

# Global climate justice and the future of air quality co-benefits in low-income and middle-income countries: an energy, climate, and health modelling study

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## Summary

**Background** Despite the need to limit climate change and transition to low-carbon energy, there is disagreement about how to share the burden of reducing CO<sub>2</sub> emissions. We assess different approaches to global mitigation, accounting for three key factors: avoided climate harms, health (co)benefits from improved air quality, and the economic cost of CO<sub>2</sub> policies. We then rank the approaches according to different preferences for inter-generational and intra-generational equity.

**Methods** We compare a reference scenario to three scenarios that limit warming to 2°C: one through least cost, one that shifts mitigation burden towards higher-income countries (referred to as the international equity scenario), and a third that is identical to international equity, but within which low-income and middle-income countries (LMICs) also adopt air quality policies to reduce air pollution to the levels that occur in least-cost. Emissions and policy costs are modelled with Global Change Analysis Model, air quality with GEOS-Chem, health impacts with the Global Exposure Mortality Model, and climate benefits with Greenhouse Gas Impact Value Estimator.

**Findings** Climate action to limit global warming to 2°C results in more than 13·5 million avoided premature deaths from air pollution between 2020 and 2050, mostly in middle-income countries. Opting for the least-cost scenario rather than international equity reduces the mitigation burden for LMICs but also reduces their health co-benefits by several million deaths, highlighting a trade-off between mitigation effort (an important component of climate justice) and the urgent need to reduce environmental health burdens in LMICs. The extent to which equity is prioritised determines what to do about that trade-off; as more priority is given to lower-income countries, the international equity scenario is preferred. The most favourable scenario is the combined international equity and air quality scenario, whereby higher-income countries pay more climate mitigation costs, and LMICs use the cost savings to implement conventional air quality controls that offset foregone health co-benefits.

**Interpretation** Justice-centred climate mitigation strategies must ensure that LMICs do not miss an opportunity to realise transformative reductions in air pollution.

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## Introduction

Climate change and energy use are inextricably linked. Anthropogenic emissions of greenhouse gases from fossil fuel combustion, the main driver of climate change, began at scale during the industrial revolution, and have continued more or less unabated.<sup>1</sup> Since 1750, more than 1·8 trillion tonnes of carbon dioxide (CO<sub>2</sub>) have been released into the atmosphere, and atmospheric concentrations of CO<sub>2</sub> have increased by 50%.<sup>2,3</sup> Although the pace of new renewable energy capacity is growing rapidly,<sup>4</sup> the vast majority of total energy consumption in most of the world is still derived from fossil fuels;<sup>5</sup> as a result, global greenhouse gases have not seen meaningful declines.<sup>6</sup> Around 90% of global CO<sub>2</sub> emissions come from fossil fuel use, and

energy accounts for more than 75% of total global greenhouse gases.<sup>6–8</sup> The challenge, then, is how to reduce greenhouse gas emissions by transitioning to clean energy such as wind and solar, while not compromising on the health and other social gains that have accompanied fossil fuel use since the industrial revolution, such as dramatic (albeit unequal) gains in life expectancy.<sup>9</sup>

Globally averaged warming of more than 1°C above the preindustrial era has already occurred.<sup>10,11</sup> Associated effects of increased heat exposure and other climate-sensitive health risks are now responsible for tens of thousands of deaths annually, as well as affecting morbidity.<sup>12–14</sup> As warming increases, the health burdens from climate change will almost certainly worsen,<sup>10,13,15–18</sup>

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## Research in context

### Evidence before this study

We searched PubMed with no language restrictions from Jan 1, 2000, to Dec 20, 2025, using the search string (“Climate Change”[Mesh] OR “climate change”[tiab]) AND (“co-benefit\*”[ti] OR benefit\*[ti]) AND health[tiab]. We included multi-country quantitative modelling studies and systematic reviews assessing the impact on human health of improvements in air quality that would result from actions to reduce greenhouse gas emissions. Commentaries and single-location case studies were excluded. Previous work consistently shows large air quality and health benefits from decarbonisation. Among studies providing economic analyses, some find that these health gains can offset policy costs. However, most previous analyses focus on global least-cost mitigation strategies and thus rarely consider a priori justice-oriented burden sharing options, do not integrate equity-weighted welfare across countries and time, and typically omit direct assessment of climate benefits.

### Added value of this study

To our knowledge, this study offers the most detailed and equity-focused assessment to date of the welfare implications of alternative mitigation burden-sharing strategies, with particular attention to health co-benefits. We developed an integrated modelling framework that combines state-of-the-art approaches for emission reductions, technology costs, air quality and associated health impacts, and (avoided) climate damages (or harms). By applying both equity-agnostic and equity-sensitive decarbonisation scenarios, we evaluated

national-level outcomes using economic methods that explicitly account for cross-country inequalities, enabling direct comparison of welfare impacts across scenarios, countries, and income groups.

### Implications of all the available evidence

Action to reduce greenhouse gas emissions presents a major public health opportunity, especially for countries facing high burdens of air pollution. The scale of climate ambition directly influences the magnitude of health benefits, as greater mitigation yields greater reductions in air-pollution-related mortality. Regardless of how mitigation responsibilities are distributed, limiting global warming to approximately 2°C is clearly preferable to inaction, as the cumulative climate and health benefits substantially outweigh the costs, particularly in low-income and middle-income countries (LMICs). The results suggest that LMICs should not ignore the loss of health co-benefits from less ambitious greenhouse gas reductions, even in the context of global justice in the distribution of mitigation burden. At the same time, scenarios in which richer nations assume a greater share of greenhouse gas reduction efforts, while LMICs also implement more stringent domestic air pollution controls, could lead to improved health and wellbeing outcomes for LMIC residents. Maximising benefits in LMICs might involve mechanisms such as financial transfers from higher-income countries to support greenhouse gas reductions, or enabling LMICs to redirect cost savings from reduced greenhouse gas mitigation burdens towards other health-promoting environmental policies.

along with burdening ecosystems and the economy more generally.<sup>18–21</sup>

To prevent wider harms of future climate change, countries around the world have committed to reducing greenhouse gas emissions.<sup>22</sup> The Paris Agreement, signed by 194 nations, aims to limit warming to under 2°C while pursuing efforts to keep the increase to 1.5°C. Achieving a 1.5–2°C target requires greenhouse gas emissions to fall rapidly, with profound implications for the energy system.<sup>23,24</sup> The challenge increases with each passing year.<sup>10</sup>

Despite widespread consensus on the need to limit future climate change, there is disagreement about how to share the burden of reducing emissions.<sup>25,26</sup> The global nature of the problem, combined with the scale of the mitigation challenge, implies a need for action from all countries. However, as nations have radically different levels of historical responsibility for climate change, and also differ in their capacity to pay for emission reductions, proposals that place heavy mitigation burdens on low-income and middle-income countries (LMICs) might be inconsistent with principles of climate justice, which holds that climate action should be fair and should address the responsibilities for and capacity to address

climate change across different communities and countries.<sup>27–29</sup> In general, LMICs have had fewer opportunities to develop industrially, contributed fewer emissions per person overall, and are typically more vulnerable to the effects of climate change than their high-income counterparts.<sup>28,30–32</sup> Within this climate justice context, many argue that LMICs should continue to have opportunities to use fossil fuels for development, thus shifting the mitigation burden to high-income countries (HICs).<sup>33,34</sup> Under the Paris Agreement, for example, climate justice is enshrined by linking emissions pledges to principles such as “common but differentiated responsibilities” across countries.

