



Impact of population growth and population ethics on climate change mitigation policy

Noah Scovronick^{a,1,2}, Mark B. Budolfson^{b,1}, Francis Dennig^c, Marc Fleurbaey^{a,d}, Asher Siebert^e, Robert H. Socolow^f, Dean Spears^{g,h,1}, and Fabian Wagner^{a,i,j}

^aWoodrow Wilson School, Princeton University, Princeton, NJ 08544; ^bDepartment of Philosophy, University of Vermont, Burlington, VT 05405; ^cYale–NUS College, Singapore 138527; ^dCenter for Human Values, Princeton University, Princeton, NJ 08544; ^eInternational Research Institute for Climate and Society, Columbia University, Palisades, NY 10964; ^fDepartment of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544; ^gDepartment of Economics, University of Texas at Austin, Austin, TX 78712; ^hEconomics and Planning Unit, Indian Statistical Institute, Delhi, India, 110016; ⁱAndlinger Center for Energy and the Environment, Princeton University, Princeton, NJ 08544; and ^jInternational Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria A-2361

Edited by William C. Clark, Harvard University, Cambridge, MA, and approved September 26, 2017 (received for review November 4, 2016)

Future population growth is uncertain and matters for climate policy: higher growth entails more emissions and means more people will be vulnerable to climate-related impacts. We show that how future population is valued importantly determines mitigation decisions. Using the Dynamic Integrated Climate-Economy model, we explore two approaches to valuing population: a discounted version of total utilitarianism (TU), which considers total wellbeing and is standard in social cost of carbon dioxide (SCC) models, and of average utilitarianism (AU), which ignores population size and sums only each time period's discounted average wellbeing. Under both approaches, as population increases the SCC increases, but optimal peak temperature decreases. The effect is larger under TU, because it responds to the fact that a larger population means climate change hurts more people: for example, in 2025, assuming the United Nations (UN)-high rather than UN-low population scenario entails an increase in the SCC of 85% under TU vs. 5% under AU. The difference in the SCC between the two population scenarios under TU is comparable to commonly debated decisions regarding time discounting. Additionally, we estimate the avoided mitigation costs implied by plausible reductions in population growth, finding that large near-term savings (\$billions annually) occur under TU; savings under AU emerge in the more distant future. These savings are larger than spending shortfalls for human development policies that may lower fertility. Finally, we show that whether lowering population growth entails overall improvements in wellbeing—rather than merely cost savings—again depends on the ethical approach to valuing population.

population | climate change | social cost of carbon | social welfare | emissions

The size of the human population, in the near-term and distant future, is a key determinant of climate policy: All else equal, a larger population entails more emissions and therefore more mitigation to achieve a given climate target (1–3), and it also means more future people will be vulnerable to climate-related impacts. The extensive time lag between the environmental pressure (emissions) and the impacts (fully realized climate damages) differentiates the climate problem from other issues at the human population and environment nexus, as the costs of mitigation will be borne largely by people now, but most of the benefits will be experienced by a future stream of people which is uncertain in size.

Our paper joins a large literature that estimates the social cost of carbon dioxide (SCC), which is the economic cost, expressed in present-day dollars, caused by the consequences for climate change of an additional ton of carbon dioxide emissions (or its equivalent)*. Because in economic theory the optimal carbon price is equal to the SCC (under certain optimality conditions), we use these terms interchangeably.

Any framework for estimating the SCC and optimal mitigation effort has two prerequisites with respect to population: (i) Emissions pressure: Analyses must explicitly account for a range of plausible future population growth rates—which have proved difficult to estimate even over relatively short time periods (4)—and their corresponding links with greenhouse gas emissions. (ii) A social objective: There must be a consistent and transparent approach for valuing the wellbeing of future populations through time.

The link between population and emissions (point *i* above) has been the topic of a large literature (1, 2, 5–11) (*SI Appendix, section 2*).

The same is not true for the link between population and the valuation of wellbeing in the context of climate change (point *ii* above) (12). This aspect is of critical importance because how population is valued by society will determine the SCC and also establish whether a policy that reduces population for climate purposes is desirable overall.

Our paper addresses these questions by using Dynamic Integrated Climate-Economy model 2013 (DICE2013), a leading

Significance

We investigate how future population growth is relevant to climate change policy. The answer depends importantly on ethical questions about whether our ultimate goal should be to increase the number of people who are happy or rather to increase the average level of people's happiness. We calculate the best (optimal) emissions reduction pathway given each of these two different goals that society might have and calculate how much cheaper it would be to avoid dangerous interference with the climate given a smaller rather than a larger population. We also show that whether it is ultimately better to have a smaller population in response to climate change depends on which of these two goals society chooses.

