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The Mortality Cost of Carbon[i]

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Abstract:

A large body of scholarly literature has projected that climate change is expected to cause a significant number of excess deaths over the 21st century ([1–11]). However, no studies have yet quantified the number of excess deaths caused by marginal emissions. This is crucial because the effect of marginal emissions today is more important for informing both policy and individual decision-making than the total effect resulting from the emissions of all global economic activity in aggregate across time ([12–15]). This study determines the effect of marginal emissions on excess deaths by creating a coupled climate-economy-demographics integrated assessment model called DICE-EMR that includes a climate-mortality response function estimated from an interdisciplinary systematic research synthesis of 100 studies. The impact of marginal emissions on excess deaths is captured in a new metric introduced in this paper -- *the mortality cost of carbon* (MCC) -- that avoids many of the pitfalls that plague discussion of the social cost of carbon (SCC) because it measures the marginal mortality impact of climate change in units of excess deaths without discounting or valuing lives. We find that due to widespread estimates of a nonlinear relationship between temperatures and mortality, marginal 2020 emissions have a surprisingly large mortality impact over the 21st century: in a baseline emissions scenario, the 2020 MCC is 2.35×10^{-4} excess deaths per metric ton of 2020 emissions. This implies that on the current margin, the lifetime emissions of 3.3 average Americans cause one excess death globally between 2020-2100. In addition, DICE-EMR updates the climate policy prescribed by Nobel Prize-winning economist William Nordhaus by extending his influential DICE model to include the effect of climate change on human mortality, which has largely been left out of previous integrated assessment models including DICE. Before incorporating mortality costs, the 2020 SCC in DICE is $37 per metric ton in the baseline emissions scenario and optimal climate policy involves an emissions plateau and then gradual reductions starting in 2050. After incorporating mortality costs in DICE-EMR, the 2020 SCC increases over seven-fold to $265 per metric ton in the baseline emissions scenario and optimal climate policy involves large immediate emissions reductions and full decarbonization by 2050.

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Main Text:

The social cost of carbon (SCC) is arguably the single most important concept in the economics of climate change ([16]). It represents the marginal social damage from emitting one metric ton of carbon-dioxide-equivalent at a certain point in time ([17]). According to standard economic theory, it represents the tax that should be put on carbon to reduce emissions to socially optimal levels ([18]). The SCC has been highly influential in informing climate policy. Regulations with benefits totaling over $1 trillion in the United States have used the SCC in their economic analysis ([16]). The SCC is estimated by climate-economy integrated assessment models (IAMs). The purpose of IAMs is to synthesize the state of scientific knowledge in the current peer-reviewed literature to inform policy ([19,20]). Climate-economy IAMs that produce an SCC also project the optimal path of future emissions by comparing climate damages with the cost of reducing emissions.

Despite the theoretical and policy importance of the SCC, many commentaries have argued that current estimates of the SCC remain inadequate ([20–27]). One major line of criticism is that IAMs do not represent the latest scientific understanding of climate impacts. Although substantial advances in climate change impact research have been made in recent years, IAMs are still omitting a significant portion of likely damages ([28,29]). Another major line of criticism is that a wide variety of climate damages – sea level rise, extreme weather, the direct effects of heat on productivity, agricultural impacts, and many more – must be monetized and summarized into a single number, and the relative contribution of these damages is often unclear ([26,28,30]). In addition, the magnitude of climate damages is sensitive to subjective choices around the monetization of non-market damages, and, since damages occur over long timescales, the discount rate at which future damage is converted into present value ([20,25,26,30]).

In this paper, we take a step forward in addressing some of these challenges. A large body of recent scholarly literature has projected that climate change will cause an increase in future mortality rates. A Lancet report concluded that "Climate change is the biggest global health threat of the 21st century" ([31]). Yet, climate mortality damages are currently limited in the most widely used IAMs, representing less than 5% of climate damages (see research design section)**.** A 2017 National Academy of Sciences report specifically mentioned mortality as a damage source that could be immediately updated in IAMs ([20]). In this study, we do this by creating an extension to DICE-2016 – the most influential climate-economy IAM – called DICE-EMR (Dynamic Integrated Climate-Economy Model with an Endogenous Mortality Response). DICE-2016 includes a review of the economics literature to estimate the damage function that determines the effect of climate change on economic output levels ([23]). In this study, we construct an additional reduced-form mortality response function that estimates the effect of climate change on the mortality rate. We estimate this mortality response function through a systematic research synthesis of 100 studies in the climate-mortality literature. While the original DICE damage function only includes studies from the economics literature, our systematic research synthesis considers studies from all disciplines that study the climate-mortality relationship, especially public health, economics, and medicine.

The systematic research synthesis shows that the consensus is that climate change is likely to increase the future mortality rates through a number of channels including the direct effects of ambient heat ([1–5,31–66]), interactions between higher temperatures and surface ozone formation ([6–8,38,54,56,62,65–73]), changes in disease patterns ([4,5,31,54,56,59,60,62–65,74–76]), flooding ([4,31,54,60,62–66,74–76]), and the effect on food supply ([4,5,31,54,62,64–66,69,76–79]). A pervasive finding in the literature is that extremely hot days (>35° C) are especially severe and the mortality impact of these days increases at an increasing rate with higher temperatures. Because the frequency of these dangerously hot days is expected to increase exponentially as global average temperatures increase ([80,81]), studies that project mortality rates as a function of global average temperatures found that mortality impacts are expected to be highly convex (i.e increasing at an increasing rate) in global average temperatures.

We use DICE-EMR to produce a new metric that avoids some of the limitations of the SCC: *the mortality cost of carbon (MCC).* The 2020 MCC is the number of expected excess deaths globally from 2020 to 2100 caused by the emission of one additional metric ton of carbon-dioxide-equivalent emissions in 2020. Excess deaths are deaths attributable to climate change that occur prematurely relative to a counterfactual scenario in which the marginal emission did not occur. To provide further resolution into the mortality damage of marginal emissions over time, the MCC can be disaggregated across years, an exercise we do in the discussion section. The SCC is similar to the MCC in that both metrics quantify the damage from a marginal increase in emissions in a certain year. The main differences between the SCC and the MCC are: (1) The SCC is intended to include all market and non-market damages from marginal emissions whereas the MCC only measures the effect of marginal emissions on excess deaths (2) The SCC monetizes all climate damages into a single consumption-equivalent value whereas the MCC does not monetize damages because it is in units of excess deaths (3) The SCC converts future damages to present value through discounting whereas the MCC is simply the number of excess deaths from 2020-2100. Discounting and valuing lives is a complex and controversial issue. The MCC provides a measure of the mortality damage from marginal emissions without discounting or valuing lives. For these reasons, the MCC is a more straightforward and transparent estimate of the marginal effect of carbon emissions compared to the SCC.

Like the SCC, the MCC is useful for determining the social impact of new marginal activities or projects that produce greenhouse emissions, or, equivalently, the benefit from forgoing these activities. In the DICE baseline scenario that results in 4.1° C warming above preindustrial temperatures by 2100, the 2020 MCC is 2.35×10^{-4} lives per metric ton (see table 1). This implies that the emission of 1 million metric tons of carbon-dioxide-equivalent emitted in 2020 -- which is roughly equal to the average annual emissions of 35 commercial airliners, 216,000 passenger vehicles, 115,000 homes, and 0.26 coal-fired powerplants in the United States ([82,83]) -- causes 235 excess deaths from 2020 to 2100 in the baseline emissions scenario. The MCC also implies that on the current margin, the lifetime emissions of 3.3 average Americans cause one excess death globally between 2020-2100 (see figure 1).[ii]

[ii] Average lifetime emissions are calculated as 2017 carbon dioxide emissions production per capita ([84]) multiplied by 2017 life expectancy at birth ([85]). The 2020 mortality cost of carbon implies that adding 4,262 metric tons of carbon-dioxide-equivelent emissions on the margin in 2020 causes one excess death in expectation between 2020 and 2100. 4,262 metric tons is equivalent to the lifetime emissions of 3.3 average s, 15.0 average Mexicans, and 140.5 average Nigerians (see figure 1).

Although the MCC is a useful and more transparent metric for determining the mortality consequences of marginal emissions choices, the SCC is still necessary for determining the optimal price on carbon. Like DICE-2016, DICE-EMR also estimates the SCC and an optimal emissions trajectory through 2100. Excess deaths do not need to be monetized and discounted to estimate the MCC, but they do need to be monetized and discounted to estimate the SCC and optimal emissions trajectories. To do this, we leverage recent methodological advances in economic theory to calibrate the welfare loss from excess deaths in general equilibrium as consumption-equivalents ([86,87]). The SCC in DICE-EMR includes two sources of climate damages: (1) Climate damages to economic output from the original DICE damage function, which we retain, and (2) The consumption-equivalent welfare loss from excess deaths due to climate change (see research design section for mathematical detail). Besides adding the mortality response function and incorporating the welfare loss from excess deaths, DICE-EMR adopts all other structure, equations, base parameters including discount rates, and the baseline emissions scenario of the DICE-2016 model in order to isolate the effect of accounting for mortality in DICE.

This study reveals an important implication of mortality projections in the climate-mortality literature. As discussed above, a widespread finding is that mortality increases are expected to be highly convex in global average temperatures, i.e. mortality increases at an increasing rate in global average temperatures. Marginal increases in global average temperatures are projected to be especially damaging to mortality in climate scenarios where global average temperatures exceed 3° C. Because a significant portion of marginal carbon dioxide emissions remains in the atmosphere for centuries ([88]), marginal 2020 emissions continue to marginally increase temperatures for centuries. Because of the convexity of the mortality response function in temperature, marginal temperature increases are highly damaging, especially in scenarios where global average temperatures exceed 3° C. This implies that the mortality effect of marginal 2020 emissions is significant, and this is reflected in a relatively high MCC and SCC (see methods and discussion sections for more detail): explicitly accounting for mortality significantly increases the 2020 SCC from \$37 per metric ton in DICE-2016 to \$265 in DICE-EMR in the same baseline scenario (see table 2).

Another implication of the highly convex mortality response function is that societies now have a stronger incentive to avoid scenarios where global average temperatures are especially damaging, in particular above 3° C. This causes a large difference in optimal climate policy in DICE-EMR compared to DICE-2016 (see figure 2). Optimal climate policy in DICE-2016 involves an emissions plateau and then gradual reductions starting in 2050. This results in 3.48° C warming by 2100. Optimal climate policy in DICE-EMR involves large immediate emissions reductions and full decarbonization by 2050. This results in 2.45° C warming by 2100. It is important to note that recent literature has identified other shortcomings in the DICE model ([89,90]). Besides adding the effect of climate change on mortality, DICE-EMR takes the rest of the DICE model as given without updating other factors. Therefore, this optimal climate policy should not be interpreted as a definitive optimal policy, but as an update to the DICE optimal policy that accounts for the impacts of climate change on human mortality.

If the world undertakes the optimal emissions path in DICE-EMR and restrains global average temperatures to 2.45° C, we largely avoid the temperatures where marginal increases in temperature resulting from a marginal emission today are most damaging. This implies that the MCC and the SCC are highly sensitive to future climate policy: in the optimized emissions scenario, the 2020 MCC drops by 51% from the baseline scenario to 1.15×10^{-4} lives per metric ton (see table 1). This implies that under DICE-EMR's optimal climate policy, the lifetime emissions of 6.8 average Americans cause one excess death globally between 2020-2100 (see figure 1). On the optimal emissions path, the 2020 SCC drops by 43% to $150 per metric ton (see table 2).

Table 1. 2020 Mortality Cost of Carbon. DICE-EMR projects that a metric ton of carbon-dioxide-equivalent emitted in 2020 causes an additional 2.35×10^{-4} deaths from 2020-2100 in its central estimate.