Another consideration is the potential health co-benefits that can result from climate action. Health co-benefits occur when actions to limit future climate change also produce public health benefits that are not tied to avoided climate harms.<sup>35–38</sup> The most straightforward example is through air quality, as fossil fuel combustion emits both air pollutants and CO<sub>2</sub>. Therefore, actions targeting fossil fuels are likely to produce a climate benefit as well as a local health benefit from reduced air pollution, which is responsible for millions of deaths annually across the globe

(approximately 90% of which occur in LMICs).<sup>39,40</sup> Air quality-related health co-benefits associated with strong climate actions are likely to be large and could outweigh costs of reducing emissions (policy costs), at least in some (generally LMIC) countries.<sup>35,36,38,41–52</sup>

Therefore, as we highlight below, there may be a trade-off between countries' decisions about climate justice and the health co-benefits they achieve, whereby reducing the mitigation burden on LMICs could inadvertently bypass an opportunity to close cross-country disparities in air pollution exposures and associated health burdens. By developing stylised scenarios illustrating these considerations, we inform these trade-offs by drawing attention to the air-quality-related health co-benefit implications of different future emissions trajectories. This analysis could be particularly insightful when countries update their emission-reduction pledges.

First, we model differences in climate benefits, health co-benefits, and climate mitigation costs of multiple approaches to global mitigation, including a least-cost (global cooperation) approach, an explicit justice-based approach, and a justice-based approach that also incorporates additional conventional air quality controls. Second, we use standard economic methods to quantitatively rank the approaches, incorporating justice-relevant facts about inequality both across countries and over time.

## Methods

Here we briefly describe the core methods. Further details and a graphical summary of the methods are presented in the appendix (pp 3–9).

### Scenario development

We estimate differences in mitigation policy costs, air pollution benefits, and climate benefits between three core scenarios for the period 2020–2100: one reference scenario without climate policy, and two scenarios that limit warming to 2°C by the end of the century. In the reference scenario, we assume that countries do not implement explicit climate change mitigation policies. For example, there is no implementation of climate policy targets (eg, net-zero emission by 2050) or climate policy actions (eg, those included in emission pledges and other domestic climate and clean energy policies). We assume that there are modest shifts towards clean energy in some locations because of economic forces bringing the prices of low-carbon technologies down; the result is that global mean temperature in 2100 is approximately 3.6°C above preindustrial levels (appendix p 10).

For the two 2°C scenarios, we assume that global total CO<sub>2</sub> emissions are identical but the countries where they are reduced differ, illustrating two different approaches to mitigation burden sharing. In the first, which we refer to as least-cost, we assume that the world achieves a 2°C

limit to warming through a global least-cost approach via a uniform global carbon price (ie, a fee levied on CO<sub>2</sub> emissions). As the carbon price is the same in all countries, and across all economic sectors, emissions reductions occur first where they can be achieved at the lowest cost. In the second, which we call international equity (or simply, Equity), we assume that HICs reduce their emissions to a greater extent than do LMICs. The scenario is implemented by applying regionally varying carbon prices that are proportional to income. Setting lower carbon prices in most LMICs compared with the global average ensures that the mitigation burden for lower-income countries is lower than in the least-cost case that assumes a global uniform carbon price (appendix p 11). This scenario approximates the capabilities dimension of the United Nations Framework Convention on Climate Change principle of “common but differentiated responsibilities and respective capabilities” but only indirectly captures the responsibility dimension to the extent that responsibility is correlated with current wealth. If responsibility were fully captured, arguably even more mitigation effort would shift towards high-income countries.

After characterising differences between the three climate mitigation scenarios above, we also introduce a fourth scenario: equity and air quality (or Equity+AQ). In this scenario, CO<sub>2</sub> mitigation effort is identical to the international equity scenario, but LMICs adopt conventional end-of-pipe air quality policies domestically, such as scrubbers fitted to power plants, to reduce air pollution (and associated health effects) to the levels that occur in the least-cost scenario.

See Online for appendix

### Energy and emission modelling

We used the open-source Global Change Analysis Model (GCAM; version 7.0)<sup>33</sup> to estimate emissions in the future. GCAM is a global human-Earth system model representing the behaviour of, and interactions between, five systems: the energy system, water, agriculture and land use, the economy, and the climate. GCAM is calibrated to 2015 and then projects energy and emission patterns at 5-year intervals in a partial equilibrium economic modelling framework.

To estimate the future emissions in the scenarios described above, we first set the reference scenario with default assumptions plus simple adjustments for coal retirements to make it consistent with historical data from the World Energy database.<sup>5</sup> Global emission targets in the 2°C scenarios are then implemented via a single exogenously specified annual global CO<sub>2</sub> emission trajectory based on the estimated emission budget to reach the 2°C goal. In the least-cost case, the model computes a uniform global carbon price to reach the global emission target in each period. In contrast, in the international equity case, an additional constraint is added specifying the relative ratios of the carbon prices (proportional to country or regional income), and then

the model computes the regionally differentiated carbon prices that conform to those ratios to reach the same global emission target in each time period.

### Spatial downscaling of emissions

Global emissions in the 32 GCAM regions (appendix pp 21–23) were downscaled based on a method developed for the Coupled Model Inter-comparison Project Phase 6 for use by the climate and atmospheric modelling community.<sup>54</sup> In essence, the emissions at the regional and aggregate sector level are mapped to 0.5° latitude × 0.5° longitude spatial grids using different country and sector-varying patterns based on historical trends. Using this method, the GCAM emissions of air pollutants (nitrogen oxides, sulfur dioxide, carbon monoxide, ammonia, black carbon, organic carbon, and volatile organic compounds) were converted from regional emissions to gridded emissions for five aggregate sectors: power, transport, industry, residential and commercial, and land use.

### Air quality modelling

The air quality simulations were conducted with the three-dimensional chemical transport model GEOS-Chem (version 14.0.1).<sup>55</sup> GEOS-Chem is widely used to simulate the formation, transport, and removal processes of atmospheric aerosols and gases based on meteorological data, global and regional emission inventories, and algorithms that represent the physics and chemistry of atmospheric processes.

For 2020, 2030, 2050, and 2100, we simulated hourly PM<sub>2.5</sub> concentrations on a 2° latitude × 2.5° longitude grid. These simulations were driven by different emission patterns as described in previous steps,<sup>56</sup> but we applied the 2020 meteorological conditions to all the future year simulations to control for the effects of meteorological factors. Each year of the simulations included a 6-month spin-up (the period at the beginning of a full chemistry GEOS-Chem simulation to ensure chemical species reach equilibrium) starting from July, 2019. More details on the GEOS-Chem configurations can be found in our previous work.<sup>57</sup>

We evaluated the base model simulations against ground measurements of PM<sub>2.5</sub> and found that the modelled PM<sub>2.5</sub> concentrations agree well with those datasets (appendix p 12), and are comparable to other global simulation studies.<sup>58–60</sup>

### Mortality assessment

We quantified air pollution mortality using relative risks from the Global Exposure Mortality Model, estimated by Burnett and colleagues,<sup>61</sup> for five diseases associated with long-term ambient PM<sub>2.5</sub> exposure: chronic obstructive pulmonary disease, ischaemic heart disease, lung cancer, lower respiratory infections, and stroke. For each of the 5-year age groups in each of the 169 included countries, we estimate the premature

deaths from air pollution attributable to each of the five diseases, where:

$$\text{Mort} = \text{AF} \times y_0 \times \text{Pop}$$

$y_0$  is the age-specific and disease-specific baseline mortality rate projected by the International Futures model (version 7.64);<sup>62</sup> Pop is the population in each age group, taken from the second Shared Socioeconomic Pathway (SSP2), available from the International Institute for Applied Systems Analysis SSP database;<sup>63</sup> AF is the attributable fraction, which changes with PM<sub>2.5</sub> concentrations (c) in each region, and is calculated as:

$$\text{AF}(c) = \frac{\text{RR}(c) - 1}{\text{RR}(c)}$$

where c is the annual mean PM<sub>2.5</sub> concentration in each country and RR is the age-specific and disease-specific relative risk. The annual mean PM<sub>2.5</sub> concentrations are from the GEOS-Chem simulations.