Author contributions: N.S., M.B.B., and D.S. designed the research; M.B.B. led the computer modeling; N.S., M.B.B., F.D., M.F., D.S., and F.W. performed research; N.S., M.B.B., F.D., M.F., A.S., R.H.S., D.S., and F.W. analyzed data; and N.S., M.B.B., and D.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

This open access article is distributed under [Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 \(CC BY-NC-ND\)](https://creativecommons.org/licenses/by-nc-nd/4.0/).

See Commentary on page 12103.

¹N.S., M.B.B., and D.S. contributed equally to this work.

²To whom correspondence should be addressed. Email: Noah.Scovronick@princeton.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1618308114/-DCSupplemental.

*Here we are referring exclusively to the impact of carbon dioxide emissions on the climate through its action as a greenhouse gas. We do not address other externalities associated with burning carbon-based fuels, such as those related to air quality, which are increasingly encompassed in the term “social cost of carbon.”

cost–benefit climate–economy model, to explore how population growth affects the SCC, optimal peak temperature, and mitigation costs under alternative approaches to valuing wellbeing.

The structure of this paper is as follows. In the Introduction we introduce two population-sensitive approaches for valuing human wellbeing (these approaches are known as “social objectives”) and explain the treatment of population in cost–benefit climate–economy models (CEMs). In *Main Results: Population Growth and the SCC*, we use a range of recent population projections, together with the DICE model, to show that population growth has a large effect on climate policy and the SCC. This is true, although quantitatively different, using either of the two most common approaches for comparing social wellbeing across populations of different size, known as total utilitarianism and average utilitarianism (described below). We then extend our analysis by quantifying what these differences imply in terms of mitigation expenditures, observing that smaller-population futures imply lower mitigation costs under either ethical approach, but on different timescales and with different conclusions about the overall desirability of different population pathways.

Population and Wellbeing in CEMs

CEMs are the main tool for estimating the SCC and corresponding optimal mitigation trajectories. It is important to differentiate CEMs from other types of “integrated assessment models.” Here CEMs refer specifically to cost–benefit models that evaluate the impact on wellbeing of climate change and associated policy decisions and are the basis of estimates of the SCC. They are distinct from other types of integrated assessment models in that they quantify the economic damage from increased temperatures, alongside descriptions of the economy and emission processes (13). Three widely used cost–benefit-type models are DICE, Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Effect (PAGE) (14).

The key tradeoff in these models is between mitigation and climate damages, where mitigation expenditures disproportionately subtract from the wellbeing of people now, while damages disproportionately subtract from the wellbeing of people in the more distant future. The tradeoff is made in a way that maximizes the objective of the model, called a “social welfare function” (SWF). All leading optimization CEMs share a total utilitarian (TU) SWF, according to which the (social) objective is to maximize the sum of (discounted) wellbeing across time (15–18). Globally aggregated CEMs such as DICE calculate the wellbeing of the average individual for each point in time as the average consumption transformed into wellbeing by a utility function which embodies “inequality aversion.” The TU objective is the sum of the total wellbeing at each time point (average wellbeing multiplied by the population size), with each time point discounted to a present value at a chosen rate of “time preference.”

Although not currently applied in CEMs, other non-TU social objectives are common in the population literature and could be used instead (19). As a central example, an average utilitarian (AU) social objective focuses on per capita wellbeing and ignores population size, unless population size influences average wellbeing. The average utilitarian concept has had multiple implementations in the literature. The AU SWF that this paper uses provides a clear contrast with TU and integrates straightforwardly with the discrete-time structure of DICE and other CEMs: It calculates levels of wellbeing from average consumption in each time period and then maximizes the sum of those multiplied by the discount factor, but not by the population. However, other implementations exist: Asheim (20), studying the value of population in the genuine savings criterion, uses a similar AU as we do, while Arrow et al. (21) instead use an imple-

mentation which Dasgupta (19) calls “dynamic average utilitarianism” and which divides the discounted sum of total utility across time by the discounted sum of total population across time. TU and AU each have theoretical advantages and disadvantages which have been explored in the population ethics literature (12, 19, 22), alongside other social objectives (23). AU and TU are formally introduced as SWFs in *SI Appendix*, section 1.

In leading CEMs, population size is an exogenous variable calibrated to a population projection at the time of the model parameterization (15, 18). Although it is clear that updated population projections are one source of variation in results estimated by different model versions (15), systematic testing of alternative projections has not been standard in major assessments (although see refs. 1 and 24 and more recently ref. 25); even less research has focused on analyzing the importance of assumptions about how population is valued by society and what that means for climate policy. In stark contrast, there has been comprehensive treatment of the ethical parameters that determine the discount rate referred to above—the inequality aversion parameter and the rate of time preference—with the choice of these parameters becoming one of the most prominent debates in climate economics (16, 26–29). The lack of attention to the social valuation of population growth is particularly surprising because population size, unlike the discounting parameters, is modifiable by policy intervention.