	Low Estimate Mortality Response	Central Estimate Mortality Response	High Estimate Mortality Response
Baseline Emissions Scenario	-1.86×10^{-4}	2.35×10^{-4}	6.58×10^{-4}
Optimal Emissions Scenario	-2.06×10^{-4}	1.15×10^{-4}	4.47×10^{-4}

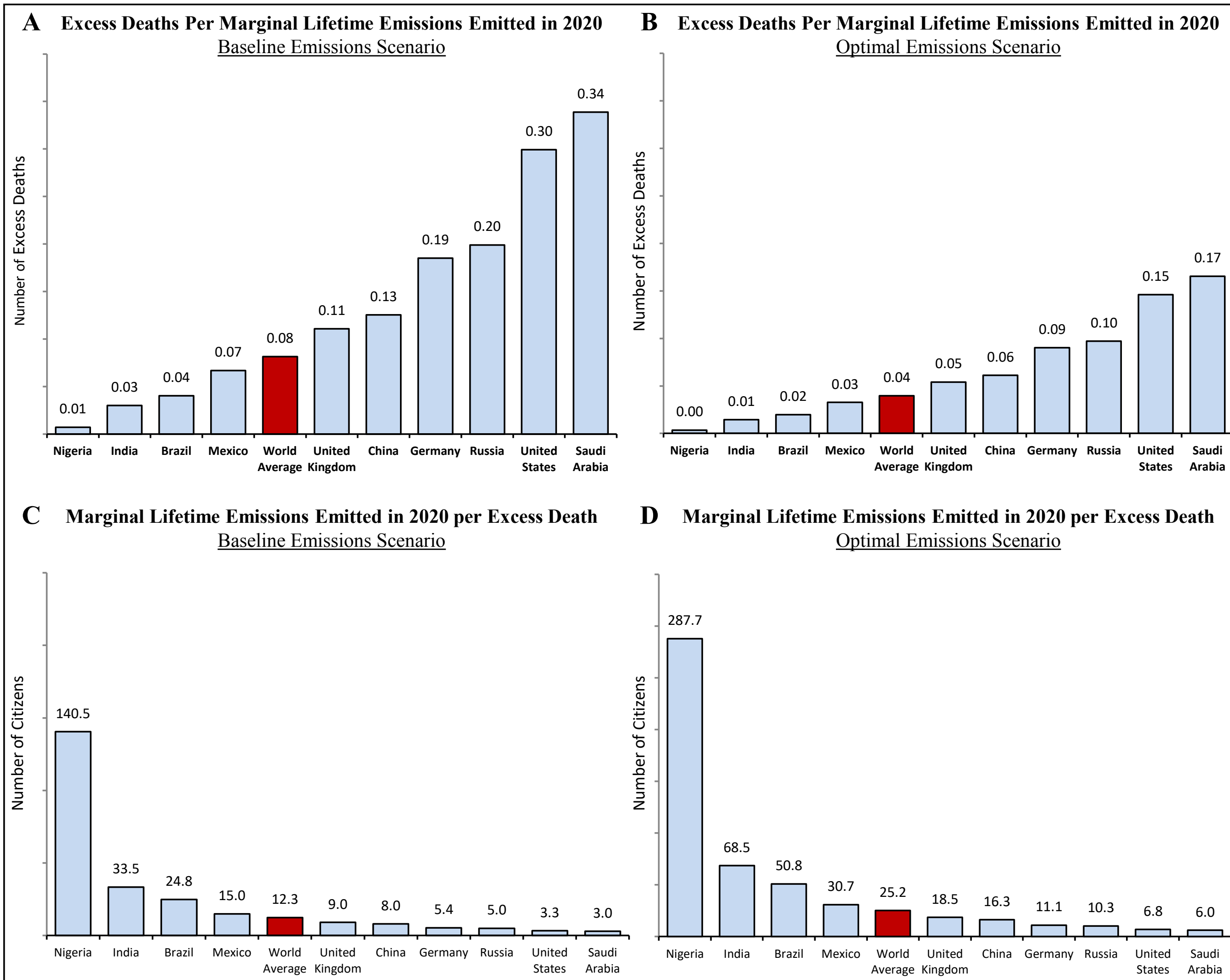

Fig. 1. Implications of the 2020 Mortality Cost of Carbon. Projections use the MCC from the central estimate mortality response. (**A**) On the current margin in the baseline emissions scenario, the average lifetime emissions of an American emitted in 2020 causes 0.30 excess deaths globally from 2020-2100 while the average lifetime emissions of a Nigerian emitted in 2020 causes 0.01 excess deaths over this time period. (**B**) On the current margin in the optimal emissions scenario, the average lifetime emissions of an American emitted in 2020 causes 0.15 excess deaths globally from 2020-2100 while the average lifetime emissions of a Nigerian emitted in 2020 causes <0.01 excess deaths over this time period. (**C**) On the current margin in the baseline emissions scenario, the average lifetime emissions of 3.3 Americans emitted in 2020 causes an excess death globally from 2020-2100 while the average lifetime emissions of 140.5 Nigerians emitted in 2020 causes an excess death over this time period. (**D**) On the current margin in the optimal emissions scenario, the average lifetime emissions of 6.8 Americans emitted in 2020 causes an excess death globally from 2020-2100 while the average lifetime emissions of 287.7 Nigerians emitted in 2020 causes an excess death over this time period.

Table 2. 2020 Social Cost of Carbon. In the primary specification, DICE-EMR projects that the 2020 social cost of carbon is $265 in the baseline emissions scenario and $150 in the optimized emissions scenario. These figures vary with value of statistical life (VSL) estimates, but even with a low VSL estimate in the optimized scenario, the SCC still exceeds $107.

	Low VSL *(VSL=2x consumption)*	**Medium VSL** *(VSL=4x consumption)*	**High VSL** *(VSL=8x consumption)*
Baseline Emissions Scenario			
2020 SCC	$182	**$265**	$447
Mortality Response Uncertainty	[-$36,$340]	[-$76,$530]	[-$153,$907]
Optimized Emissions Scenario			
2020 SCC	$107	**$150**	$235
Mortality Response Uncertainty	[-$69,$294]	[-$137,$444]	[-$251,$765]

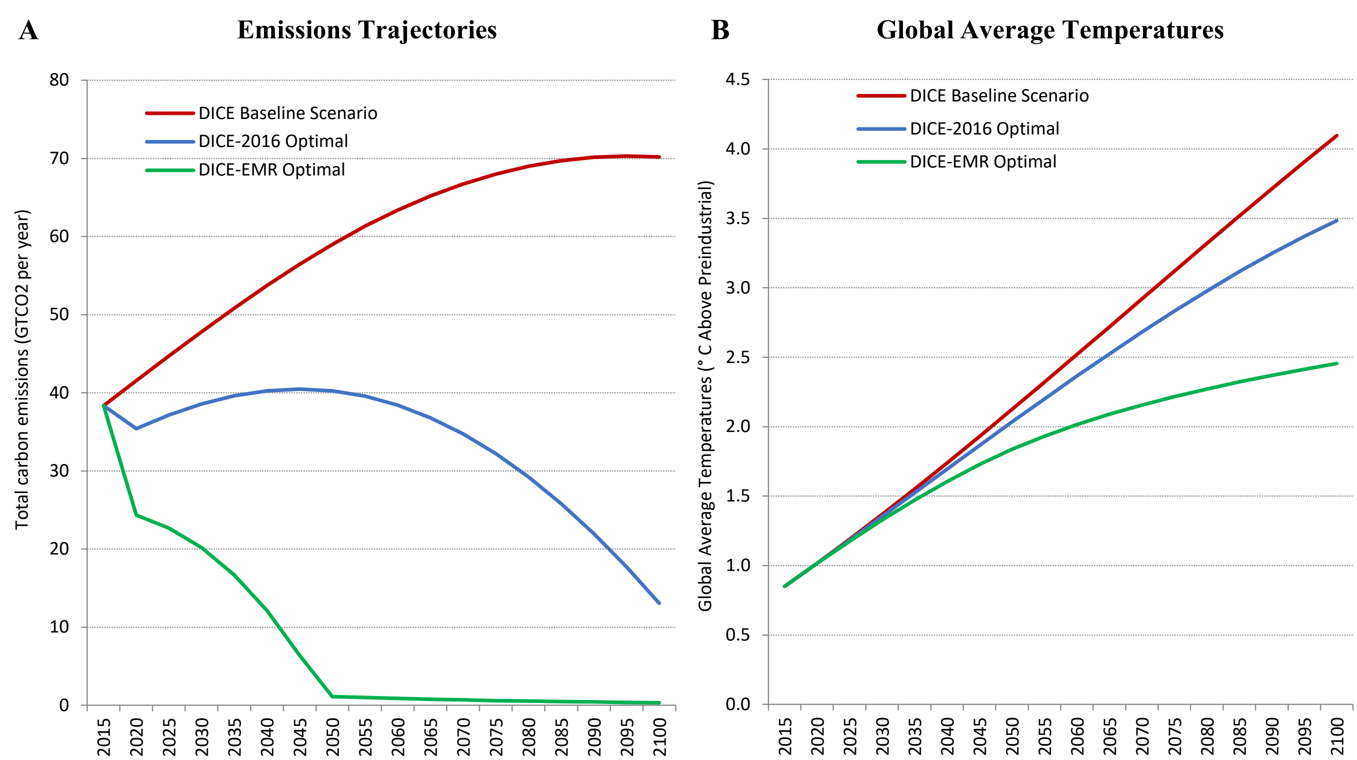

Fig. 2. Optimal Climate Policy. IAMs assess the cost of reducing emissions and the damages from climate change in a dynamic general equilibrium model that includes coupled interactions between the economy and the climate. They can be used normatively to determine optimal climate policy. They do this by using optimal control to determine a path of emissions trajectories that optimizes the net present value of social welfare. (**A**) Optimal climate policy in DICE-2016 involves gradual emissions reductions starting in 2050 while optimal climate policy in DICE-EMR involves immediate emissions reductions and full decarbonization by 2050. (**B**) Optimal climate policy in DICE-2016 results in 3.48° C warming by 2100 while optimal climate policy in DICE-EMR results in 2.45° C warming by 2100.

Methods:

A high-level summary of the DICE-2016 model is shown in panel A of Fig. 3 below. This figure shows that DICE-2016 has three major systems: economic, welfare, and climate. It is a global model as it models gross world product (GWP) and it calculates global average temperatures. Without the climate system, the DICE model is essentially the standard Ramsey-Cass-Koopmans Neoclassical Macroeconomic Model of long-run economic growth ([91,92]). William Nordhaus's innovation in creating the original DICE model was integrating macroeconomic and climate models into a single model by modelling the economy's production of greenhouse gas emissions, the effect of these emissions on global average temperatures, and feedback of higher temperatures back on the economy through the damage function. DICE-2016 is useful in informing climate policy by determining the SCC and an optimal path of emissions that maximizes the net present value of social welfare.

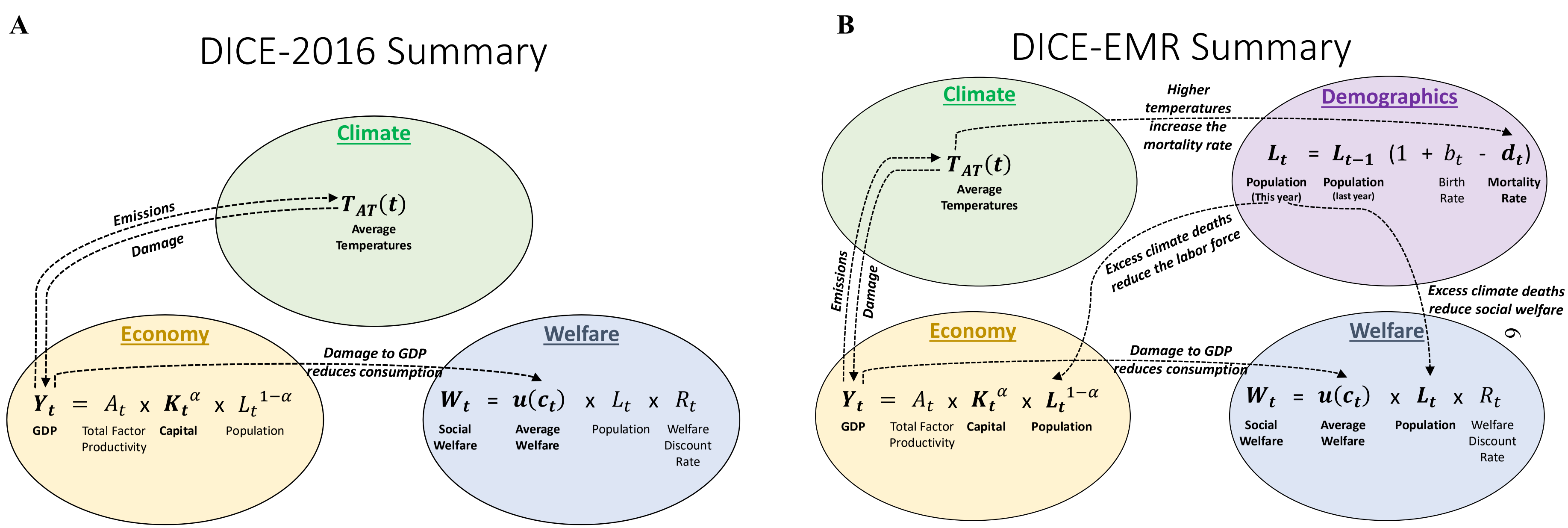

Fig. 3. A summary of the DICE-2016 and DICE-EMR IAMs. Endogenous components (determined by the model) are in bold. Exogenous components (inputs to the model) are not bold. **(A)** is a summary of the DICE-2016 model. In this model, the economy affects the climate through emissions and climate only affects society through the damage function that reduces GDP. Our review of ([8]) – the review study that constructs the DICE-2016 damage function – concludes that mortality costs account for <5% of the damages in the damage function. **(B)** is a summary of the DICE-EMR model. DICE-EMR takes the rest of DICE-2016 as given and adds a fourth system: demographics. The climate affects the mortality rate through the mortality response function, which is estimated by a systematic research synthesis of the scholarly literature. This directly reduces welfare due to the welfare cost of these excess deaths, and this effect is calibrated to estimates for value of a statistical life.