In sensitivity analyses, we report health impact estimates when using mortality rates from the other four SSPs, while keeping the population size projections at the level of SSP2, since changing the population size for only the health impact calculations would introduce inconsistencies with the energy system and emission modelling.<sup>64</sup> In another sensitivity analysis, we use the Integrated Exposure Response function<sup>65</sup> instead of the Global Exposure Mortality Model.

### Climate policy costs

To quantify climate policy costs, we first mapped out the marginal abatement curve for the least-cost and international equity scenarios and then estimated the area under the marginal abatement curve as the total mitigation policy costs. Specifically, for each of the least-cost and international equity scenarios, we first added two more GCAM runs that assume the annual global mitigation of greenhouse gases is 30% and 70% of that in the 2°C scenario, and that the mitigation is achieved with global uniform (least-cost) or regionally varying (international equity) carbon prices. Then, based on the increase in the mitigation level and the associated increased carbon prices in these four models runs (ie, reference, two intermediate mitigation runs, and the least-cost or the international equity scenario) we mapped out the non-linear marginal abatement curves for each scenario and for each region. We then sum the area under those curves to calculate regional climate policy costs and downscale the mitigation costs to countries within each GCAM region based on the present size of their economy.

### Air quality policy costs

As an additional experiment, in the equity and air quality scenario only, we estimated the costs of reducing air

For more on ground measurements of PM<sub>2.5</sub> see <https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database>

pollution in LMICs in the international equity scenario—where LMICs shoulder relatively less of the climate mitigation burden—to the levels achieved in the least-cost scenario through conventional air quality policies (as opposed to climate policy), primarily through end-of-pipe controls. In this way, we can estimate the total cost of a scenario where the 2°C climate target is met through a climate justice approach to mitigation, but where the additional air pollution controls ensure that there is no missed opportunity in terms of health benefits in LMICs.

To estimate these air quality control costs, we used the International Institute of Applied System Analysis' Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model,<sup>66–68</sup> which represents 182 world regions and is designed to explore cost-effective emission control strategies by incorporating information on future economic, energy, and agricultural development, emission control potentials and costs, atmospheric dispersion, and environmental sensitivities towards air pollution.

Although in principle GAINS covers the whole chain from emissions to impacts, here we use GAINS only to derive marginal abatement cost curves for each relevant pollutant and each GCAM region. We then use the region-specific and pollutant-specific marginal abatement cost curves to estimate the total pollution control costs to reduce the pollution in the international equity scenario to reach the same level as in the least-cost scenario.

### Climate benefits

The primary reason to implement carbon mitigation is to reduce the harms from future climate change. To quantify the climate benefit of achieving the 2°C warming limit, we use the Greenhouse Gas Impact Value Estimator model, which was developed to provide social cost of carbon (SC-CO<sub>2</sub>) estimates for regulatory impact analyses.<sup>18</sup> The SC-CO<sub>2</sub> is a monetised estimate of the climate harms society experiences from emitting one additional tonne of CO<sub>2</sub> into the atmosphere, and is a way to account for climate change impacts in policy design and analysis. This model has been thoroughly described elsewhere.<sup>18</sup>

### Policy ranking

The steps outlined above yield results on the climate policy costs, health co-benefits, and avoided climate harms (ie, climate benefits) associated with each 2°C scenario compared with the reference. As these impacts differ across countries and time, we use a social welfare function framework—widely applied in climate economics—to aggregate the impacts to health and wellbeing along different dimensions and then rank the scenarios accordingly.<sup>69–71</sup>

Some impacts, such as the cost of climate mitigation, are natively estimated in monetary terms, whereas other impacts, such as health co-benefits, are natively estimated in non-monetary terms (ie, number of

avoided premature deaths). To determine the monetary equivalent of preventing mortality, we multiply the country-specific and period-specific number of avoided deaths by country-specific and period-specific value-per-statistical-life estimates.<sup>72,73</sup> Then, for each period, we aggregate the monetary costs and benefits across countries using country-specific and period-specific weights.<sup>74</sup> The social welfare function we use attaches greater weight to impacts affecting low-income populations relative to higher-income ones on the grounds that an additional dollar, for example, to a person in an LMIC contributes more to their wellbeing than an additional dollar to a person in an HIC. The results are reported as the equity-weighted net present value (NPV), a measure of wellbeing. NPV is the total value of a scenario's benefits minus its costs, with all future impacts discounted to reflect their value in today's terms; scenarios with a more positive NPV are preferred. The equity-weighting aspect refers to our use of the social welfare function to account for differences in the value of a dollar in LMICs versus HICs. In our main results, we use a middle-of-the-road equity weighting in the social welfare function that is broadly in line with many governmental recommendations and extant research,<sup>75,76</sup> but test alternatives in sensitivity analyses.

### Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

### Results

Achieving a 2°C climate target entails substantial reductions in carbon emissions (figure 1, appendix p 23). Instead of growing from 41 GtCO<sub>2</sub> in 2020 to 55 GtCO<sub>2</sub> in the reference scenario in 2050, (net) emissions are predicted to fall by more than half to 18 GtCO<sub>2</sub> in the 2°C scenarios. However, the 2°C scenarios differ from each other in terms of where those emissions occur; in the least-cost scenario, HICs still emit the most carbon per capita, whereas in the international equity scenario—where the mitigation burden shifts towards wealthier countries—they emit the least. All three of the other (lower) income groups can emit more in the international equity scenario than in the least-cost scenario.

The falling emissions of co-emitted air pollutants are also reflected in the atmospheric concentrations of PM<sub>2.5</sub>, which are predicted to drop in all countries in both 2°C scenarios compared with the reference (figure 2A), resulting in a higher percentage of the global population meeting WHO air quality guidelines (figure 2B). The distribution of reductions in air pollution mirrors the changes in emissions to a large extent, where air quality improves more in the least-cost scenario compared with the international equity scenario for many low-income and lower-middle-income countries, whereas air quality

improves more in the international equity scenario in HICs. For example, India in 2050 has a projected  $PM_{2.5}$  concentration that is about  $16.5 \mu\text{g}/\text{m}^3$  lower in the least-cost scenario compared with the reference, whereas the difference is approximately  $11.1 \mu\text{g}/\text{m}^3$  in the international equity scenario. In contrast, the USA is predicted to lower its  $PM_{2.5}$  levels by about  $0.5 \mu\text{g}/\text{m}^3$  in

the least-cost scenario and  $0.7 \mu\text{g}/\text{m}^3$  in the international equity scenario. Overall, the air pollution gap in 2050 between HICs and LMICs is projected to close in both  $2^\circ\text{C}$  scenarios compared with 2020 but is on average  $2.0 \mu\text{g}/\text{m}^3$  greater in the international equity compared with the least-cost scenario (appendix p 24).

