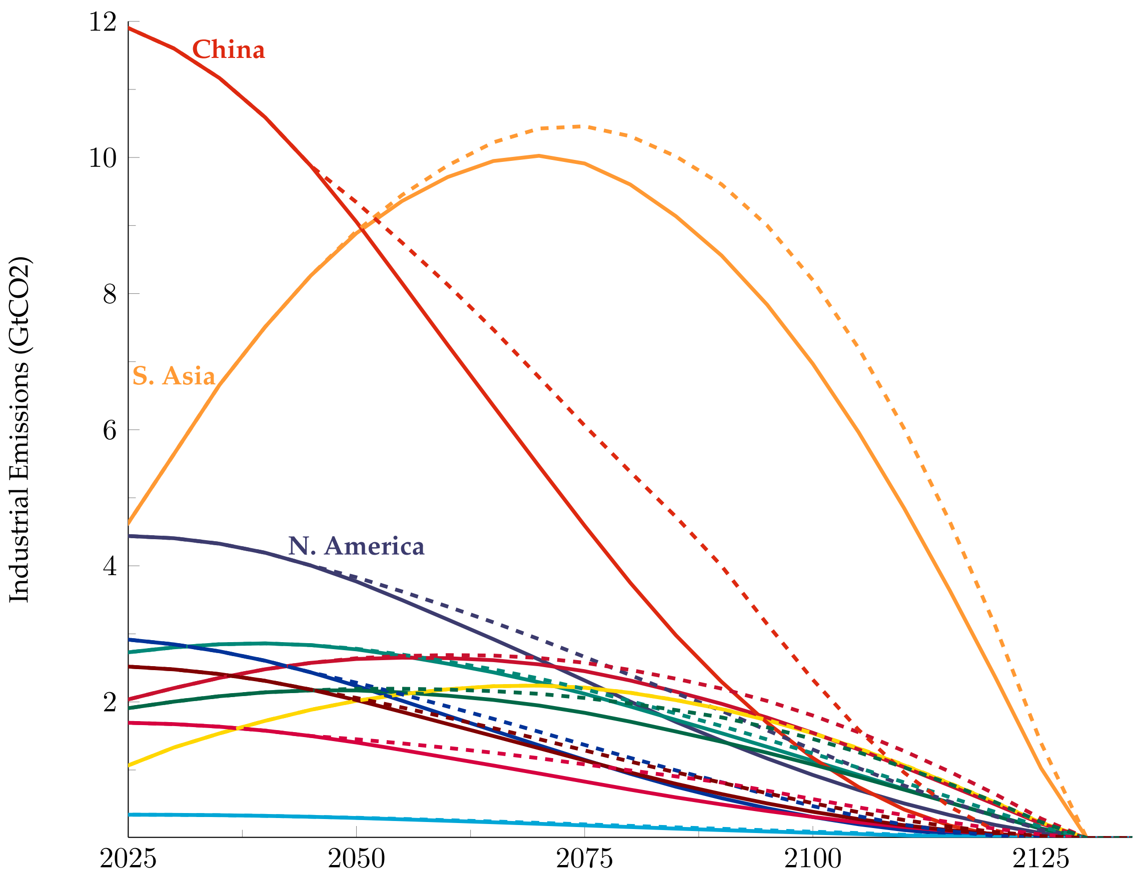
Notes: A replication of our results in which the climate representation has been replaced by the FaIR model. FaIR produces less warming conditional on the same path of emissions (see Figure 2 where warming exceeds 4°C for this emissions path with DICE's atmospheric module). However, the *difference* in warming between population scenarios remains small, and therefore *Stabilization* continues to have a significant advantage in long-run GDP per capita relative to *Depopulation*.

Figure A6: Regional Populations



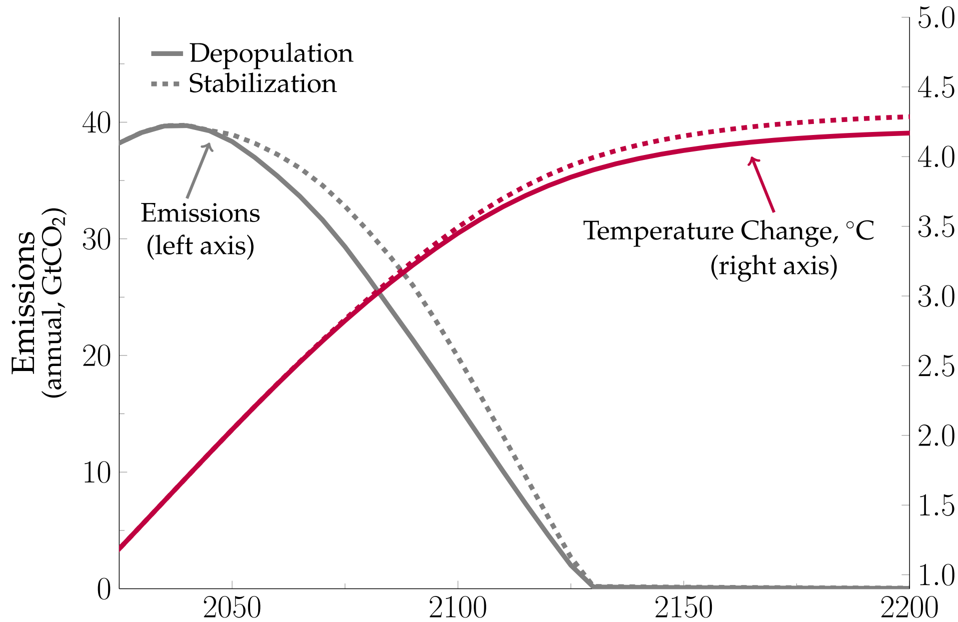
Notes: Plot of regional populations under *Depopulation* and *Stabilization*. Population paths are aggregated from country-specific population projections. The three largest regions (Sub Sahara Africa, South Asia and China) are labeled directly on the plot. Other regions are difficult to see visually and matter much less quantitatively given their much smaller size.

Figure A7: Regional Emissions



Notes: Plot of regional emissions under *Depopulation* and *Stabilization*, for the "Current Policy" scenario. The three largest emitters (China, South Asia and North America) are labeled directly on the plot. Other regions are difficult to see visually and matter much less quantitatively given their much smaller size.

Figure A8: Regional Model: Long-run warming is similar between populations



Notes: Emissions (left-axis) and temperature above pre-industrial (right axis) in each of the two population paths described in Section 3.4 when read through the climate-economy model. Annual emissions in each year approximately scale with the population—for example, emissions are approximately 10% higher in 2100, just as population is—but are a small share of remaining cumulative emissions by the time population change becomes significant.