Limitations of Current IAM Damage Functions

In the most widely used climate IAMs (DICE, FUND, and PAGE) that have been formally adopted by the U.S. government to calculate the SCC used in cost-benefit analysis ([93]), all climate damages including mortality damages are calculated as damage to economic output. In FUND, mortality costs account for ~3% of total damages ([28]). In DICE-2016, the climate affects society through only one equation: the damage function. The damage function is a reduced-form equation of global average temperatures that represents the portion of economic output lost due to climate change. ([23]) surveyed the climate impacts literature and selected 26 studies that were used in a median-weighted regression to estimate the damage function. However, most of these 26 studies were heavily de-weighted because they were either superseded by later studies that were also included or they were determined to have poor methods. Although the damage function is meant to capture both the market and non-market damages from climate change, in actuality it captures only the damages that are included in the studies that are used to determine the damage function. A closer look at the studies used in the survey reveals that there is significant heterogeneity in the non-market impacts that are included, including mortality. Some of the studies include the impacts of climate-induced mortality while some do not. The studies that include mortality do so to a limited extent. Among the most heavily weighted studies, the study that ascribes the highest damages to mortality impacts projects that mortality accounts for only 10% of total damages; this study was done in 1992 and it projected damages to the United States even though it is used as one of the most heavily weighted studies in estimating the global climate damage function in DICE ([94]). From this review, we conclude that less than 5% of the damages in the DICE-2016 damage function come from mortality (see supplementary materials for more detail).

A Systematic Research Synthesis of the Climate Mortality Literature

We conducted a systematic research synthesis of the scholarly literature on the mortality effects of climate change to find studies that met the following criteria: [iii]

1. Comprehensive of all human mortality impacts.
2. Provides a projection of human mortality impact for a specific warming scenario or scenarios.
3. Accounts for the effects of defensive adaptation.
4. Done on a global basis.
5. Published in the last 20 years.

We surveyed 100 candidate studies to determine if they adequately met the criteria described above. A wide variety of scientific disciplines assess the effect of climate change on human mortality, especially public health, economics, and medicine. To assess the latest scientific understanding of the climate-mortality relationship, we considered papers from all scientific disciplines. More detailed information on the approach and methods is given in the supplementary materials.

[iii] See ([23]) for a definition of systematic research synthesis vs. other research synthesis techniques such as meta-analysis and non-systematic research synthesis. See supplementary materials for more detailed information on the methods used to identify the 100 studies.

The systematic research synthesis showed that the consensus is that climate change is likely to increase the future mortality rates through a number of channels including the direct effects of ambient heat ([1–5,31–66]), interactions between higher temperatures and surface ozone formation ([6–8,38,54,56,62,65–73]), changes in disease patterns ([4,5,31,54,56,59,60,62–65,74–76]), flooding ([4,31,54,60,62–66,74–76]), and the effect on food supply ([4,5,31,54,62,64–66,69,76–79]). A widespread finding is that extremely hot days have an especially damaging nonlinear effect on human mortality. One frequently mentioned mechanism for this is that extremely hot days make it difficult for humans to thermoregulate themselves: when the wet-bulb ambient temperature exceeds skin temperature (~35° C), humans can no longer dissipate heat into the environment, causing hyperthermia and greater mortality risk ([34,95,96]). Because the frequency of extremely hot days is expected to increase exponentially in global average temperatures ([80,81]), mortality effects are expected to be highly convex in global average temperatures. Places with already hotter climates are projected to be harmed more due to the exponentially greater frequency of extreme hot days. Places with colder climates are likely to see some mortality benefits from climate change due to the lower frequency of extreme cold days. Studies that assessed global mortality impacts projected climate change to cause mortality increases in their central estimates ([1,2,4–10]).

In addition, we specify that studies need to account for the effect of defensive adaptation. It is necessary to account for the effect of adaptation when making projections because individuals and societies are likely to take actions that will reduce the mortality effects of climate change. There is high uncertainty around the future effects of adaptation. Methods to project future mortality net of adaptation are a large area of active research. Of the 100 studies surveyed, few attempted to account for adaptation; all the studies that did were published in 2011 or later. The majority of the studies that account for adaptation project it to have a large role in limiting the damage done from climate change ([1,4,9,52]).

The five study criteria used for inclusion in the mortality response function are demanding. Making full global climate-mortality response projections requires a large and comprehensive historical dataset of human mortality statistics to understand underlying climate-mortality mechanisms. Many of the studies surveyed did not adequately meet the criteria because they focused on limited geographic areas, they made projections through a limited number of health channels, and/or they were literature reviews (see supplemental materials for full detail). Although the inclusion criteria are demanding, they are necessary in the context of DICE-EMR. DICE-EMR is a global model, and therefore the mortality response function must be global. To provide the best estimate of the climate-mortality response, it is necessary to ensure that the mortality response function includes as many of the climate-mortality pathways as possible.

Although no study perfectly met all five criteria, a few studies came sufficiently close, and these studies were used to construct the mortality response function. The studies ultimately chosen were a 2014 WHO Report *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s* ([4]), a 2019 Climate Impact Lab report *Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits* ([9]), and a 2017 Lancet Planetary Health article *Projections of temperature-related excess mortality under climate change scenarios* ([3]). Due to their scope, each of these studies were large multi-institution research collaborations between 16, 17, and 45 authors respectively.

Many of the 97 studies that were not chosen were used indirectly because their data, methodologies, and results were utilized in these three studies. Each of the three chosen studies featured authors who had worked extensively on the climate-mortality relationship and who had authored some of the other 97 papers that were among those surveyed in the systematic research synthesis. Many studies came sufficiently close to meeting the criteria but were excluded because they were either reused by one of the three studies above (Hales et. al 2014 in particular was largely an agglomeration of past studies) or the methods they developed were later applied to a larger dataset that could more accurately capture the global mortality effects of climate change. A more thorough description of each of these three studies, including their advantages and drawbacks, is provided in the supplementary materials.

Central estimates from these three studies were used to run a quadratic weighted regression. Mortality estimates in warmer scenarios (>3° C) were especially damaging, and this is reflected in the mortality response function (see figure 4). In its central estimate, the mortality response function projects that a scenario in which global average temperatures increase by 4.1° C causes the mortality rate to increase by 3.8%.

Each of the studies also projected uncertainty. Uncertainty is driven by uncertainty in adaptation, uncertainty in the underlying mortality-temperature relationship, and uncertainty in climate model projections. However, the uncertainty measures in the three studies are not all given statistically. The WHO Report ([4]) does not provide specific percentiles for their aggregate excess mortality results, but instead gave estimates as the "highest and lowest estimates." The Climate Impact lab report ([9]) provides a high 90^{th} percentile estimate and a low 10^{th} percentile estimate. The 2017 Lancet Planetary Health ([3]) report provides a high 97.5^{th} percentile estimate and a low estimate 2.5^{th} percentile estimate. Because of the approach taken by the WHO report, we cannot calculate precision-weighted confidence intervals as is common in other metanalyses, e.g. ([97]). We, therefore, communicate uncertainty in the mortality response as "high (>90^{th} percentile)" and "low (<10^{th} percentile)." Like the central mortality response estimate, we also produce projections for the high and low estimates through a quadratic weighted regression with the high and low estimates given by the three studies. We present sensitivities in our MCC and SCC results using these high and low projections. The original DICE-2016 climate-output damage function ([23]) does not include uncertainty; it only takes central estimates from surveyed studies to produce the damage function even when uncertainties are given.

Climate change is expected to have heterogeneous effects on different age groups depending on the channel. The direct effect of ambient heat is expected to have a larger mortality effect on the elderly ([4,9]). The effect of climate change on undernutrition and diarrheal disease is expected to have a larger mortality effect on children ([4]). However, we are limited by the available literature in capturing heterogeneous mortality rates for different age groups, as age-stratified mortality estimates are not yet widely projected in the literature, including in ([3]) and ([4]). Because of this, the MCC captures excess deaths, not lost life years. For the SCC, this implies that the welfare loss from an excess death is treated the same regardless of the age of the person dying, which is consistent with the way cost-benefit analysis is conducted in the United States (see SCC section below for more detail). A wider range of future studies are expected to produce age-stratified mortality projections, and future work may calculate an MCC that projects lost life-years instead of excess deaths.

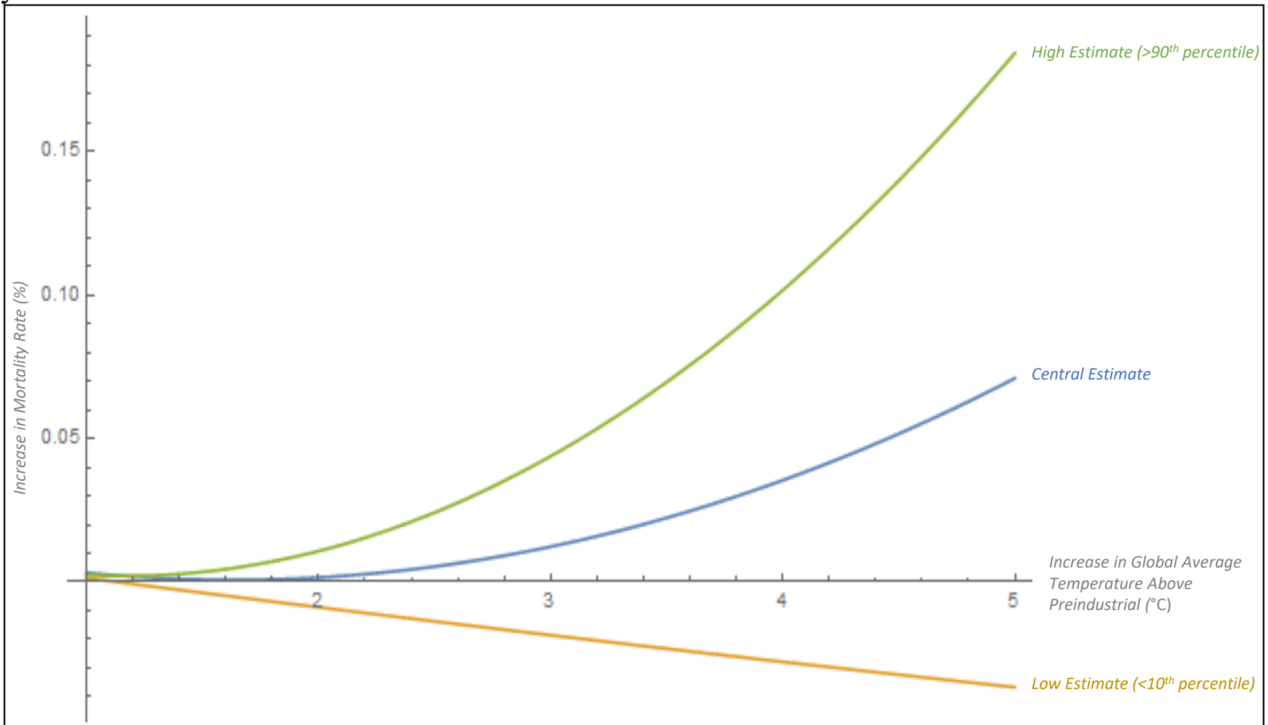

Fig. 4. Mortality Response Function Derived from Systematic Research Synthesis. Estimates the mortality response function: $\delta(T_T) = \beta_1 * T_T + \beta_2 {T_T}^2$ where T_T is the increase in global average atmospheric temperatures above preindustrial, $\beta_i \in \{\beta_1, \beta_2\}$are the estimated coefficients, and $\delta(T_T)$ is the % increase in the mortality rate. See supplementary materials for detailed explanation of methods.