The same features are evident in relation to avoided premature deaths from air pollution. In both  $2^\circ\text{C}$  scenarios, more than 13.5 million deaths are expected to be avoided cumulatively from 2020 to 2050, but in the international equity scenario nearly 4 million avoidable premature deaths are not realised, because more of the mitigation burden is borne by higher-income countries where there are fewer people and where the air is already relatively clean (figure 2C); these foregone avoided deaths occur almost entirely in low-income and lower-middle-income countries (figure 2C, D). These features persist using alternative mortality rates and a different concentration-response function (appendix pp 14, 26). For many LMICs, the (monetised) health co-benefits counterbalance a large percentage, and sometimes all, of the climate mitigation policy costs in both the least-cost and international equity scenario, although more strongly in the international equity scenario (appendix p 15).

The differences between the least-cost and international equity scenarios highlight a trade-off between equity in

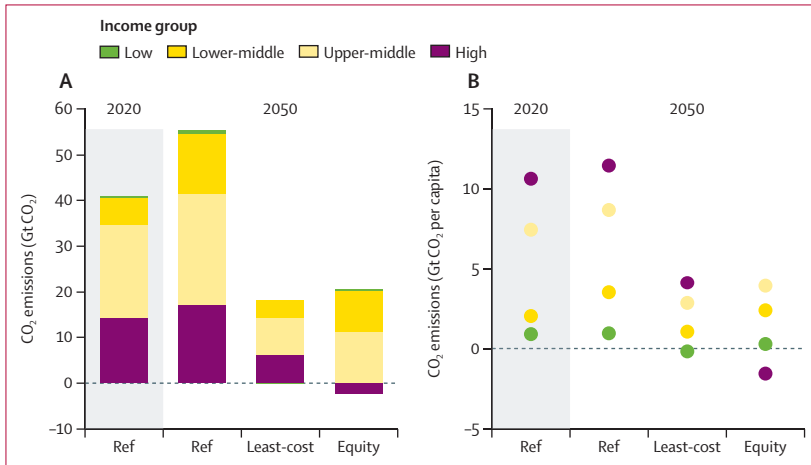


Figure 1: Total (A) and per capita (B)  $\text{CO}_2$  emissions in 2020 and 2050 by World Bank income groupings. Emissions of other greenhouse gases and air pollutants are reported in the appendix (p 13).

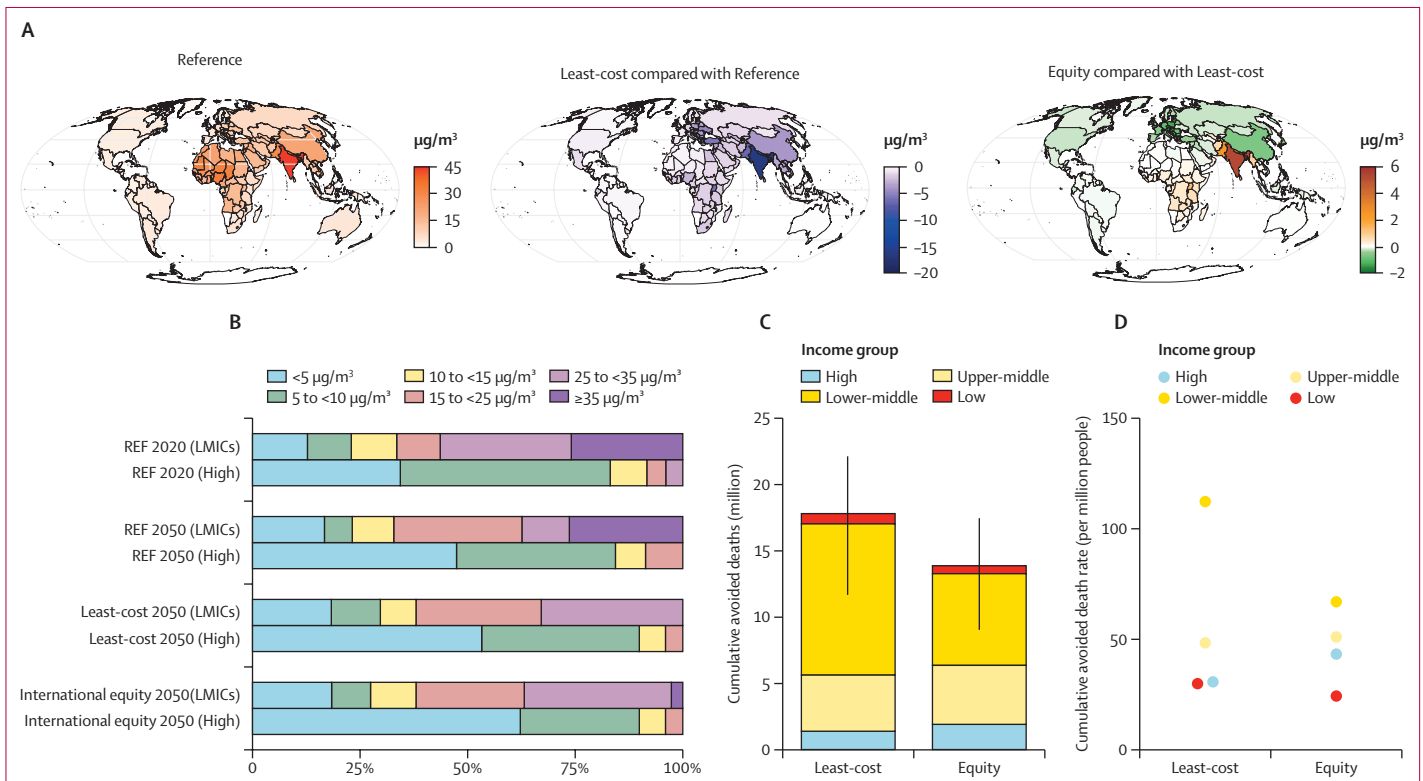


Figure 2: Global distribution of ambient  $PM_{2.5}$  concentrations in 2050 (A), the percentage of the population meeting WHO air quality guidelines (B), and cumulative avoided deaths from air pollution both in total (C) and per capita (D). Error bars in (C) reflect 95% CIs in the Global Exposure Mortality Model concentration-response functions. LMICs=low-income and middle-income countries.

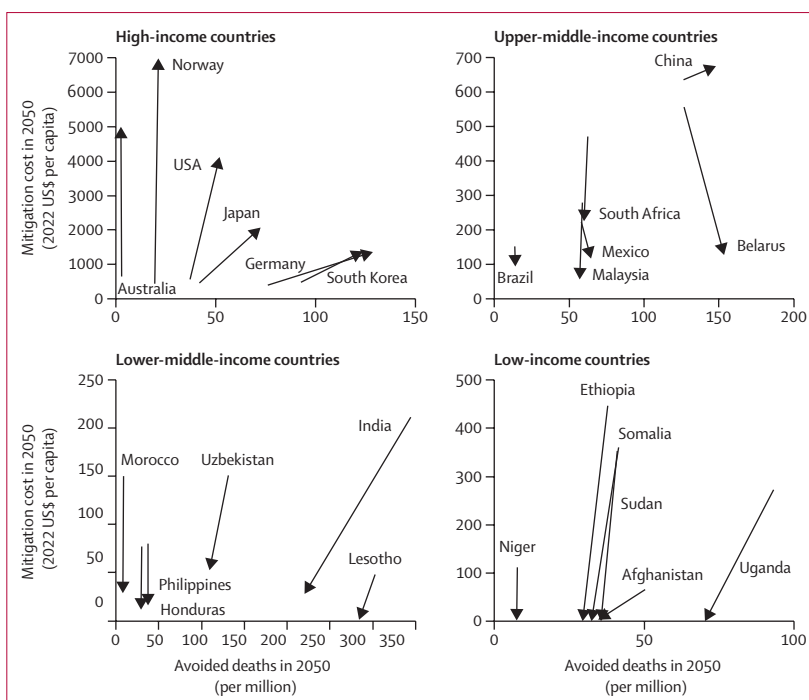
mitigation burden and air quality co-benefits. When mitigation burden shifts towards higher-income countries, lower-income countries pay less of the cost to reduce carbon emissions but also forfeit some of the health benefits associated with cleaner air. The trade-off is illustrated explicitly in figure 3, which shows the change in per capita climate mitigation costs against the change in health co-benefits in select countries in 2050 when opting for the least-cost rather than the international equity scenario. Although the slopes and lengths of the lines differ, there is a clear pattern whereby higher-income countries generally move from the lower left, indicating relatively low mitigation costs and avoided deaths, towards the upper right—which indicates higher costs but also more benefits. The opposite occurs in LMICs, with a few exceptions (eg, China) that are on the richer end of their income group. A small number of countries do not follow these trends because they are affected by transboundary air pollution from high-emitting neighbours that are in a different income group (eg, Mexico; figure 3).