Main Results: Population Growth and the Social Cost of Carbon Dioxide

In this section, we explore the consequences for the mitigation policy of assuming different potential future populations and social objectives (TU vs. AU). We take our population projections from the 2015 revision of the United Nations (UN)-medium, -low, and -high population scenarios (30) as well as a more extreme (“Ultralow”) case based on Basten et al. (31) (Fig. 1A). Although we retain the names of the UN projections, we have modified them by extending them beyond 2100, when they end (*Materials and Methods*).

Analyses were conducted using a variant of the 2013 version of the DICE model (15), with results summarized as differences in optimal global harmonized carbon prices (Fig. 1B) and future temperature rise (Fig. 1C) over time. We depart from the official DICE2013 model only by fixing the savings rate at 25.8%, which is consistent with other CEMs; this change has little impact on results, as shown in *SI Appendix*, Fig. S1 (ref. 32, *Materials and Methods*, and *SI Appendix*, section 2).

Each of these results is an optimal mitigation policy path under DICE, meaning that mitigation effort maximizes intertemporal discounted wellbeing, according to the chosen social objective. Below, we also discuss results for the same population scenarios but constrained by temperature targets. Unless otherwise noted, all model runs assume a 1.5% annual rate of time preference and a 1.45 inequality aversion parameter (representing the diminishing marginal utility of consumption), the values chosen for DICE2013 by William Nordhaus, the architect of the model. In *SI Appendix* a wider range of population projections are tested, based on the shared socioeconomic pathways (SSPs) and the UN’s probabilistic scenarios (*SI Appendix*, Fig. S2), as well as sensitivity to the assumption of a near-zero (0.1%) rate of time preference (*SI Appendix*, Fig. S3). *SI Appendix* also contains results based on a regionalized version of DICE, demonstrating that our general findings are unaffected when region-specific differences in economic and climate variables, as well as population estimates, are explicitly represented (*SI Appendix*, Fig. S4).

Carbon Price. The solid lines in Fig. 1B present results with the standard TU social objective; dashed lines represent AU. The results demonstrate that future population has a large effect on

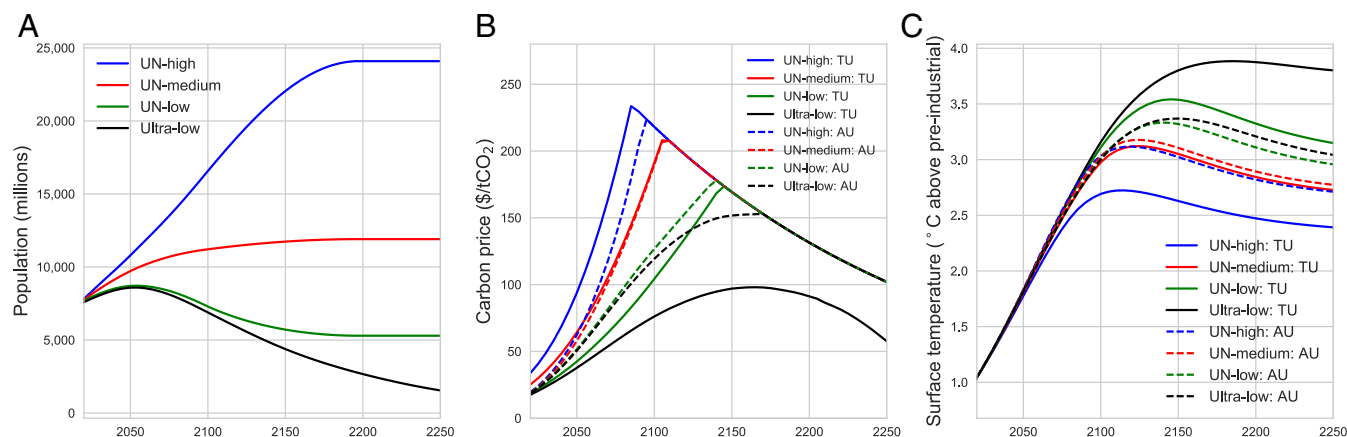


Fig. 1. Population scenarios and corresponding influences on optimal mitigation and temperature under the TU and AU social objectives. (A) UN-high, -medium, and -low population scenarios (with extrapolations beyond 2100) and the Ultralow scenario. (B) Optimal prices. (C) Global average temperature rise.