Estimates of the Effect of Climate Change on Fertility

DICE-EMR incorporates an endogenous mortality response but not an endogenous birth response; the fertility rate remains exogenously determined by the 2019 UN World Population Prospects. Although climate change is likely to affect the fertility rate ([98]), the emerging literature on the topic suggests that climate will affect fertility through several different channels, some of which will tend to increase the fertility rate ([98]) and some of which will tend to decrease the fertility rate ([99]). The overall effect of climate on the fertility rate is not yet clear from the literature, even directionally (see supplemental materials for more detail). In keeping with the rest of the analysis, we only model the effect of climate on demographics where the central estimates of the empirical literature are clear directionally.

Integrating Mortality into Integrated Assessment

To determine population gross of the climate mortality response in DICE-EMR, we use data from the 2019 UN World Population Prospects, which projects mortality and fertility rates from 2020 – 2095 ([100]). Population before the climate mortality response accumulates according to the following difference equation:

$$L_{t+1} = L_t + b_t L_t - d_t L_t = L_t(1 + b_t - d_t) \quad (1)$$

Where L_t is the population in period t, b_t is the fertility rate, and d_t is the mortality rate. Before accounting for the climate mortality response, b_t and d_t are determined by the figures given in the 2019 UN report, which makes projections largely based on past trends that do not factor in the likely future mortality effects of climate change (see supplementary materials for more detail on the UN methodology and projections).

We then incorporate the mortality response function estimated from the systematic research synthesis in the previous section, $\boldsymbol{\delta(T_t)}$, so that population is now calculated net of climate impacts according to the following difference equation:

$$L_{t+1}(T_t) = L_t(T_t)\{1 + b_t - d_t[1 + \delta(T_t)]\} \quad (2)$$

Now, the global human population level, L_t, is a function of global average temperature, T_t, through its effect on the mortality response function.

Calculating the Social Cost of Carbon (SCC) in DICE-EMR

The 2020 SCC is determined by the following equation ([16]):

$$SCC(2020) = \frac{\partial W}{\partial E(2020)} / \frac{\partial W}{\partial C(2020)}$$

See figure 3 for variable names and explanations. $\frac{\partial W}{\partial E(2020)}$ represents the welfare damage from marginal carbon-equivalent emissions and dividing it by the term $\frac{\partial W}{\partial C(2020)}$ turns this welfare loss into 2020 consumption-equivalent units. Focusing on the damage term (the SCC numerator), the welfare loss in DICE-2016 simplifies to the following equation (see supplementary materials for full derivation):

$$\sum_{t=2020}^{t=2510} \frac{\partial u(c_t)}{\partial c_t} \frac{\partial c_t}{\partial E(2020)} L_t R_t$$

As the equation shows, emissions cause damages only through their effect on reduced consumption. $\frac{\partial c_t}{\partial E(2020)}$ is the loss in the average person's consumption multiplied by the marginal utility of consumption, $\frac{\partial u(c_t)}{\partial c_t}$, and then scaled by the exogenously determined population. The marginal welfare loss from a marginal 2020 emission is determined in each period of the model and then aggregated across time and discounted by the exogenous rate of social time preference, R_t.

In DICE-EMR, there is an endogenous mortality response, and therefore the population term L_t is now endogenous. The damage term in DICE-EMR becomes (see supplementary materials for full derivation):

$$\frac{\partial W}{\partial E(2020)} = \sum_{t=2020}^{t=2510} \frac{\partial u(c_t)}{\partial c_t} \frac{\partial c_t}{\partial E(2020)} L_t R_t + \sum_{t=2020}^{t=2510} \frac{\partial L_t}{\partial E(2020)} u(c_t) R_t \qquad (3)$$

Equation **3** can be broken into two terms that are useful for intuition:

(1) *The consumption effect:*

$$\sum_{t=2020}^{t=2510} \frac{\partial u(c_t)}{\partial c_t} \frac{\partial c_t}{\partial E(2020)} L_t R_t \qquad (4)$$

(1) *The welfare effect of mortality:*

$$\sum_{t=2020}^{t=2510} \frac{\partial L_t}{\partial E(2020)} u(c_t) R_t \qquad (5)$$

As in DICE-2016, an additional ton of emissions in 2020 affects social welfare through its effect on consumption as captured in *(1) the consumption effect term*. However, DICE-EMR has an additional *(2) welfare effect of mortality term* that captures the direct loss in welfare resulting from excess deaths caused by climate change. To accurately capture this effect, it is necessary to calibrate the utility function to a value of a statistical life (VSL).

We leverage recent methodological advances in economic theory to calibrate the welfare loss from higher mortality in general equilibrium to VSL as a multiple of consumption (see supplementary details). DICE-EMR is a single representative agent global macroeconomic model, so this is calibrated as a multiple of global average consumption, which is just under $12,000 in 2020. The structure of DICE-EMR as a single representative agent model has an important implication for valuing loss of life in the SCC: all deaths are valued at the global average VSL and therefore all excess deaths are given equal weight. Alternative methodologies give greater weight to richer individuals that die compared to poorer individuals based on their willingness to pay to avoid a higher probability of death. Since richer individuals have more financial resources, they have a higher willingness to pay to avoid a higher probability of death ([101]). The implication of these alternative methodologies is that lives in richer countries (e.g. in Western Europe, North America) are weighed more than lives in poorer countries (e.g. in Africa, South Asia). The IPCC states that the approach taken by DICE-EMR – valuing all lives at the same level – is nearer the truth than the alternative approach of valuing the lives of the rich more than the lives of the poor ([12]). This approach is also consistent with policies undertaken by national governments: although there are often significant regional heterogeneities in incomes within countries, no national governments currently assign higher VSLs to richer citizens or lower VSLs to poorer citizens in cost-benefit analyses. Since our level of analysis is global, we also take this approach.

Calculating the Mortality Cost of Carbon (MCC) in DICE-EMR

The MCC assesses the marginal mortality effect of carbon emissions in units of excess deaths. It represents the number of excess deaths over some time period from one ton of carbon-equivalent emissions. It is estimated according to the following equation (see supplementary materials for derivation):

$$MCC(2020) = \sum_{t=2020}^{t=2100} \frac{\partial \delta(T_t)}{\partial T_t} \frac{\partial T_t}{\partial E_{2020}} L_t d_t \qquad (7)$$

This expression is useful for intuition. It shows that the MCC is driven by two factors:

(1) $\partial \delta(T_t)/\partial T_t$: The marginal effect of slightly higher global average temperatures on the mortality response, i.e. the first derivative of the mortality response function $\delta(T_t)$.
(2) $\partial T_t/\ \partial E_{2020}$: The marginal effect of 2020 emissions on global average temperatures, which is determined by the climate model.

Factor (1) shows why the MCC is so sensitive to the convexity of the mortality response function. $\partial \delta(T_t)/\partial T_t$ is relatively small under the lower temperatures in the first half of the 21st century, but because the mortality response function is highly convex, as the century progresses and temperatures rise past 2° C, $\partial \delta(T_t)/\partial T_t$ becomes much larger, as shown in figure 4. This implies that a marginal emission in 2020 causes significant damage, mostly coming towards the end of the century when temperature levels are higher. This explains why the marginal effect of carbon emissions on excess deaths is surprisingly large compared to what may be expected from the total effect of carbon emissions, shown in figure 5A.

Discussion

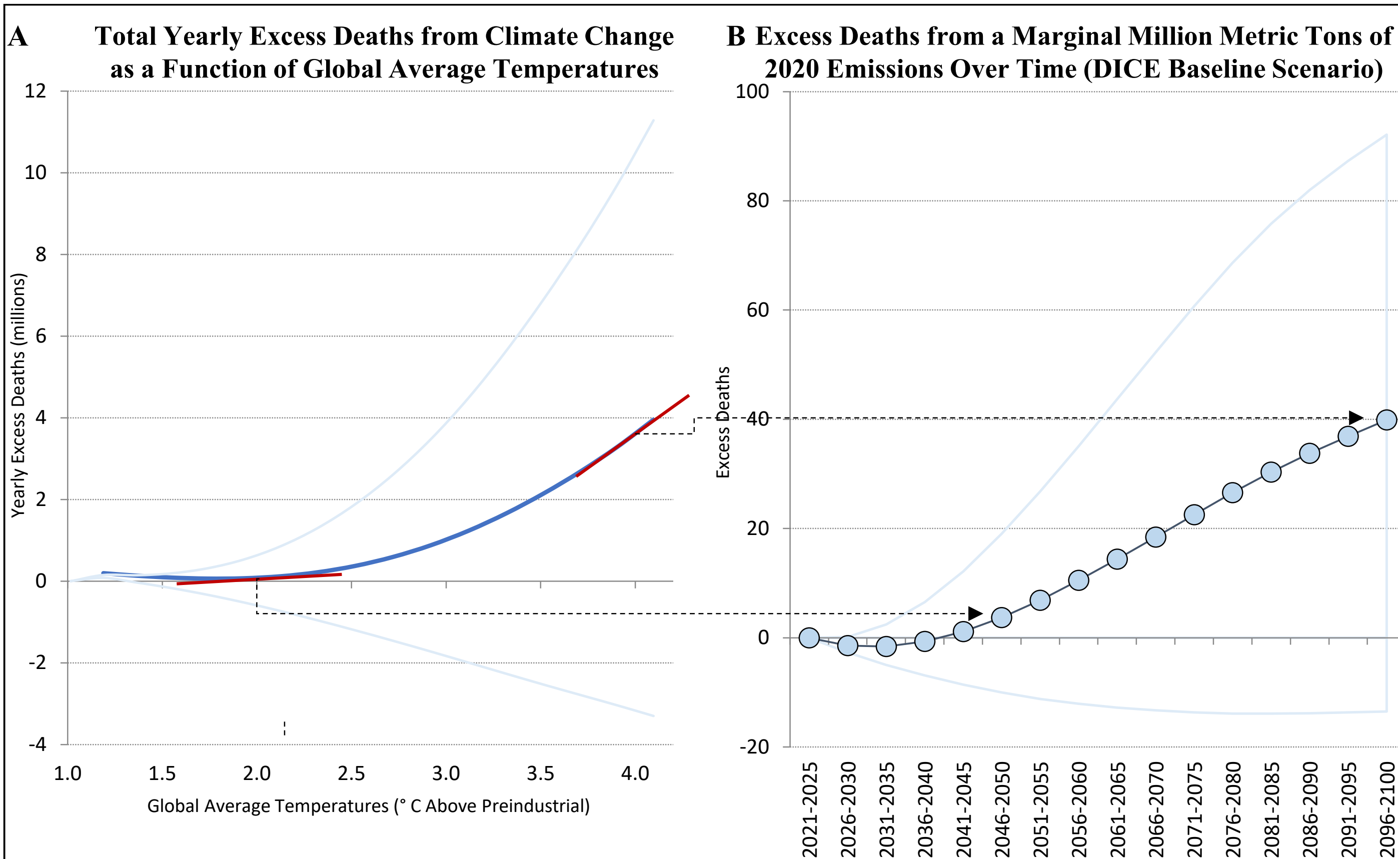

Fig. 5. The Mortality Cost of Carbon is Driven by the Convexity of the Mortality Response. (**A**) Below 2° C, projected yearly excess deaths from climate change are relatively constant at around 100,000 per year in the central estimate. Above 2° C, projected yearly excess deaths from climate change increase at an increasing rate in global average temperatures, rising to nearly 4 million excess deaths at 4° C. This implies that the number of excess deaths from a marginal increase in temperatures (the first derivative – represented by the red tangent lines on the graph at 2° C and 4° C) is initially relatively modest but increases substantially with increasing temperatures. (**B**) Because a significant portion of carbon dioxide emissions remain in the atmosphere for centuries after they are emitted, adding 1 million metric tons of carbon-dioxide-equivalent emissions in 2020 marginally increases global average temperatures through 2100. The magnitude of excess deaths from marginal 2020 emissions shown in (B) is driven by the steepness of the mortality response curve shown in (A), which becomes progressively steeper with increasing temperatures. In the five years between 2046-2050, (when global average temperatures are 2.0° C above preindustrial in the baseline emissions scenario), the mortality response curve is comparatively shallow, and 1 million marginal metric tons of carbon-dioxide-equivalent emissions in 2020 are projected to cause 4 excess deaths in this timespan. In the five years between 2096-2100 (when global average temperatures are 4.0 ° C above preindustrial in the baseline emissions scenario), the mortality response curve is comparatively steep, and these marginal 2020 emissions are projected to cause 40 excess deaths in this timespan. In total, 1 million marginal metric tons of carbon-dioxide-equivalent emissions in 2020 are projected to cause 235 excess deaths in the 80 years between 2020-2100 in the baseline emissions scenario. These are concentrated at the end of the century when global average temperatures are highest and marginal changes to temperatures are most damaging. In both graphs, the high and low lines represent uncertainty with high (>90th percentile) and low (<10th percentile) estimates.