**Climate benefits**

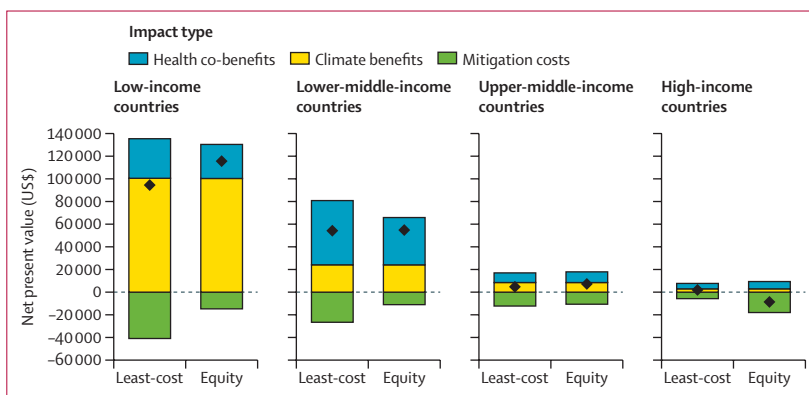
Unlike the health co-benefits, climate benefits do not differ substantially between the 2°C scenarios (figure 4), which is by design—the scenarios are identical in CO<sub>2</sub> emissions cumulatively, and in each time period, with only (small) differences resulting from non-CO<sub>2</sub> climate forcers (appendix pp 10, 13). The estimated equity-weighted present value of the different impacts varies by income group. Low-income countries have, by far, the most favourable benefit:cost ratio from action to keep the world to 2°C, with the present value of the climate benefits alone far outweighing the mitigation costs in both scenarios. Climate benefits also outweigh climate mitigation costs in the lower-middle-income group, especially in the international equity scenario. In lower-middle-income and upper-middle-income countries, air pollution gains considerably shift the benefit:cost ratio in favour of mitigation action in both scenarios. The health co-benefits also mean that HICs benefit in the least-cost scenario, but these co-benefits are not enough to fully offset their climate mitigation costs in the equity scenario. Further information on impact over time for select countries can be found in the appendix (p 17).

**Policy implications**

The trade-off between paying for climate-related emission reductions and benefiting from the associated improvements in air quality, combined with variation in the timing of the different types of costs and benefits, means that it is not obvious which scenario is preferable from a global perspective. To integrate these different dimensions of impacts across countries and time, we compute the change in equity-weighted NPV (a measure of wellbeing) when moving from the least-cost to the international equity scenario. The equity-weighted NPV

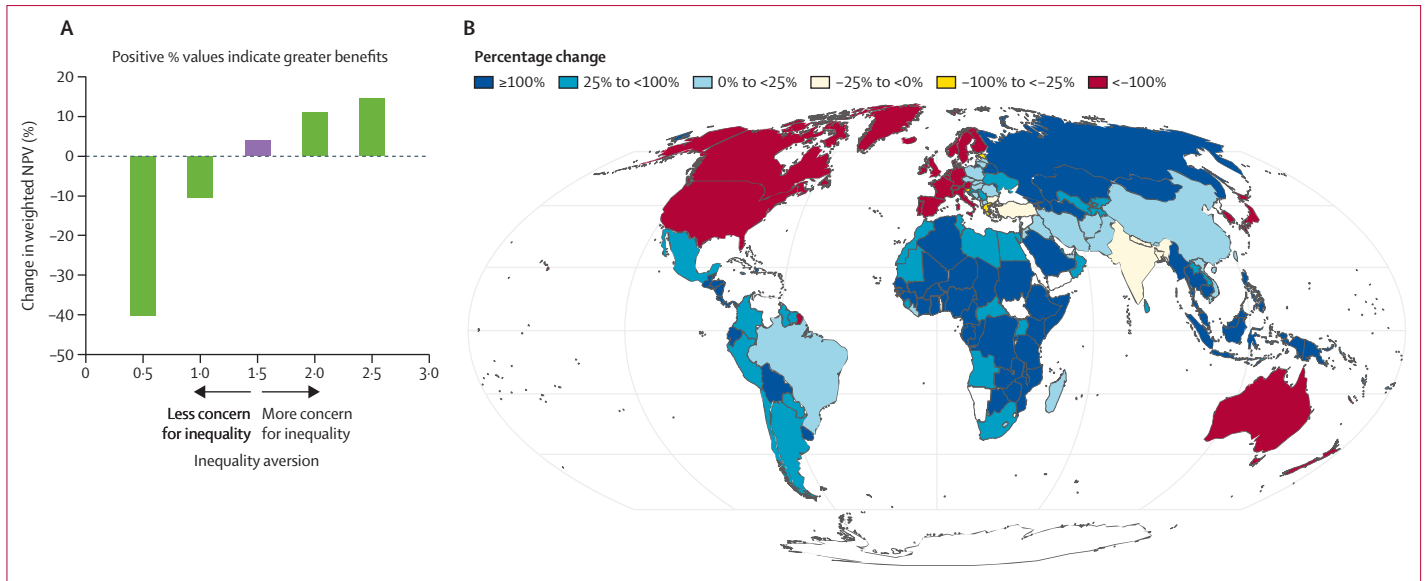


**Figure 3:** Change in avoided deaths and climate mitigation costs for select countries when moving from the least-cost to the international equity scenario, by income group. An analogous figure with all regions is presented in the appendix (p 16).