optimal policy, with carbon prices over 85% higher in 2025 and 120% higher in 2050, assuming the UN-high compared with the UN-low population scenario given the TU objective. Relatedly, full abatement (100% decarbonization)—the point in Fig. 1B where each carbon price path peaks and subsequently declines along a single line (representing an assumed “backstop price” at which zero carbon technologies are competitive with all fossil fuels)—occurs more than half a century later under the UN-low vs. UN-high scenario. Carbon prices in the Ultralow scenario stay far lower still, and full abatement is never optimal given the TU objective. A regionally disaggregated comparison of the UN-medium with the UN-low scenario—as well as an alternative comparison of an SSP-inspired population scenario—shows that the differences in the SCC across alternative population projections are principally driven by differences in the future population paths of developing countries, with sub-Saharan Africa the greatest contributor (*SI Appendix, Fig. S5 and Table S1*).

The dashed lines in Fig. 1B present results under AU and compared with the TU results (solid lines) elucidate the distinct mechanisms by which population influences optimal climate policy. Note in particular that the AU curves diverge slowly, since AU does not weight time periods by population size. In contrast, the TU price paths quickly diverge from each other, even in the near term, because TU is sensitive to the role of future population growth in its weighting of period wellbeing.

In other words, in the near term, the AU price paths are insensitive to the size of the future population because population assumptions do not influence the social objective; it is the average level of wellbeing that matters. In the long run, however, the AU price paths do diverge as the increasing difference in population size begins to cause an increasing disparity in emission pressure. As a result, AU-optimal price paths become more like their TU counterparts as more time passes. Further results in *SI Appendix, section 6* separate the effects on the optimized results of the population weighting effect of future population growth from the emission effects of future population growth: These two mechanisms can be isolated by the use of diagnostic model runs that mix one population path’s role in economic consumption (emissions) with another population’s role in the social objective.

To help explain the mechanism of this result, consider a hypothetical case of constant exponential population growth. Under TU, the rate of population growth would be linearly added to or subtracted from the rate of pure exponential time discounting to determine the weight put on average wellbeing of future time periods: The weighting roles of time preference and population growth are analogous (ref. 3, p. 136 and *SI Appendix, section 1*).

Because the difference in population growth to 2200 between the UN-high and -low scenarios is comparable to a 1.4 percentage point constant difference in population growth, we show in *SI Appendix, Fig. S6* that the difference in optimal policy under TU between these population trajectories is similar to changing the rate of pure time preference from 0.1% to 1.5%. A rate of time preference ranging from 0.1% to 1.5% bounds the values for time preference common in the climate economics and policy literature (16, 26, 28). Therefore, under TU, the importance of population assumptions for optimal carbon policy is quantitatively comparable to the assumptions frequently debated about time preference. Under AU, the rate of population growth has no weighting effect.

Optimal Peak Temperature. Strikingly, temperatures increase less in the higher-population optima (Fig. 1C). This is especially true under TU, because a given level of climate damages registers as a greater social cost when more people suffer from it.

Increasing the future population growth rate could theoretically increase or decrease optimal peak temperature under AU and under TU. But the theoretically unambiguous prediction—which our results display—is that population growth will reduce optimal peak temperature more under TU than AU, because there is an additional weighting effect of population. Further, under both TU and AU, increasing the future population increases the SCC, which accelerates the date of full mitigation (100% decarbonization), causing peak temperature rise to be lower and occur sooner. This effect is stronger under TU, again because of the population weighting effect. (For more detail on the result that TU optimal peak temperature falls with increasing population and comparison with the literature, see *SI Appendix, section 3*.)

One policy implication of these results is that whether differences in the assumed future population trajectory influence near-term mitigation policy depends upon the choice of the social objective: Under TU, near-term optimal climate policy is sensitive to future population growth, but under AU it is much less so. This finding has a direct bearing on potential mitigation cost savings from putting the world on a lower-population trajectory, which we consider in the next section.

Mitigation Cost Savings from Smaller Population Under TU and AU

An important prior literature has explored whether human development policies that reduce population size could lead to large benefits through avoided climate mitigation costs (1, 2, 5, 7, 9–11).

Accordingly, in this section we explore potential cost savings, in quantitative terms, of achieving the UN-low vs. UN-medium scenario. These two population scenarios were chosen because our goal is to compare mitigation costs under the central population projection against the costs under a lower-population alternative that may be roughly achievable given additional investments in human development.

To compute mitigation cost savings, we depart from the previous section, which presented optimal mitigation trajectories without any constraint on the level of temperature increase, by here estimating the mitigation costs (and savings) needed to achieve targets of 2 °C and 3 °C under both population scenarios. This allows us to compare costs when the level of temperature rise is held constant, including at the 2 °C target that is often considered necessary to prevent dangerous climate change. (Note that a target of 2 °C and 3 °C requires greater than optimal mitigation effort in DICE—see Fig. 1C for optimal peak temperatures.) Further results in *SI Appendix, Table S4* investigate the effect of population growth on mitigation costs when mitigation effort is suboptimally low (i.e., results in higher peak temperatures).