This paper introduced a new metric: the mortality cost of carbon (MCC). This metric is useful for calculating the marginal mortality effects of emissions. We have shown that in the DICE baseline emissions scenario that results in 4.1° C warming by 2100, the MCC is significant. It implies that on the current margin, the average lifetime emissions of 12.3 average world people or 3.3 Americans cause one excess death globally between 2020-2100. This large marginal effect may seem counterintuitive compared to a relatively more modest aggregate effect shown in Figure 5A. Below 2° C, climate change is projected to cause around 100,000 excess deaths a year in the central estimate. Above 2° C, the projected yearly excess deaths from climate change increase at an increasing rate in global average temperatures, rising to nearly 4 million yearly excess deaths at 4° C. In total, there are 89 million projected cumulative excess deaths between 2020-2100 in the central estimate in the DICE baseline emissions scenario. By the end of the century, the projected 4 million excess yearly deaths would put climate change 6th on the 2017 Global Burden of Disease risk factor risk list ahead of outdoor air pollution (3.4 million yearly excess deaths) and below obesity (4.7 million yearly excess deaths) ([102,103]). However, just considering the total effect belies the significant impact that marginal emissions decisions today have on mortality over the 21st century. What matters for the impact of marginal emissions is not the aggregate number of deaths, but the first derivative of the mortality response curve, i.e. how many excess deaths result from an incremental increase in temperatures, which would result from an incremental increase in 2020 emissions. Figure 5.A. shows that when global average temperatures exceed 2° C, the first derivative is quite steep and increasingly so as the world continues to warm. This is what accounts for the significant MCC.

From the perspective of policy, the effect of marginal emissions is more important than the aggregate effect that results from all global economic activity in aggregate ([12–15]): the optimal price on carbon, the SCC, is determined by considering the net present value of damages from a marginal ton of emissions. Optimal climate policy is determined by comparing the marginal cost of reducing emissions with the marginal benefits of reducing climate damages. Indeed, accounting for the marginal impact of emissions on mortality as we have done in this analysis causes significant changes to both the SCC and the optimal climate policy. This analysis shows that after accounting for the direct mortality costs of climate change through channels that are well established in the scientific literature, the SCC is much higher than estimates widely used in policy. In addition, the optimal climate policy in DICE-EMR involves immediate emissions reductions and full decarbonization by 2050 as opposed to an emissions plateau and then gradual reductions starting in 2050 implied by the DICE-2016 optimal climate policy.

Separate from policy, marginal effects are also more important than aggregate effects in informing the decisionmaking of individuals, households, companies, and other organizations if they want to determine the social impact of the emissions generated by their activities. The emissions contributions of these groups are marginal relative to the aggregate emission production of the world economy. Therefore, the social impact of changes in their activities that either reduce or increase emissions should be quantified using estimates of marginal impacts. This analysis presented and quantified two measures of the effect of marginal emissions: (1) the MCC, which is the effect of marginal emission on excess deaths, and (2) the SCC, which is the full monetized damages from marginal emissions. Because the MCC in the DICE Baseline scenario is 2.35×10^{-4} excess deaths per metric ton of 2020 emissions, this implies that 1 million metric tons of carbon-dioxide-equivalent emissions emitted in 2020 (roughly equal to the average annual emissions of 35 commercial airliners, 216,000 passenger vehicles, 115,000 homes, and 0.26 coal-fired powerplants in the United States ([82,83])) cause 235 excess deaths over the course of the 21st century. In addition, because the SCC is $265 per metric ton of 2020 emissions, this implies that those same 1 million metric tons cause $265 million in monetized net present value climate damages. Both metrics can be useful for individuals and groups seeking to determine the social impact of choices that affect emissions, such as choices around transportation, energy generation, diet, and energy efficiency.

While the SCC is a crucial figure for climate policy, it requires all climate damages to be valued and discounted. To do this, modelers must make subjective ethical choices around how to value non-market damages and how to discount the welfare of future generations relative to current generations. Differences of opinion over how to address these issues result in wildly different estimates for the SCC, even when the projections of the climatic and socioeconomic consequences of climate change are similar ([104,105]). A recent study has suggested that these differences in opinion are so intractable that the SCC has little value in informing carbon prices ([106]). With current techniques, the importance of these ethical choices in driving the results is often obscured because the SCC represents the net effect of all climatic and socioeconomic projections in addition to ethical assumptions. For this reason, we suggest that the best practice should be that in addition to providing an SCC, IAMs should also provide estimates of the non-market marginal effects of emissions in original units without being valued or discounted. This study shows how to do that in the context of the mortality effect of climate change by providing an MCC that quantifies the marginal impact of emissions in units of excess deaths, and by showing how the MCC disaggregates over time (figure 5.B.). This best practice provides greater transparency into the results, and empowers users to make their own assumptions on how to value and discount the nonmarket effects of climate change.

It is important to note that this paper has several important limitations. First, the mortality response function only represents mortality through the pathways that are included in the literature used in the systematic research synthesis. This literature leaves out some potential climate-mortality pathways such as the effect of climate change on civil and interstate war.[iv] In addition, this analysis only includes the direct mortality effects of climate change. It does not consider likely mortality co-benefits of stricter climate policies such as decreases in particulate matter pollution. In future work, DICE-EMR could be combined with IAMs that quantify the mortality co-benefits of stricter climate policy ([108]) to fully quantify the net effect of climate policy on mortality. Finally, the mortality response function accounts for the effects of defensive adaptation in reducing the impact of climate change on mortality as discussed earlier. However, these adaptations are likely to be costly, and DICE-EMR does not directly model the costs of these adaptations. The costs of some adaptations to reduce mortality are included in the original DICE-2016 damage function, although our review concludes that the costs are likely understated (see supplementary materials). Each of these limitations likely contribute towards this analysis

[iv] There is an extended version of DICE-EMR that includes estimates of the effect of climate change on intergroup and interpersonal conflict, and then projects the effect of these changes in conflict on the mortality rate using estimates from ([97,107]). However, we ultimately concluded that this literature was too nascent to fully meet the criteria specified in the systematic research synthesis to be included in this study. In particular, it was unclear how to project the likely effects of adaptation since adaptation to avoid intergroup conflicts in the face of climate change is not well-established yet theoretically or empirically.

understating the effect of mortality. If these limitations were accounted for, they would likely increase the SCC and MCC further and result in a more stringent optimal climate policy. heal

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Supplementary Materials

Systematic Research Synthesis Detailed Methodology

To find relevant scientific literature to construct the mortality response function, we typed the following string into Google Scholar: "climate change AND mortality AND Death AND Global AND Projection." Because there are a wide variety of disciplines studying the effect of climate change on human mortality, we chose to use Google Scholar to produce results from a wide variety of scholarly literatures.[v] To avoid using outdated studies, we specified that the study had to be published within the last 20 years (September 1999 to the present). This review was conducted in September 2019. This returned a total of 18,800 results. Because Google Scholar sorts its results by relevance, we just considered the first 100 studies.

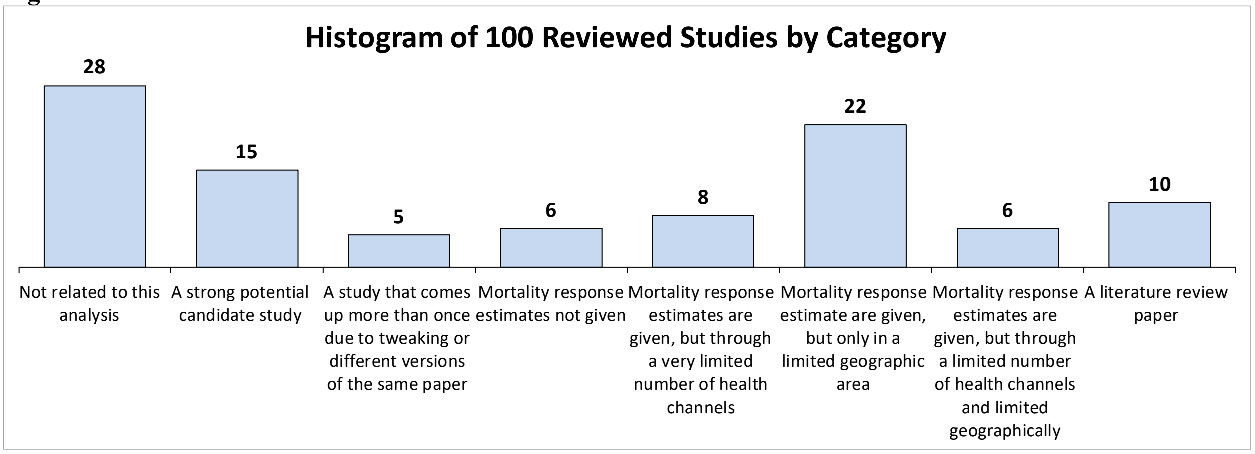
For each of these 100 studies, we conducted a first pass in which we classified each of the studies according to the following coding:

- 0 – Note related to this analysis (e.g. doesn't assess human mortality)
- 1 – A strong potential candidate study
- 1tweak – A study that comes up more than once due to tweaking or different versions of the same paper; all papers where multiple versions occur are given this coding
- 2 – Mortality response estimates not given
- 3 – Mortality response estimates are given, but through a very limited number of health channels
- 4 – Mortality response estimate are given, but only in a limited geographic area
- 5 – Mortality response estimates are given, but through a limited number of health channels and limited geographically
- 6 – A literature review paper

A histogram of the 100 reviewed studies is shown below:

[v] A variety of disciplines – especially public health, economics, and medicine – have produced studies of the effect of climate change on human mortality. The research synthesis that created the original DICE-2016 damage function ([23]) sought to produce an estimate of economic damages from climate change, and therefore conducted their proposed systematic research synthesis using EconLit, which only queries economics literature.

Fig. S1.



A full list of the 100 candidate studies and their coding is given below:

Table S1.