**Figure 4:** Change in net present value (2030–2100) compared with the reference scenario in relation to climate policy costs, climate benefits, and health co-benefits by country income group and scenario. Here per capita is relative to the 2030 population. The net present value accounts for the time trajectory of the different impacts as well as the higher value of benefits per US dollar to low-income and middle-income countries versus high-income countries. CIs for the net benefits by income group and scenario and ratios of net benefits between the scenarios by income group are reported in the appendix (pp 24–25).

captures the fact that a US dollar gained (or lost) affects the wellbeing of an average person in an LMIC more than an average person in an HIC. Using the same middle-of-the-road value in climate economics for this parameter assumed in figure 4, we find that the two 2°C scenarios lead to a difference in global wellbeing of approximately 4% between the least-cost and international equity scenarios (figure 5). Increasing the aversion to inequality, which weights impacts in lower-income countries even more



**Figure 5:** Change in NPV when selecting the international equity instead of the least-cost scenario (2030–2100), both globally given different levels of inequality aversion (A) and by country given a middle-of-the-road inequality aversion of  $\eta=1.5$  (B)

A positive change in per capita NPV means that the international equity scenario provides overall more net benefits than the least-cost scenario. As an example, for a hypothetical country, suppose the change in NPV compared with the reference in the least-cost case is +\$1000 and the change in NPV compared with the reference in the equity case is -\$500. The percent change is:  $(-500 - \$1000) / |\$1000| \times 100 = -150\%$ . To help with the interpretation of  $\eta=1.5$ , consider an average person in an LMIC with an income of US\$1000 compared with one in an HIC with US\$10 000. When  $\eta=1.5$ , US\$1 of benefits produces a welfare gain roughly 30 times greater for the person in an LMIC relative to the one in an HIC. Increasing  $\eta$  (ie, moving to the right along the x-axis) weights the person in the LMIC even more, and vice versa. Here the rate of pure time preference is set at 1% per year (results with other values are reported in the appendix [p 27]). HIC=high-income country. LMIC=low-income and middle-income country. NPV=net present value.

strongly compared with higher-income ones, makes the equity scenario increasingly preferable; with less inequality aversion, the least-cost scenario wins out (figure 5; appendix p 27).

At the national level, there is a marked distinction by country income grouping whereby most LMICs would prefer the equity scenario and HICs would prefer the least-cost scenario (figure 5)—a finding that holds for other values of inequality aversion (appendix p 18). India is a notable exception, where the large health co-benefits make the least-cost scenario more beneficial even though mitigation costs are higher.

Finally, we find that combining the international equity scenario with air quality policies to achieve the number of avoided deaths in the least-cost scenario has the potential to increase global wellbeing above either of the two 2°C scenarios alone (appendix pp 19, 28), because HICs shoulder the majority of the mitigation burden, but LMICs benefit from the avoided climate harms as well as air pollution benefits achieved through relatively inexpensive end-of-pipe technologies; for almost all LMICs, the mitigation cost savings in equity are more than enough to pay for those domestic air quality control costs (appendix p 20).

## Discussion

We find that the transition to clean energy required to limit future warming to 2°C would result in many millions of avoided premature deaths over the coming

decades, overwhelmingly in LMICs. The general finding that reducing carbon emissions can lead to large air-quality-related health co-benefits has been reported in previous studies.<sup>37,38,41,42</sup> Air pollution is the leading environmental risk factor for mortality globally, responsible for an estimated 8·1 million deaths per year, and is particularly high in many parts of the world where populations are large and increasing.<sup>39</sup> The scale of the energy transition required to achieve warming of 2°C or lower entails major reductions in fossil fuel combustion<sup>23,24</sup>—the leading source of both anthropogenic CO<sub>2</sub> emissions and air pollutants—and thus will profoundly improve air quality, especially in LMICs.

Here we show that substantial improvements in air quality will occur regardless of whether 2°C is achieved through least-cost measures, or, alternatively, if HICs shoulder more of the burden as in the international equity scenario. The international equity scenario entails lower costs for LMICs but also results in about 20% fewer total avoided deaths in those same countries cumulatively through 2050. The trade-off between the costs of paying for emission reductions and the health co-benefits from cleaner air means that these two scenarios might be much more similar from a global wellbeing perspective than if health co-benefits were not part of the analysis. The results show how avoided harms from air quality improvements that accompany climate action are relevant to understanding

the global costs and benefits of different mitigation scenarios, and especially to LMIC policies aimed at navigating competing considerations of climate justice and population health.

Our work connects to climate justice debates about how countries should share the burden of mitigation, which will be costly in many cases. Specifically, we illustrate a potential trade-off between equity in the distribution of mitigation effort, and exposure to air pollution and associated health burdens. In 2020, LMICs had a modelled population-weighted exposure to  $PM_{2.5}$  of approximately  $23.2 \mu\text{g}/\text{m}^3$ , compared with approximately  $8.1 \mu\text{g}/\text{m}^3$  in HICs. Although both  $2^\circ\text{C}$  scenarios would substantially reduce air pollution levels and close that gap compared with 2020 (and the reference scenario), the remaining disparity would be more pronounced in the international equity compared with the least-cost scenario.

Of all the scenarios we analysed, the stylised equity and air quality scenario was the most favourable overall, driven by LMICs that gain large health benefits by combining more modest climate policy with relatively cheaper end-of-pipe controls; the end-of-pipe control costs are typically more than offset by the lower cost of mitigation for LMICs in the international equity scenario versus least-cost. In combination, our results strongly affirm that climate policy offers a substantial opportunity to improve public health, but they also show that optimising health and wellbeing might entail other types of pollution-reduction policies alongside climate policies. The upshot is that, first, LMICs should not ignore the potential loss of health co-benefits from lower-ambition greenhouse gas emissions reductions. But second, the cost savings to LMICs from a climate justice scenario (eg, the international equity scenario) that achieves strong global greenhouse gas reductions are typically more than adequate to pay for increased domestic air quality controls to capture those foregone health improvements; however, in many cases they would require LMIC policy makers to implement much more aggressive air quality policies.

As a result, justice-centred mitigation strategies should consider the potential for transformative reductions in ambient air pollution in LMICs alongside other issues such as historical responsibility and current capacity. However, we note that there are other approaches to climate justice that we did not evaluate. For example, the transfer of funds from HICs to LMICs to pay for mitigation could prioritise health co-benefits in LMICs while minimising their mitigation cost burden. We did not model such a scenario because our objective was to illustrate and quantify the potential for welfare gains beyond a least-cost scenario without transfers. Transfer payments from HICs to LMICs could further increase global welfare.<sup>29,34,77,78</sup> More generally, here we have assumed that global climate equity must be achieved within a bottom-up regime involving different national

mitigation actions, rather than via a highly redistributive scheme involving a global cap and trade system where permits for emissions are allocated mostly to poorer nations. This latter system would have the theoretical potential to combine the least-cost scenario's distribution of emissions reductions with the international equity scenario's progressive distribution of mitigation cost; however, it would entail large international transfers beyond what is currently under consideration.

Our results should be interpreted considering the study's key assumptions and limitations. First, we have only quantified a subset of possible co-benefits.<sup>79,80</sup> For example, we only included the mortality impacts of  $PM_{2.5}$  and not those related to morbidity, which can be large, or the effects on crops or ecosystems.<sup>46,81–83</sup> Potential interactions between heat and air pollution on health<sup>84</sup> were also not accounted for, and would likely push in the direction of greater co-benefits as both reducing emissions and limiting temperature rise could yield health benefits. We also did not include impacts on ozone, which would also be reduced with fewer precursor emissions and in a relatively cooler climate, as in the  $2^\circ\text{C}$  scenarios.<sup>85,86</sup> We do note, however, that health co-harms to some populations are also possible,<sup>87,88</sup> and could be incorporated in future work, although they are generally considered to be smaller in magnitude than co-benefits and often avoidable or reducible with good policy design.<sup>43,64,87–89</sup>

Second, we follow much of the co-benefits literature by relying on exogenous demographic projections. In sensitivity analyses, we investigated different exogenous SSP demographic projections, which indicated that the overall story would be unlikely to qualitatively change with other demographic assumptions. At the same time, a limitation of our approach is that the SSP scenarios are still exogenous, whereas Malley and colleagues<sup>90</sup> showed how an endogenous demographic model could increase estimates of mortality related to  $PM_{2.5}$ ; as a result, investigating the interplay of our results and an endogenous demographic model could be a useful extension in future work.