With the standard TU social objective, smaller population entails lower near-term carbon prices and therefore results in near-term mitigation cost savings (Fig. 2 and *SI Appendix, Tables S2 and S3*). Regional disaggregation for the 2 °C target shows that it is the wealthier regions—those most able to finance sustainable development—that would save the most, in per capita terms (*SI Appendix, Fig. S7*). With AU, cost savings occur only in the more distant future. Results with additional population scenarios, robustness checks, and an explanation of the cost savings calculation are available in *SI Appendix, section 2 and Tables S2 and S3*).

One debate within the climate literature is whether interventions that reduce population growth rates would be effective climate policy, because a smaller future population will have lower emissions, all else equal. Our results have an implication for that debate: Under TU, a smaller future population implies near-term mitigation cost savings in the tens of billions of dollars annually. As a result, we show in Fig. 2 and associated results and discussion in *SI Appendix, section 4 and Tables S2 and S3*

that some feasible, noncoercive policies (e.g., education and family planning programs) to promote human development in the developing world—and thereby reduce fertility—can result in avoided near-term climate mitigation costs more than large enough to pay for the programs.

In contrast, because population growth has a smaller effect on the near-term SCC under AU, policy to reduce future population growth entails almost no near-term mitigation cost savings. In fact, in the 2 °C case, the “savings” are slightly negative in the first few periods: Although the theoretical prediction is clear that reducing population growth would reduce overall mitigation costs over the full future time horizon studied, there is no necessary theoretical prediction about this numerical result in these few periods where mitigation costs are very low under either population path. Reduced population growth would eventually offer mitigation cost savings under both TU and AU as reduced population eventually causes reduced emissions pressure (Fig. 2).

This result suggests a possible rethinking of the reason why reducing future population growth would reduce climate mitigation costs. The standard argument is that a reduced population would influence mitigation policy because a smaller population would have less emissions pressure. However, our AU and TU results have identical populations and associated emissions pressure. The large near-term difference in mitigation cost savings with TU compared with AU therefore suggests another reason: For any given level of climate change, increasing the future population increases the social valuation of climate damages under TU but not under AU.

Does Reducing Population Improve Overall Wellbeing?

We have seen that mitigation cost savings arise, albeit on different timescales, under both TU and AU. Does this imply that both TU and AU recommend policies to reduce population size? Not necessarily, because mitigation cost savings are only one way population size influences wellbeing. Because AU and TU value population differently, the full valuation of a population path is a further question.

Table 1 shows that the answer again depends on whether AU or TU is chosen: In the context of our CEM, the sign of recommended population policy depends on the treatment of

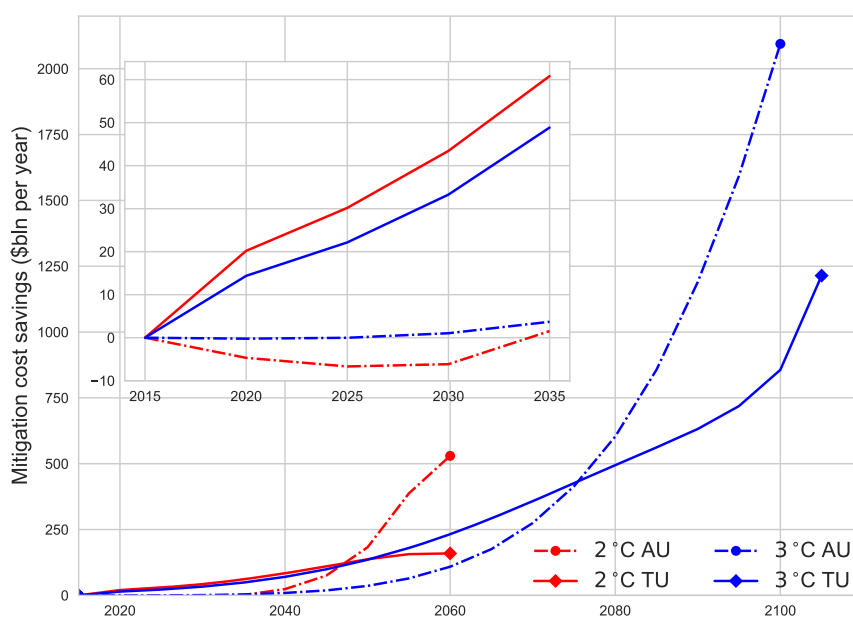


Fig. 2. Mitigation cost savings from moving from the UN-medium to the UN-low population path, under TU and AU social objectives, given 2 °C and 3 °C temperature targets. Cost savings stop when full abatement is reached in both population scenarios.