Number	Title	Lead Author	Year	Coding
1	Toward a quantitative estimate of future heat wave mortality under global climate change	RD Peng	2011	5
2	Impacts of 21st century climate change on global air pollution-related premature mortality	Y Fang	2013	3
3	Heat-related mortality risk model for climate change impact projection	Y Honda	2014	1tweak
4	Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought	HD Adams	2009	0
5	Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls	SC Anenberg	2012	0
6	Projecting future heat-related mortality under climate change scenarios: a systematic review	C Huang	2011	1
7	Global risk of deadly heat	C Mora	2017	1
8	Global and regional health effects of future food production under climate change: a modelling study	M Springmann	2016	3
9	Projections of seasonal patterns in temperature-related deaths for Manhattan, New York	T Li	2013	4
10	Impact of climate change on ozone-related mortality and morbidity in Europe	H Orru	2013	5
11	Impact of climate change on ambient ozone level and mortality in southeastern United States	HH Chang	2010	5
12	Avoided heat-related mortality through climate adaptation strategies in three US cities	B Stone Jr	2014	5
13	A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests	CD Allen	2010	0
14	Associations between elevated atmospheric temperature and human mortality: a critical review of the literature	SN Gosling	2009	1

15	Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of …	SN Gosling	2009	4
16	Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution	JE Jackson	2010	4
17	Projections of global health outcomes from 2005 to 2060 using the International Futures integrated forecasting model	BB Hughes	2011	3
18	The contribution of outdoor air pollution sources to premature mortality on a global scale	J Lelieveld	2015	0
19	Projections of temperature-related excess mortality under climate change scenarios	A Gasparrini	2017	1
20	The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States.	MA McGeehin	2001	6
21	Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China	T Li	2015	5
22	Impact of regional climate change on human health	JA Patz	2005	1
23	Assessing mortality risk from heat stress due to global warming	K Takahashi	2007	1
24	Variability in temperature-related mortality projections under climate change	T Benmarhnia	2014	1
25	Environment and health: 2. Global climate change and health	A Haines	2000	6
26	The interplay of climate change and air pollution on health	H Orru	2017	0
27	Analysis and valuation of the health and climate change cobenefits of dietary change	M Springmann	2016	0
28	Projecting heat-related mortality impacts under a changing climate in the New York City region	K Knowlton	2007	4
29	Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s	S Hajat	2014	4
30	Climate change and human health: impacts, vulnerability, and mitigation	A Haines	2006	1tweak
31	On the causal link between carbon dioxide and air pollution mortality	MZ Jacobson	2008	0
32	Climate change and human health: impacts, vulnerability and public health	A Haines	2006	1tweak
33	Comparative risk assessment of the burden of disease from climate change	D Campbell-Lendrum	2006	1tweak
34	Prevented mortality and greenhouse gas emissions from historical and projected nuclear power	PA Kharecha	2013	0
35	Climate change, heat waves, and mortality projections for Chicago	K Hayhoe	2010	4
36	Global climate change, widening health inequalities, and epidemiology	J Sunyer	2006	0
37	Future global mortality from changes in air pollution attributable to climate change	RA Silva	2017	3
38	Climate change and human health: present and future risks	AJ McMichael	2006	1tweak

39	Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s	World Health Organization	2014	1
40	Current and projected heat-related morbidity and mortality in Rhode Island	SL Kingsley	2016	4
41	Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits	T Carleton	2019	1
42	Climate change and extreme heat events	G Luber	2008	6
43	Impact of climate change on heat-related mortality in Jiangsu Province, China	K Chen	2017	4
44	Health and climate change: policy responses to protect public health	N Watts	2015	1
45	Regional vegetation die-off in response to global-change-type drought	DD Breshears	2005	0
46	Global climate change and children's health: threats and strategies for prevention	PE Sheffield	2011	6
47	Dirty-water: estimated deaths from water-related diseases 2000-2020	PH Gleick	2002	0
48	Addressing Global Mortality from Ambient PM2.5	JS Apte	2015	0
49	Climate change and future temperature-related mortality in 15 Canadian cities	SL Martin	2012	4
50	Climate-induced forest dieback: an escalating global phenomenon	CD Allen	2009	0
51	Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa	R Bailis	2005	0
52	Projection of future temperature-related mortality due to climate and demographic changes	JY Lee	2016	4
53	Managing the health effects of climate change: lancet and University College London Institute for Global Health Commission	A Costello	2009	1
54	Food, livestock production, energy, climate change, and health	AJ McMichael	2007	0
55	Human health and climate change in Oceania: a risk assessment	AJ McMichael	2003	4
56	Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements	DD Breshears	2008	0
57	Simultaneously mitigating near-term climate change and improving human health and food security	D Shindell	2012	3
58	Projected heat-related mortality in the US urban northeast	E Petkova	2013	4
59	Projection of heat wave mortality related to climate change in Korea	DW Kim	2016	5
60	Towards more comprehensive projections of urban heat-related mortality: estimates for New York City under multiple population, adaptation, and climate scenarios	EP Petkova	2014	2
61	Public health impact of global heating due to climate change: potential effects on chronic non-communicable diseases	T Kjellstrom	2010	6
62	Climate change, tropospheric ozone and particulate matter, and health impacts	KL Ebi	2008	6
63	Assessing ozone-related health impacts under a changing climate	K Knowlton	2004	4
64	Empirical and process-based approaches to climate-induced forest mortality models	HD Adams	2013	0

65	The 2003 heat wave in France: dangerous climate change here and now	M Poumadere	2005	2
66	Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based Poisson approach	JD Schwartz	2015	4
67	Global climate change and children's health	KM Shea	2007	6
68	The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble	RA Silva	2015	3
69	Projection of temperature-related mortality due to cardiovascular disease in Beijing under different climate change, population, and adaptation scenarios	B Zhang	2018	4
70	Long-term projections and acclimatization scenarios of temperature-related mortality in Europe	J Ballester	2011	4
71	Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health	JJ West	2013	3
72	Erosion of lizard diversity by climate change and altered thermal niches	B Sinervo	2010	0
73	Mitigation potential and global health impacts from emissions pricing of food commodities	M Springmann,	2017	0
74	Climate change-related health impacts in the Hindu Kush–Himalayas	KL Ebi	2007	4
75	Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA	A Marsha	2016	4
76	On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene	CD Allen	2015	0
77	The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada	B Doyon	2008	4
78	Climate change. A global threat to cardiopulmonary health	MB Rice	2014	6
79	Economic risks of climate change: an American prospectus	T Houser	2014	4
80	Apparent climatically induced increase of tree mortality rates in a temperate forest	PJ Van Mantgem	2007	0
81	Urban vegetation for reducing heat related mortality	D Chen	2014	0
82	Mortality trends and setbacks: global convergence or divergence?	AJ McMichael	2004	0
83	Global climate change and health: recent findings and future steps	RS Kovats	2005	6
84	Projecting future temperature-related mortality in three largest Australian cities	Y Guo	2016	4
85	How much disease could climate change cause	DH Campbell-Lendrum	2003	1
86	Global trends in tropical cyclone risk	P Peduzzi	2012	0
87	Climate change: challenges and opportunities for global health	JA Patz	2014	1

88	Climate change, humidity, and mortality in the United States	AI Barreca	2012	4
89	Heat, cold and climate change	A Woodward	2014	6
90	Heatwaves in Vienna: effects on mortality	HP Hutter	2007	2
91	Economic implications of climate change impacts on human health through undernourishment	T Hasegawa	2016	3
92	Estimating global impacts from climate change	S Hitz	2004	1
93	Temperature and mortality in 11 cities of the eastern United States	FC Curriero	2002	2
94	Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts	T Kjellstrom	2016	0
95	Multi-scale predictions of massive conifer mortality due to chronic temperature rise	NG Mcdowell	2016	0
96	Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality, premature mortality and radiative forcing	E Saikawa	2009	0
97	Global trends of fossil fuel reserves and climate change in the 21st century	BR Singh	2012	0
98	Attributing human mortality during extreme heat waves to anthropogenic climate change	D Mitchell	2016	2
99	Climate change and health in the urban environment: adaptation opportunities in Australian cities	HJ Bambrick	2011	2
100	Climate change and human health: estimating avoidable deaths and disease	RS Kovats	2005	1

Of the 100 candidate studies, we found 15 studies that were strong potential candidate studies. We then performed a second pass in which we decided which of the studies would be included in the analysis. Ultimately, we decided on 3 studies that sufficiently met the criteria to be included in constructing the mortality response function: a 2014 WHO Report *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s* ([4]), a 2019 Climate Impact Lab (a collaboration between the University of Chicago, University of California Berkeley, and Rutgers) report *Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits* ([9]), and a Lancet Planetary Health article 2017 *Projections of temperature-related excess mortality under climate change scenarios* ([3]).

The 2014 WHO report projects global excess mortality from a wide variety of channels including undernutrition, malaria, dengue, diarrheal disease, and heat in 2030 and 2050. It accounts for adaptation in the mortality projection from heat, although the effects of adaptation in the undernutrition and disease-related risks appear to be limited. The authors emphasize that despite their efforts to quantify important mortality pathways, their estimates of the future mortality effects of climate change remain incomplete because they could not calculate other pathways including river flooding, water scarcity, and conflict.

The 2019 Climate Impact Lab Report uses an econometric strategy that exploits historical variations in temperatures to find a relationship between mortality and temperature in regions across the globe. They exploit spatial heterogeneities in the mortality-temperature relationship to understand the role that different income levels and demographics play in affecting the climate-mortality relationship. They break the world into 24,378 regions and project incomes, populations, and climate into the future to estimate excess mortality that results from climate change in these regions. Importantly, their approach allows them to account for the benefits of higher incomes and climate adaptations to gain a more accurate estimate of the effect of climate change on mortality accounting for future adaptation. We utilize their reduced-form global projection of the effect of climate change on mortality accounting for adaptation. Their approach allows them to account for climate-mortality effects that are driven by direct changes in the short-run distribution of temperatures such as the net mortality effect of more hot days and fewer cold days, the mortality effect of increased surface ozone formation, and even the effect of hot days on murders and suicides. However, their approach arguably does not fully capture climate-mortality channels that are driven in part by longer-term pathways that are not econometrically identified from shorter-term temperature fluctuations such as some diseases, flooding, and undernutrition.

The 2017 Lancet Planetary Health Report uses a dataset of daily observed mean temperature and mortality counts from locations around the globe from 1984-2015 to estimate temperature-mortality relationships. They project excess mortality for cold and heat and their net change in a number of locations around the globe under RCP 2.6, 4.5, 6.0, and 8.5. Given their statistical strategy, this report has similar limitations to the 2019 Climate impact lab report: climate-mortality effects driven by direct changes in the distribution of temperatures are likely to be captured, but more complex climate-mortality channels such as changes in contagious diseases, flooding, and the effect on food supply are unlikely to be captured. Among the three studies, this study was the most borderline as to whether it would be included. While the study does include projections for a number of locations around the globe, it does not cover all of the world's population. It covers 9 regions that include all the Americas, Europe, Australia, East Asia, and South East Asia. This represents about 40% of the world's projected population in 2050 ([100]). Importantly, the study is missing data for regions that are expected to bear the most severe climate change mortality impacts: South Asia, the Middle East, and Africa. To project a global mortality response from this report, we used the 2019 UN population prospects projections for the percentage of the world population that is expected to reside in each of the 9 regions used in the report in 2055 and 2095. We then calculated the world population residing in each of the 9 regions as a percentage of the total projected population in each of the 9 regions in 2055 and 2095 so that this percentage for each of the 9 regions adds to 100%. We then multiplied this percentage by the expected percentage increase in the mortality rate in the region given in the report to create a population-weighted global estimate of the increase in the mortality rate. However, this is an underestimate of the global mortality response because the original paper leaves out projections for South Asia, the Middle East, and Africa. In addition, unlike the 2019 Climate Impact lab report, this report does not assume adaptation changes. Although this violates one of the criteria we specified, economics literature on climate-mortality adaptation has suggested that in the United States, there has already been significant adaptation to climate change that has ameliorated the mortality effect of hot days, in particular through the adoption of air conditioning ([109]). This has likely already occurred in other rich regions that have widely adopted air conditioning, such as in Europe, much of the Americas, and some countries in East Asia. Much of the expected future benefit of climate-mortality adaptations can be expected to come from emerging countries that adopt air conditioning. The exclusion of the most vulnerable regions contributes towards understating the future global mortality projection while the exclusion of adaptation contributes towards overstating the future global mortality projection. Utilizing the methodology described above, the 2017 Lancet Planetary Health report projects that in RCP 8.5 in 2100, climate change causes a 4.0% increase in the mortality rate. The 2019 Climate Impact Lab Report makes a global projection and accounts for adaptation, and they project that in RCP 8.5 in 2100, climate change causes a 6.6% increase in the mortality rate. Given similarities in the methods of the two reports, this suggests that the net effect of excluding the most vulnerable regions and excluding adaptation may be to understate the risk of mortality. In addition, we ran alternative specifications of DICE-EMR in which the mortality response function does not use the Lancet Planetary Health 2017 report. This results in a larger MCC and SCC effects and more stringent optimal climate policy.

After selecting the studies through the systematic research synthesis described above, we used the studies' projected increase in the mortality rate under different warming scenarios to construct a dataset that is used for the construction of a reduced-form mortality response function. For each study, we considered their projections for the increase in the mortality rate in 2030, 2050, 2075, and 2100 for all of the scenarios provided by the study. A summary of this dataset is given below:

Table S2.