Third, assumptions about future air quality policies can importantly affect the results. Reductions in air pollution can be achieved through climate policies, but also independently through non- $\text{CO}_2$  actions, such as end-of-pipe technologies targeting nitrogen oxides, sulfur oxides, or primary  $PM_{2.5}$ . As air quality improves, the potential for health co-benefits decreases,<sup>43,81</sup> which could in turn diminish incentives to mitigate it. The interplay between climate policy and air quality policy, and how to optimise them, requires additional investigation, but as we showed here, the two can be used complementarily to address environmental health issues.

Fourth, due to computational constraints, it was only feasible to run a few mitigation scenarios using a framework that couples several particular models. Although the models we employed are state-of-the-art, it

is true that multi-model ensembles (far beyond the scope of this study, requiring coordinated effort of many modelling teams throughout the world over many years) would ultimately be preferable for characterising uncertainties and the full range of possible outcomes. More model runs (single model or multi-model) would also enable an assessment of the importance of inputs, such as socioeconomic assumptions.

Fifth, several real-world complexities could modulate the conclusions suggested here. For example, if future geopolitical conditions provide a higher likelihood for large international transfers to meet mitigation costs in low-income countries, then LMICs in particular could benefit from larger emission reduction pledges. These pledges could be conditional on financial transfers and yield greater emissions reductions and accompanying air pollution co-benefits. Conversely, if transfers remain unlikely, then LMICs might decide to aim at lower mitigation levels and use the cost savings on end-of-pipe air pollution measures, analogous to our equity and air quality scenario. Further, our modelling of the human system here is limited. Real-world constraints could restrict the rate of near-term emission reductions resulting from these simulations, which would alter detailed results, but not the overall qualitative conclusions of the study.

Finally, we have focused exclusively on country-level impacts. Although countries are a natural unit of analysis when thinking about decision making and about climate justice, impacts will also differ across population subgroups within countries.<sup>91,92</sup> Accounting for impacts both within and across countries would be a more holistic approach to answering questions about equity and justice as it relates to mitigation, and could unify salient objectives from global climate justice with those related to national environmental justice and health disparities.

#### Contributors

Conceptualisation: NS, JS, MFe, FW, FE, WP, MB. Methodology: JS, MFe, WP, FW, SZ, GK, SJS, WP, DT, XY, FD, NS, MB. Modelling: JS, WP, MFe, FW, SZ, GK, WP, DT, XY, PW. Post-modelling data analysis: JS, MFe, FW, FE, WP. Funding acquisition: NS, WP, MB. Project administration: NS, WP, MB. Visualisation: JS, FE. Writing—original draft: NS, WP, MB, JS, NKD. Writing—review and editing: all authors. Accessing and verifying data: WP, JS. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

#### Declaration of interests

We declare no competing interests.

#### Data sharing

All data and code supporting this study's findings are available on a public GitHub repository.

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To access the repository see  
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FrankErrickson/paper\\_2026\\_  
lancet\\_climate\\_health](https://github.com/FrankErrickson/paper_2026_lancet_climate_health)

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# THE LANCET

## Global Health

### Supplementary appendix

This appendix formed part of the original submission and has been peer reviewed. We post it as supplied by the authors.

Supplement to: Scovronick N, Shiwang J, Ferranna M, et al. Global climate justice and the future of air quality co-benefits in low-income and middle-income countries: an energy, climate, and health modelling study. *Lancet Glob Health* 2026; **14**: e512–23.

## SUPPLEMENTARY MATERIAL

### Global climate justice and the future of air quality co-benefits in low-income and middle-income countries: an energy, climate, and health modelling study

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## Supplementary Text: Expanded Methods

### Energy and emission modeling

We used the open-source Global Change Analysis Model<sup>1</sup> (GCAM) to estimate emissions in the future. GCAM is a global human-Earth system model representing the behavior of, and interactions between, five systems: the energy system, water, agriculture and land use, the economy, and the climate. GCAM is calibrated to 2015 and then projects energy and emission patterns at five-year intervals in a partial equilibrium economic modeling framework. For the GCAM version used in this study (v7.0), the energy-economy system operates in 32 regions globally, land is divided into 384 subregions, and water is tracked for 233 basins worldwide. The Earth system module operates at the global scale using the Hector reduced-form climate model.

To estimate the future emissions in the scenarios described above, we first set the Reference scenario with default GCAM7.0 assumptions plus simple adjustments of coal retirement to make it consistent with historical data from the World Energy database. Global emission targets in the 2 °C scenarios are then implemented via a single exogenously specified annual global carbon dioxide (CO<sub>2</sub>) emission trajectory based on the estimated emission budget to reach the 2 °C goal. In the “Least-cost” case, the model computes a uniform global carbon price to reach the global emission target in each time period. In contrast, in the international equity (“Equity”) case, an additional constraint is added specifying the relative ratios of the carbon prices (proportional to country/regional income, e.g. if region A has twice the per capita income of region B at a time, then the carbon price in A must be twice that in B at that time), and then the model computes the regionally differentiated carbon prices that conform to those ratios to reach the same global emission target in each time period.

Future greenhouse gas (GHG) emissions are projected for 32 GCAM regions by technology and by fuel types. CO<sub>2</sub> emissions from fossil fuel consumption and limestone used in cement production are estimated based on global emissions factors by fuel from the CDIAC global inventory.<sup>2</sup> Fugitive emissions from fossil resource production are also included, based on the Community Earth-atmosphere Data System (CEDS) inventory.<sup>3</sup> The land-use and land-cover change emissions are tracked separately. Non-CO<sub>2</sub> GHGs and air pollutants are initialized from the CEDS inventory<sup>3</sup>; we use parameterized functions for future emissions controls (for air pollutants) and Marginal Abatement Cost curves (for GHGs) to change emission factors over time.

### **Air quality modeling**

The air quality simulations were conducted with the three-dimensional chemical transport model GEOS-Chem version 14.0.1.<sup>4</sup> GEOS-Chem is widely used to solve for the evolution of atmospheric aerosols and gases based on meteorological data, global and regional emission inventories, and algorithms that represent the physics and chemistry of atmospheric processes. More details are described in <https://geos-chem.readthedocs.io/en/stable/index.html>.

For 2020, 2030, and 2050, we simulated hourly PM<sub>2.5</sub> concentrations on a 2° latitude × 2.5° longitude grid at 47 vertical layers across the globe for the whole year. The model was run based on full chemistry simulations<sup>5</sup> (O<sub>3</sub>–NO<sub>x</sub>–hydrocarbon–aerosol) in 2020 with a 6-month spin-up starting from July 2019. All the historical and future simulations are driven by assimilated meteorological data for 2019–2020 from Goddard Earth Observing System Forward Processing (GEOS-FP) from the NASA Global Modeling and Assimilation Office (GMAO). The anthropogenic emissions are based on the GCAM downscaled emissions as described in previous sections. The Model of Emissions of Gases and Aerosols from Nature (MEGAN2.1) emissions<sup>6</sup> and Global Fire Emissions Database (GFEDv4) dataset<sup>7</sup> are used for the emissions from biogenic process and wildfires, respectively. Other individual emission sources, such as soil NO<sub>x</sub><sup>8</sup> and lightning NO<sub>x</sub><sup>9</sup>, are also included in these simulations.