Table 1. Social valuation of population paths by AU and TU, at optimal climate policies, as a percentage of valuation of the UN-medium path

Social objective	UN-high, %	UN-medium, %	UN-low, %
AU	99.5	100	100.6
TU	192.3	100	40.4

population in the social objective. AU regards moving from UN-medium to UN-low population as a slight improvement, because average wellbeing is increased and there is no loss in wellbeing from foregone people. In contrast, TU regards moving to a smaller population as much worse.

This reveals a tension in the climate literature not previously recognized: For a standard CEM to reconstruct and endorse a common policy recommendation in the literature—that population growth should be reduced as a form of climate mitigation—requires an AU-like social objective. However, all CEMs with a social objective assume TU. A TU social objective could recommend policies that encourage lower population growth, but only if, beyond the emissions reductions and climate mitigation benefits entailed in DICE, other benefits of reduced population for average wellbeing are large enough to outweigh the reduction in population size.

Discussion

Climate change mitigation incurs a cost in the near term but will primarily benefit people in the future, including an unknown number of those not yet born. As a result, the number of future people is an important determinant of climate policy, depending on how society chooses to value the quantity and quality of people's lives. As O'Neill and Wexler have discussed in regard to the climate externalities of having children, “in general, comparing welfare across different population sizes introduces profound theoretical issues” (ref. 10, p. 344), with advantages and disadvantages of each approach.

Our results have used the DICE modeling framework to show that alternative approaches to valuing wellbeing—common outside of the climate literature—and alternative projections of future population have large and often immediate impacts on recommended climate mitigation policy. Moreover, these assumptions interact, with the impact of different population projections dependent on the role of population in the social valuation of wellbeing.

Our modeling approach has extended previous analyses in several respects. DICE allows for a systematic integration of economic and climatic variables alongside alternative approaches to social wellbeing and enables an investigation of population size to be placed within the SCC framework. Further investigation could consider substituting AU for the TU objective function in other CEMs.

Because the goal of our analysis is to highlight the importance to the SCC of the role of population in the social objective, there are limitations to our approach. These are discussed more fully in *SI Appendix*, but we highlight three here.

First, DICE considers only the size of the population, but not variables related to its composition. Instead, DICE subsumes these into a reduced-form model of the economy that translates population size, capital stock, and technology into production and emissions. We abstract away from population composition because our paper focuses principally on the valuation of population rather than the emissions pressure of population. However, urbanization and age structure in particular have been shown to influence greenhouse gas emissions, although studies suggest that the two may largely offset globally (2, 6, 7).

Second, although we study exogenous population paths, previous work indicates that the links between fertility and climate impacts are not uniform across regions (2). Our robustness checks in *SI Appendix*, using a regionalized version of DICE, suggest that our results are robust to disaggregation.

Third, some policies affecting population growth may also affect resilience to adverse impacts of climate change (33, 34). Although such effects may be important for climate policy, they are beyond the scope of our study, which focuses on the importance of population projections and values within the context of a standard CEM. More broadly, our model has not considered endogenous effects of climate change or climate policy on fertility or any important nonclimate benefits of policy that offers opportunities to reduce fertility.

The choice of an AU vs. TU social objective has meaningful consequences for climate mitigation policy. This choice influences the SCC and can also determine both the magnitude and sign of the appropriate population policy response to climate change: Where TU would value the additional lives of a larger population over the resulting climate damages and mitigation expenditures, AU would recommend a smaller population to avoid these costs. This choice is therefore important for climate policy, although it is not yet widely discussed within the climate change community.

Materials and Methods

We use the Excel version of the DICE2013 CEM as downloaded from William Nordhaus's website, which is freely available online (currently at aida.econ.yale.edu/~nordhaus/homepage/documents/) and has been described in detail elsewhere (15, 35). Further details of the DICE model and its assumptions are presented in *SI Appendix, section 2*. In *Dataset S1* we also present all data and the interactive, optimizable model in spreadsheet form for every result.

Briefly, DICE is a global (single-region) optimization model that includes an economic and a geophysical component that are linked. Economic activity produces emissions, which are a function of gross domestic product (output) and a time-varying ratio of emissions to output, as well as emission control policies; carbon intensity is exogenous. Population influences emissions by influencing output via a Cobb–Douglas production function. If unmitigated, emissions affect the future economy through climate-related damages (24, 36), which increase with the global surface temperature and are incurred as the loss of a percentage of output. Emission reductions (mitigation) occur through a globally uniform carbon price.