Study Authors	Study Year	Year of Impact	Region	Emissions Scenario	Average Temperature (degrees C)	Increase in Mortality Rate (Central Estimate)	Increase in Mortality Rate (Low Estimate)	Increase in Mortality Rate (High Estimate)	Analysis Style	Mortality Impact as given	Notes on Adaptation	Survey Notes
Carleton et al.	2018	2100	Global	RCP 8.5	4.8	6.6%	-2.9%	17.2%	Statistical	Additional 73 Deaths per 100,000	Fully accounts for adaptation	Used Magicc 6.0 RCP 8.5 projection for global average temperatures.
Carleton et al.	2018	2075	Global	RCP 8.5	3.6	2.8%	-2.8%	8.5%	Statistical	Additional 30 Deaths per 100,000	Fully accounts for adaptation	Used Magicc 6.0 RCP 8.5 projection for global average temperatures.
Carleton et al.	2018	2050	Global	RCP 8.5	2.4	0.7%	-2.8%	4.3%	Statistical	Additional 7 Deaths per 100,000	Fully accounts for adaptation	Used Magicc 6.0 RCP 8.5 projection for global average temperatures.
Hales et al.	2014	2030	Global	A1B	1.4	0.4%	0.0%	0.3%	Enumerative+ Statistical	Total mortality due to undernutrition, Malaria, Dengue, diarrheal disease, and heat in 2050	Accounts for some adaptations depending on source of mortality	Used Magicc 6.0 A1B projection for global average temperatures.
Hales et al.	2014	2050	Global	A1B	2.2	0.3%	0.3%	0.2%	Enumerative+ Statistical	Total mortality due to undernutrition, Malaria, Dengue, diarrheal disease, and heat in 2030	Accounts for some adaptations depending on source of mortality	Used Magicc 6.0 A1B projection for global average temperatures.
Gasparrini et al.	2017	2050-59	Partially Global	RCP 2.6	1.0	-0.1%	-0.7%	0.5%	Statistical			Used Hayhoe et. al 2017
Gasparrini et al.	2017	2090-99	Partially Global	RCP 2.6	1.1	0.0%	-0.7%	0.7%	Statistical			Used Hayhoe et. al 2017
Gasparrini et al.	2017	2050-59	Partially Global	RCP 4.5	2.1	0.0%	-1.0%	1.1%	Statistical			Use Magicc 6.0 projection for global average temperatures.
Gasparrini et al.	2017	2090-99	Partially Global.	RCP 4.5	2.6	0.4%	-1.5%	2.3%	Statistical			Use Magicc 6.0 projection for global average temperatures.
Gasparrini et al.	2017	2050-59	Partially Global	RCP 6.0	2.0	-0.1%	-1.0%	0.9%	Statistical			Use Magicc 6.0 projection for global average

												temperatures.
Gasparrini et al.	2017	2090-99	Partially Global	RCP 6.0	3.1	1.0%	-1.9%	4.2%	Statistical			Use Magicc 6.0 projection for global average temperatures.
Gasparrini et al.	2017	2050-59	Partially Global	RCP 8.5	2.7	0.5%	-1.5%	2.2%	Statistical			Use Magicc 6.0 projection for global average temperatures.
Gasparrini et al.	2017	2090-99	Partially Global	RCP 8.5	4.6	4.0%	-4.4%	11.0%	Statistical			Use Magicc 6.0 projection for global average temperatures.

See the main text for a discussion of uncertainty in the different studies. We run three separate quadratic weighted regressions for the central, high, and low estimates shown above. Each study is given 1/3 weight, and each data point within a study is given proportional weight.

One possible alternative to estimating the mortality response functions from the discrete points shown above would have been to assume that each study estimated its own mortality response function, and to then combine those curves in some way. Unfortunately, this approach is not compatible with the Hales et al. 2014 WHO study, which aggregates mortality impacts from five different sources (undernutrition, malaria, dengue, diarrheal disease, and heat) that are calculated with different models, and results are only compiled in 2030 and 2050.

Derivation of the DICE-EMR Critical Level Isoelastic Utility Function

When evaluating policies that affect life and death in specifications involving per period utility $u(c_t)$, the level of the utility function matters a great deal ([110]). Following the literature on the value of life ([87,111]), we use the following general isoelastic utility function:

$$u(c_t) = \frac{{c_t}^{1-\eta}}{1-\eta} + \bar{u} \qquad (1)$$

$\bar{u}$ is an upper bound on utility when $\eta > 1$. Following standard practice in the literature, we normalize the utility of death to 0. Equation (1) can then be interpreted as a critical level utility function ([112,113]), where $\bar{u} = -\frac{\bar{c}^{1-\eta}}{\eta-1}$ and $\bar{c}$ represents the critical level of consumption where the agent is indifferent between life and death:

$$u(c_t) = \frac{{c_t}^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta}$$

Thus, when $c_t = \bar{c}$ the agent is indifferent between life and death. To calibrate $\bar{c}$, we leverage the calibration method discussed in ([86]). The term $u(c_t)$ represents the value of life in year t in utils. Dividing by $u'(c_t)$ converts this value into consumption units, so $u(c_t)/u'(c_t)$ represents the value of life in year t in consumption units. Dividing this term by c_t then gives the value of life in year t as ratio of the level of consumption in year t: $\frac{u(c_t)/u'(c_t)}{c_t}$. We then calculate this figure as a function of $\bar{u}$ and η from equation (2):

$$\frac{u(c_t)/u'(c_t)}{c_t} = \bar{u}{c_t}^{\eta-1} + \frac{1}{1-\eta} \tag{2}$$

Following ([86]), we can then calibrate the value of life to the value of a statistical life (VSL) estimated from the empirical literature. There is a wide variance in estimates for VSL, and we use VSL estimates of 2x consumption (low VSL), 4x consumption (central VSL), and 8x consumption (High VSL). The VSL used in the United States ($10 million dollars by the EPA) is closer to the High VSL.

The central estimate is that $\frac{u(c_t)/u'(c_t)}{c_t} = 4$. Given that DICE-2016 assumes that $\eta = 1.45$, we can then solve for the critical level of utility $\bar{u}$ in the central estimate:

$$4 = \bar{u}{c_t}^{1.45-1} + \frac{1}{1-1.45}$$

Given that 2020 average world consumption in DICE-EMR is $11.86 thousand, we can solve this equation to find that $\bar{u} = 2.04$. Solving for the critical level of consumption $\bar{c}$ given that $\bar{u} = -\frac{\bar{c}^{1-\eta}}{1-\eta} = \frac{\bar{c}^{1-\eta}}{\eta-1}$, we find that $\bar{c} = 1.20$. This calibration gives the following utility function used in DICE-EMR:

$$u(c_t) = \frac{{c_t}^{1-\eta}}{1-\eta} + 2.04 \tag{3}$$

We also run alternative calibrations for low VSL (2x consumption) and high VSL (8x consumption). The 2020 value of a life as a multiple of consumption is a tweakable parameter in DICE-EMR. DICE-EMR automatically updates the utility function calibrations when the parameter is changed. In the main SCC results in table 2, we show results with alternative VSL assumptions.

DICE-2016 is a single representative agent macroeconomic model, and DICE-EMR keeps this structure while determining the welfare impact of loss in life in a single representative agent general equilibrium setting. This has an important implication: it gives equal weight to deaths no matter where they occur in the world. Alternative methodologies give greater weight to richer individuals that die compared to poorer individuals based on their willingness to pay to avoid death, which is represented by the VSL. Since richer individuals have more financial resources, they have a higher willingness to pay to avoid death. The implication of these alternative methodologies is that deaths in richer countries (e.g. in Western Europe, North America) are weighed more than deaths in poorer countries (e.g. in Africa, South Asia). This has a significant effect on the SCC because most of the deaths are projected to be in poorer countries. The IPCC states that the approach taken by DICE-EMR – valuing all lives at the same level – is nearer the truth than the alternative approach of assigning valuing lives based on willingness to pay to avoid death ([12]). Philosopher John Broome lays out this case in more detail ([114]). He argues that an approach that values lives based on willingness to pay to avoid death is mistaken. He argues that lives should be worth and counted the same no matter where they are in the world and no matter how rich the people dying.

Social Cost of Carbon (SCC) Derivation

The 2020 SCC is determined by the following equations. See figure 3 for variable names and explanations, the supplementary materials for a more detailed explanation, and ([16]) for a full description:

$$SCC(2020) = \frac{\partial W}{\partial E(2020)} / \frac{\partial W}{\partial C(2020)}$$

In DICE-2016, L_t and R_t are exogenous. Focusing on the damage term (the SCC numerator):

$$\frac{\partial W}{\partial E(2020)} = \frac{\partial \sum_{t=2020}^{t=2510} u(c_t) L_t R_t}{\partial E(2020)}$$

This is equivalent to the discounted marginal effect of carbon emissions in every period, and then applying the chain rule:

$$\sum_{t=2020}^{t=2510} \frac{\partial u(c_t)}{\partial E(2020)} L_t R_t = \sum_{t=2020}^{t=2510} \frac{\partial u(c_t)}{\partial c_t} \frac{\partial c_t}{\partial E(2020)} L_t R_t$$

In DICE-EMR, $L_t$is now affected by emissions. Focusing on the SCC numerator:

$$\frac{\partial W}{\partial E(2020)} = \frac{\partial \sum_{t=2020}^{t=2510} u(c_t) L_t R_t}{\partial E(2020)}$$

Applying the product rule, this is equivalent to:

$$\frac{\partial W}{\partial E(2020)} = \sum_{t=2020}^{t=2510} [\frac{\partial u(c_t)}{\partial E(2020)} L_t R_t + \frac{\partial L_t}{\partial E(2020)} u(c_t) R_t]$$

Applying the chain rule, this is equivalent to:

$$\frac{\partial W}{\partial E(2020)} = \sum_{t=2020}^{t=2510} [\frac{\partial u(c_t)}{\partial c_t} \frac{\partial c_t}{\partial E(2020)} L_t R_t + \frac{\partial L_t}{\partial E(2020)} u(c_t) R_t]$$

Mortality Cost of Carbon (MCC) Derivation

The MCC assesses the marginal mortality effect of carbon emissions in units of human lives. It represents the number of excess deaths over a period of time from one ton of carbon-equivalent emissions:

$$MCC(2020) = \frac{\partial Aggregate\ Deaths(2020\ to\ 2100)}{\partial E_{2020}} = \sum_{t=2020}^{t=2100} \frac{\partial L_t d_t [1 + \delta(T_t)]}{\partial E_{2020}}$$

Where $L_t d_t [1 + \delta(T_t)]$ is the number of excess deaths in each time period after accounting for the mortality response $\delta(T_t)$. Partially differentiating this term with respect to emissions:

$$\sum_{t=2020}^{t=2100} \frac{\partial \delta(T_t)}{\partial E_{2020}} L_t d_t$$

Applying the chain rule:

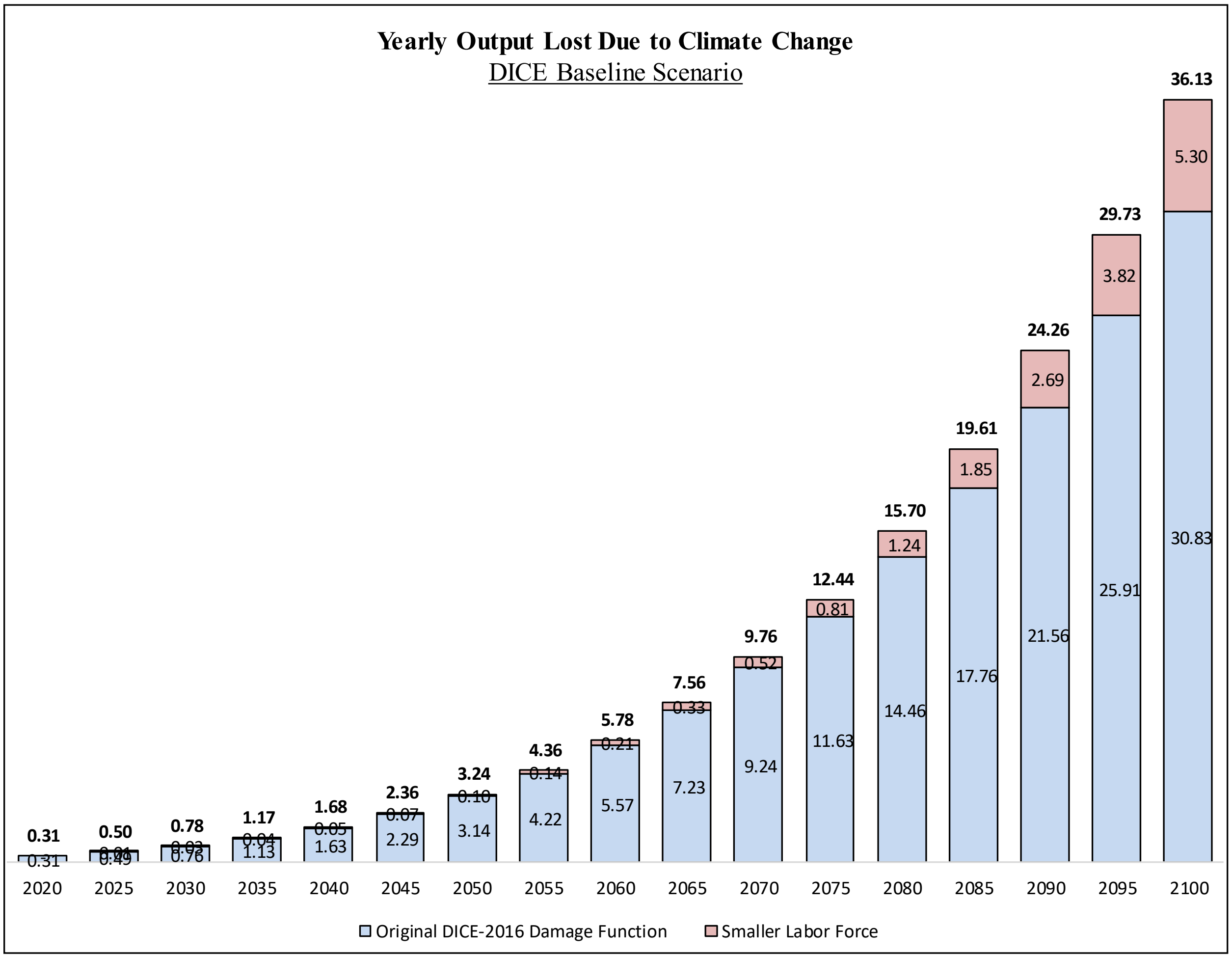
$$MC(2020) = \sum_{t=2020}^{t=2100} \frac{\partial \delta(T_t)}{\partial T_t} \frac{\partial T_t}{\partial E_{2020}} L_t d_t$$

Additional Macroeconomic Results

In DICE-EMR, climate change affects output from two sources (see figure 3): (1) the original DICE-2016 damage function that represents the portion of economic output lost due to climate change and (2) reduction in the size of the labor force under warming.

The figure below shows the relative contribution of these two factors in output loss in the DICE baseline scenario. It shows that the contribution of factor (2) is relatively small, increasing from near 0% to 15% by 2100.

Fig. S2.



Mortality Impacts in DICE-2016

Of the 26 studies used in the DICE-2016 survey, only 5 received full or nearly full weight ([94,115–118]). We reviewed the five highly weighted studies below to determine the extent to which they included mortality damage. Of the five studies, three ([115–117]) did not include mortality damages. ([118]) accounted for mortality damages from some climate-exacerbated infectious diseases, but health costs only represent 6% of total damages (and likely included some non-mortality health damages as well). ([94]) included some mortality damages, but human life costs represent 9-10% of the total climate damage at both 2.5° C and 10° C. Since these studies were highly weighted, they have the largest bearing on the DICE damage function. Provided that they are somewhat representative of the rest of the studies used in the Nordhaus and Moffat survey, we conclude that mortality damages represent less than 5% of total climate damages in DICE.

Some of the heavily weighted studies include cost estimates for plausible defensive adaptations that could be undertaken to reduce the impact of climate change on mortality. These include higher healthcare expenditures ([115,116]) and higher expenditure on air conditioning ([94]). Since these are market expenditures, they may also be included in studies that determine market impacts to GDP such as ([117]), though they are not mentioned explicitly, and the degree to which they are included is unclear. In addition, the studies that are over 20 years old ([94,118]) were published before comprehensive studies of the health impacts of global warming were available ([118]). For these reasons, we conclude that the costs of defensive adaptation to reduce the mortality impact of climate change in DICE-2016 are likely understated. Although DICE-EMR does not model the costs of defensive adaptation to climate-mortality impacts, this information might be useful for future studies that attempt to explicitly model the costs of adaptation and want to know the extent to which these costs are already included in the DICE-2016 damage function.

<u>Dellink et al. 2014</u>[vi]
Accounts for some changes in morbidity, worker productivity, and demand for healthcare. Mortality costs are not included.

"Changes in regional labour productivity are considered as the primary channel to account for health impacts. Lower mortality translates in an increased labour productivity which is one-on-one proportional to the change in the total population. The underlying assumption is that health impacts affect the active population, disregarding the age characteristic of cardiovascular and respiratory diseases. This information is complemented with changes in health expenditures, reflecting a need for households and governments to allocate increasing parts of their budget to health."

Health impacts make up a small proportion of total GDP impacts as shown in their figure 3.

<u>Bosello et. al 2012</u>
Health effects are only included for the European Union, and only addresses thermal discomfort in "on the job performance." Mortality costs are not included:

'When implemented, the climate change impacts summarized…imply that in 2050, there will be a worldwide GDP loss of -0.5%... This is mainly driven by decreases in crop productivity, followed by the redistribution of tourism flows and land loss to sea-level rise. Other impacts are negligible; however, it is worth recalling that flooding and health in particular are computed for the EU only. In addition, "health", only addresses thermal discomfort on "on the job" performance.'

Their figure 2 shows that health is a small fraction of the total damages.

<u>Nordhaus 2006</u>
Only accounts for market impacts to GDP. Mortality impacts not mentioned.

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vi ([23]) has a typo in that the "Dellink 2012" paper referred to in the research synthesis that projects a -1.1% economic impact at 2.5° C warming actually refers to this paper: ([116]). Thanks to Peter Howard for directing me to this.

Nordhaus and Boyer 2000

Only accounts for mortality costs from the increase in climate-related infectious diseases due to climate change. They project only this form of health damage because at the time the book was written, they say that "There are currently no comprehensive studies of the health impacts of global warming." They project health costs to be only 6% of the total cost of climate change.

Cline 1992

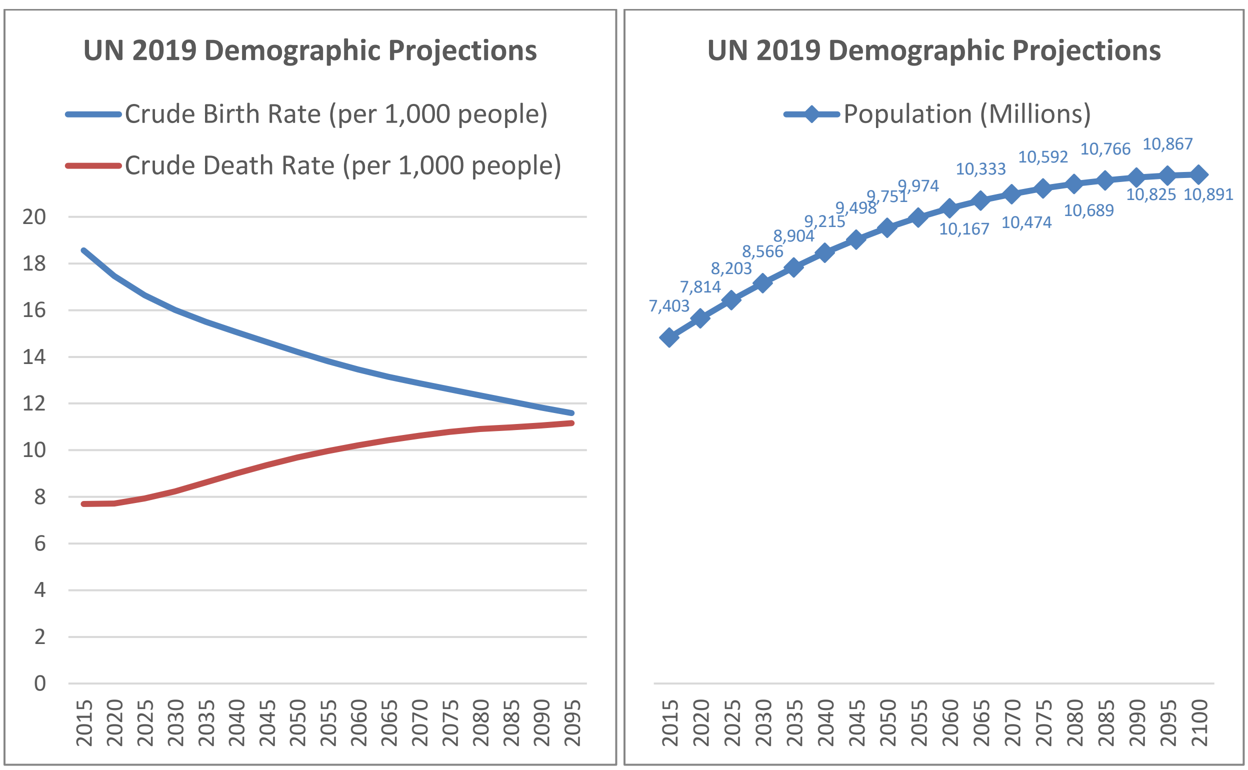
At the 2.5° C climate damage estimate, "human life" makes up 9.4% of the total damage. At the 10° C climate damage estimate, human life makes up 9.8% of the total damage. The author notes that at the time of publication, the literature on the effect of climate on health and mortality is very underdeveloped.

It should also be noted that Cline, 1992 provides a US-specific estimate of climate damages even though this study is being used to make a global damage projection in the DICE model.

Detail on UN Population Projection Methodology

The baseline population projections from the UN are given in the figures below:

Fig. S3.



The birth rate is projected to fall significantly over the 21st century due to the continued effects of the demographic transition, especially in developing countries. The mortality rate rises slightly due to an aging population, especially in developing countries.

The 2019 UN population prospects are largely projections of past trends, and the likely future mortality effects of climate change are not factored in. They use probabilistic projections of fertility and mortality rates on a country-by-country basis to derive population projections by 2095.

The demographic transition theory is the basis for projections of future country-specific fertility levels. Less developed countries exhibit high fertility rates before transitioning to a lower fertility rate as the country develops. The fertility projections are informed by historical trends and assume that the conditions facilitating fertility decline will persist in the future.

Assumptions for the projection of mortality are specified in terms of life expectancy at birth. Mortality rates are projected based on development levels. Poor developing countries exhibit some albeit slow growth in life expectancy due to the diffusion of improved hygiene and nutrition. This is followed by a period of accelerated improvements in life expectancy driven mainly by improvements in the mortality of infants and children, especially due to interventions against infectious diseases that often strike in childhood. This period is accompanied by social and economic development along with interventions in public health and basic medical care. As countries continue to develop, life expectancy improves at a slower rate. The easiest gains, mainly against infectious diseases that often strike in childhood, have already been achieved. Countries in this stage mainly improve life expectancy by preventing deaths from non-communicable diseases that more often affect the elderly. These interventions have a lower payoff in years of life expectancy gained from saving an older person compared to saving a child. See ([119]) methodology section for more detail.

Detail on Climate-Fertility Literature

([99]) found that additional days above 80°F caused a large decline in birth rates 8 to 10 months later. The initial decline is followed by a partial rebound in births over the next few months, but they conclude that the lack of a full rebound suggests that increased temperatures due to climate change are likely to cause a reduction in population growth rates in the coming century. On the flipside, ([98]) project that disruption to the agricultural sector in developing countries due to climate change is likely to reduce the returns to acquiring skills, causing parents to invest fewer resources in child education and to increase fertility in these countries.

Because we do not explicitly model the effect of climate change on fertility, DICE-EMR should not be viewed as a projection of the effect of climate change on population levels. Instead, it should be viewed as a projection of the effect of climate change on human mortality and the welfare consequences of this effect.