Like all leading CEMs, the size of the population is an exogenous variable in DICE. In this study, we compute optimal carbon prices and thus mitigation paths by exogenously specifying a variety of population trajectories, based primarily on the 2015 revision of the UN's World Population Prospects and the Shared Socioeconomic Pathway project (30, 37, 38). Both of these sources provide a range of population estimates through 2100. To project beyond 2100 we assume that the population growth rate in the timestep ending in 2100 tapers linearly to zero between 2100 and 2195 and remains constant thereafter. The Ultralow projection continues past 2100.

Other than the changes to population that are essential to our experiments, the DICE2013 model is unchanged (including default parameter values, such as a climate sensitivity of 3.2) with one exception: We specify an exogenous savings rate of 25.8%, which can be interpreted as the optimal savings rate of private savers with a time-separable and discounted objective with a logarithmic utility function (32, 39). To explain this approach, we first note that there are two alternative treatments of savings in the climate–economy modeling literature: One approach assumes that economic agents endogenously look forward to climate damages and policies and optimally adjust their planned savings (a leading example is in the official versions of DICE/Regional Integrated Climate Economy (RICE)), and another assumes that savings do not so respond to climate policy optimization (leading examples are FUND and PAGE; in a DICE/RICE framework, see ref. 32). Although both approaches are defensible, we prefer and use the second approach, because we find it more realistic to assume that society has a fixed appetite for savings that is essentially insensitive to climate change and climate policy decisions. In *SI Appendix, Fig. S1*, we demonstrate that our results are substantively identical and

quantitatively very similar if we instead endogenize optimal savings as in DICE.

In a small subset of our modeling runs, we also make an additional change to DICE to investigate our research questions. To generate one result reported in the main text, we change the rate of time preference to the value that would make the optimal mitigation trajectory of the UN-low population scenario provide the closest fit to that of the UN-high scenario (*SI Appendix, section 2 and Fig. S6*). To generate results for the runs maximizing AU, we altered the social objective accordingly (*SI Appendix, Eq. S2*). For Fig. 2, we maximize the social objective (AU or TU) subject to the constraint that temperature must never rise above the target in the 2 °C and 3 °C cases.

- Gaffin SR, O'Neill BC (1997) Population and global warming with and without CO₂ targets. *Popul Environ* 18:389–413.
- O'Neill BC, et al. (2010) Global demographic trends and future carbon emissions. *Proc Natl Acad Sci USA* 107:17521–17526.
- O'Neill BC, MacKellar FL, Lutz W (2005) *Population and Climate Change* (Cambridge Univ Press, Cambridge, UK).
- Lam D (2011) How the world survived the population bomb: Lessons from 50 years of extraordinary demographic history. *Demography* 48:1231–1262.
- Casey G, Galor O (2017) Is faster economic growth compatible with reductions in carbon emissions? The role of diminished population growth. *Environ Res Lett* 12:014003.
- Liddle B (2011) Consumption-driven environmental impact and age structure change in OECD countries: A cointegration-STIRPAT analysis. *Demogr Res* 24:749–770.
- O'Neill BC, et al. (2012) Demographic change and carbon dioxide emissions. *Lancet* 380:157–164.
- Spears D (2015) Smaller human population in 2100 could importantly reduce the risk of climate catastrophe. *Proc Natl Acad Sci USA* 112:E2270.
- O'Neill BC (2000) Cairo and climate change: A win-win opportunity. *Glob Environ Change* 10:93–96.
- O'Neill BC, Wexler L (2000) The greenhouse externality to childbearing: A sensitivity analysis. *Clim Change* 47:283–324.
- Wheeler D, Hammer D (2010) The economics of population policy for carbon emissions reduction in developing countries (Center for Global Development, Washington, DC), Available at https://www.cgdev.org/files/1424557_file.Wheeler_Hammer_Economics_Pop_Policy.pdf. Accessed October 16, 2017.
- Broome J (2012) *Climate Matters: Ethics in a Warming World* (Norton, New York).
- Weyant J (2017) Some contributions of integrated assessment models of global climate change. *Rev Environ Econ Policy* 11:115–137.
- Interagency Working Group on Social Cost of Carbon (2013) *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (US Government, Washington, DC).
- Nordhaus W, Sztorc P (2013) *DICE 2013R: Introduction and User's Manual*. Available at aida.econ.yale.edu/~nordhaus/homepage/documents/DICE.Manual.103113r2.000.pdf. Accessed October 11, 2017.
- Stern N (2006) *Stern Review: The Economics of Climate Change* (Her Majesty's Treasury, London), Vol 30.
- Hope C (2011) The social cost of CO₂ from the PAGE09 model (Cambridge Judge Business School, Cambridge, UK), Discussion Paper 2011–39.
- Anthoff D (2009) Equity and climate change: Applications of FUND. PhD thesis (Max Planck Institute, Hamburg, Germany).
- Dasgupta P (2001) *Human Well-Being and the Natural Environment* (Oxford Univ Press, Oxford).
- Asheim GB (2004) Green national accounting with a changing population. *Econ Theory* 23:601–619.
- Arrow KJ, Dasgupta P, Mäler KG (2003) The genuine savings criterion and the value of population. *Econ Theory* 21:217–225.
- Spears D (2017) Making people happy or making happy people? Questionnaire-experimental studies of population ethics and policy. *Soc Choice Welfare* 49:145–169.
- Arrhenius G *Population Ethics* (Oxford Univ Press, New York), in press.
- Nordhaus W, Boyer J (1998) What are the external costs of more rapid population growth? Theoretical issues and empirical estimates. *150th Anniversary Meeting of the American Association for the Advancement of Science* (Philadelphia), Vol 15. Available at www.econ.yale.edu/~nordhaus/homepage/pop0298.htm. Accessed October 16, 2017.
- Gillingham K, et al. (2015) *Modeling Uncertainty in Climate Change: A Multi-Model Comparison* (Covles, New Haven, CT), Discussion Paper 2022.
- Nordhaus WD (2007) A review of the 'Stern review on the economics of climate change'. *J Econ Lit* 45:686–702.
- Dasgupta P (2007) The Stern review's economics of climate change. *Natl Inst Econ Rev* 199:4–7.
- Weitzman ML (2007) A review of the Stern review on the economics of climate change. *J Econ Lit* 45:703–724.
- Adler M, et al. (2017) Priority for the worse-off and the social cost of carbon. *Nat Clim Change* 7:443–449.
- Population Division (2015) *World Population Prospects: 2015 Revision* (United Nations Department of Economic and Social Affairs New York).
- Basten S, Lutz W, Scherbov S (2013) Very long range global population scenarios to 2300 and the implications of sustained low fertility. *Demogr Res* 28: 1145–1166.
- Dennig F, Budolfson MB, Fleurbaey M, Siebert A, Socolow RH (2015) Inequality, climate impacts on the future poor, and carbon prices. *Proc Natl Acad Sci USA* 112:15827–15832.
- Lutz W, Mutarak R, Striessnig E (2014) Universal education is key to enhanced climate adaptation. *Science* 346:1061–1062.
- Lutz W, Striessnig E (2015) Demographic aspects of climate change mitigation and adaptation. *Popul Stud* 69:569–576.
- Nordhaus WD, Boyer J (2000) *Warming the World: Economic Models of Global Warming* (MIT Press, Cambridge, MA).
- Tol RS (2009) The economic effects of climate change. *J Econ Perspect* 23: 29–51.
- Lutz W, Butz WP, Samir KC, eds (2014) *World Population and Human Capital in the Twenty-First Century* (Oxford Univ Press, Oxford).
- Gerland P, et al. (2014) World population stabilization unlikely this century. *Science* 346:234–237.
- Golosov M, Hassler J, Krusell P, Tsyvinski A (2014) Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82:41–88.
- Connelly MJ (2008) *Fatal Misconception* (Harvard Univ Press, Cambridge, MA).
- Nordhaus WD (2008) *A Question of Balance: Weighing the Options on Global Warming Policies* (Yale Univ Press, New Haven, CT).
- Abel GJ, Barakat B, Samir K, Lutz W (2016) Meeting the sustainable development goals leads to lower world population growth. *Proc Natl Acad Sci USA* 113:14294–14299.
- Singh S, Darroch JE, Ashford LS (2014) *Adding It Up: The Costs and Benefits of Investing in Sexual and Reproductive Health*. Available at https://www.guttmacher.org/sites/default/files/report_pdf/addingitup2014.pdf. Accessed October 11, 2017.
- Education for All (2015) *Global Monitoring Report: Pricing the Right to Education* (UNESCO, Paris).
- Cleland J, Conde-Agudelo A, Peterson H, Ross J, Tsui A (2012) Contraception and health. *Lancet* 380:149–156.
- Bradley S, Croft TN, Fishel JD, Westoff CF (2012) *Revising Unmet Need for Family Planning* (DHS Analytical Studies, Calverton, MD), Report 25.
- Bongaarts J, Cleland J, Townsend JW, Bertrand JT, Gupta MD (2012) *Family Planning Programs for the 21st Century: Rationale and Design* (Population Council) Available at <https://www.popcouncil.org/uploads/pdfs/2012.FPfor21stCentury.pdf>. Accessed October 11, 2017.