We evaluated the base model simulations against ground measurements of PM<sub>2.5</sub> (Supplementary Figure 4) and found that the modelled PM<sub>2.5</sub> concentrations agree well with those datasets, and are comparable to other global simulation studies.<sup>10–12</sup>

### **Climate policy costs**

To quantify climate policy costs, we first mapped out the marginal abatement curve (MAC) for the Least-cost and Equity scenarios and then estimated the area under the MAC curve as the total mitigation policy costs. Specifically, for each of the Least-cost and Equity scenarios, we first add two more GCAM runs that assume the annual global mitigation is 30% and 70% of that in the 2 °C scenario and that mitigation is achieved with global uniform or regionally varying carbon prices, respectively. Then, based on the increase in the mitigation level and the associated increased carbon prices in the four model runs, i.e., Reference, two intermediate mitigation runs, and the Least-cost or the Equity scenario, we are able to map out the non-linear MAC curves for each scenario and for each region. We then sum up the area

under those curves to calculate regional climate policy costs. Notably, under the Equity scenario, for some GCAM regions, including Africa Eastern, Africa Southern, Africa Western, Pakistan, and South Asia, the regional mitigation level in the 30% run ends up higher than the 70% run, which is possibly due to the calculated regional carbon price level and the non-linearity of MAC curves. For simplicity, in these cases, we estimated the MAC and the area under the MAC just based on two scenarios, Reference and the 2 °C Equity scenarios. We then downscaled the mitigation costs to countries within each GCAM region based on size of their economy. Specifically, we use 2022 GDP data<sup>13</sup> and allocate the regional mitigation costs to each country proportional to the country's contribution to regional total GDP.

### **Air quality policy costs**

As an additional experiment, in the fourth scenario only (Equity + AQ), we estimate the costs of reducing air pollution in LMICs in the Equity scenario – where LMICs shoulder relatively less of the mitigation burden – to the levels achieved in the Least-cost scenario through conventional air quality policies, primarily through end-of-pipe controls (as opposed to climate policy). In this way, we are able to estimate the total cost of a scenario where the 2 °C climate target is met through a climate justice approach to mitigation, but where the additional air pollution controls ensure that there is no missed opportunity in terms of health co-benefits in LMICs.

To estimate these air quality control costs, we use the GAINS model, which represents 182 world regions and is designed to explore cost-effective emission control strategies by incorporating information on future economic, energy and agricultural development, emission control potentials and costs, atmospheric dispersion and environmental sensitivities toward air pollution. Air pollution impacts are considered in a multi-pollutant context, quantifying the contributions of SO<sub>2</sub>, NO<sub>x</sub>, NH<sub>3</sub>, non-methane VOCs, and primary emissions of PM<sub>2.5</sub>.

While in principle GAINS covers the whole chain from emissions to impacts, here we use GAINS only to derive marginal abatement cost curves for each relevant pollutant and each GCAM region, using the GAINS optimization module for a set of three scenarios for the year 2030. We then translate these cost curves to the GCAM context for all future years: recognizing that GCAM and GAINS may calculate different baseline emissions, we scale the air pollution emission reduction potentials derived by GAINS with GCAM emissions, at an intermediate level of sectoral aggregation in each of the GCAM regions. We first scale GCAM Equity scenario emissions to GAINS emissions to generate the MAC curve for the GCAM Equity scenario. Then, we apply this scaled MAC curve to calculate the costs of reducing air pollution in

LMICs from the level of the Equity scenario to the level of the Least-cost scenario. With this approximation, we can estimate the magnitude of the costs for reducing the emissions of air pollutants. In particular, for LMICs there typically is a cost associated with reducing the emissions from the level of the Equity scenario to the level of the Least-cost scenario.

We note that this approximation may lead to some discrepancies because the actual air quality policy could be either stronger or weaker than the conditions in any given region. For example, if in the Least-cost scenario, road emissions decline substantially because of electric vehicles, or the penetration of renewables in the power sector causes emission decreases, these might be difficult for some countries to achieve via conventional air pollution control. Conversely, there could be cases where it might be possible for stringent controls to decrease emissions below those in the Least-cost scenario.

### **Climate benefits**

The main reason to implement carbon mitigation is to reduce damages (including health harms) from future climate change. To quantify the climate benefit of achieving 2 °C, we use the Greenhouse Gas Impact Value Estimator (GIVE) model, which was recently developed to provide updated social cost of carbon (SC-CO<sub>2</sub>) estimates for U.S. federal regulatory impact analyses.<sup>14</sup> The SC-CO<sub>2</sub> is a monetized estimate of the climate harms society experiences from emitting one additional ton of carbon dioxide into the atmosphere and is a primary way to account for climate change impacts in policy design and analysis. GIVE accounts for climate impacts from agriculture, heat mortality, energy use, and sea-level rise, and has been thoroughly described elsewhere.<sup>14,15</sup> GIVE quantifies uncertainties in different model components – for example in climate and damage function uncertainties – and propagates compounding uncertainties through the entire computation. In this analysis, we ran GIVE 1,000 times for each GCAM-derived emissions scenario and sampled uncertain climate model and damage function parameters for each model iteration. We further set a seed to ensure GIVE represents the same parametric uncertainty across the different emissions scenarios. The climate benefits are then estimated as the average discounted and income-weighted damages that have been prevented as a result of the mitigation policy.

For computational simplicity we do not estimate sea-level rise damages in this analysis (which requires coupling the Coastal Impact and Adaptation Model to GIVE), but note that sea-level contributes a small fraction of total damages to GIVE's central SC-CO<sub>2</sub> estimate.<sup>14</sup> Also, to ensure that the averted deaths from climate change were valued consistently with the avoided air pollution deaths, we output results

separately for the health and non-health damages. When computing the uncertainty intervals, we calculated the upper and lower intervals for each impact sector across the 1000 model runs.

### Policy ranking

The steps outlined above yield results on the climate policy costs, health co-benefits, and (avoided) climate harms associated with each 2 °C scenario compared to the Reference. As these impacts differ across countries and time, we use a social welfare function (SWF) framework to aggregate the impacts to health and wellbeing along different dimensions, and then rank the scenarios accordingly.<sup>16-18</sup> SWFs have been widely applied in climate economics<sup>16-18</sup> and serve as a useful policy comparison tool because they allow one to incorporate societal preferences for the distribution of impacts both within and across generations.

In practice, and following standard methodologies<sup>19</sup>, we first convert all the impacts into monetary equivalents to have them expressed in a single metric. To determine the monetary equivalent of preventing mortality, we multiply the country- and period-specific number of avoided deaths by country- and period-specific value-per-statistical-life (VSL) estimates. We assume that the VSL is equal to 160 times per-capita Gross Domestic Product (GDP), following guidelines for the conduct of global benefit-cost analysis.<sup>20</sup> Then, for each period, we aggregate the monetary costs and benefits across countries using country- and period-specific weights.<sup>21</sup> The weights represent the relative importance placed on the monetary costs and benefits accruing to people living in different socioeconomic environments (proxied by countries' GDP).<sup>22,23</sup> In particular, the SWF attaches greater weight to the monetary impacts affecting low-income populations relative to higher-income ones on the grounds that an additional dollar to a poor person contributes more to their wellbeing than an additional dollar to a rich person (i.e., the marginal value of money decreases with income).

Finally, we compute the present discounted value of the period-specific weighted sums of costs and benefits<sup>24</sup>:

$$\sum_{t=0}^T e^{-rt} \sum_{c=1}^C \left(\frac{y_{ct}}{y_t}\right)^{-\eta} [VSL_{ct}D_{ct} + Dam_{ct} - M_{ct}]$$

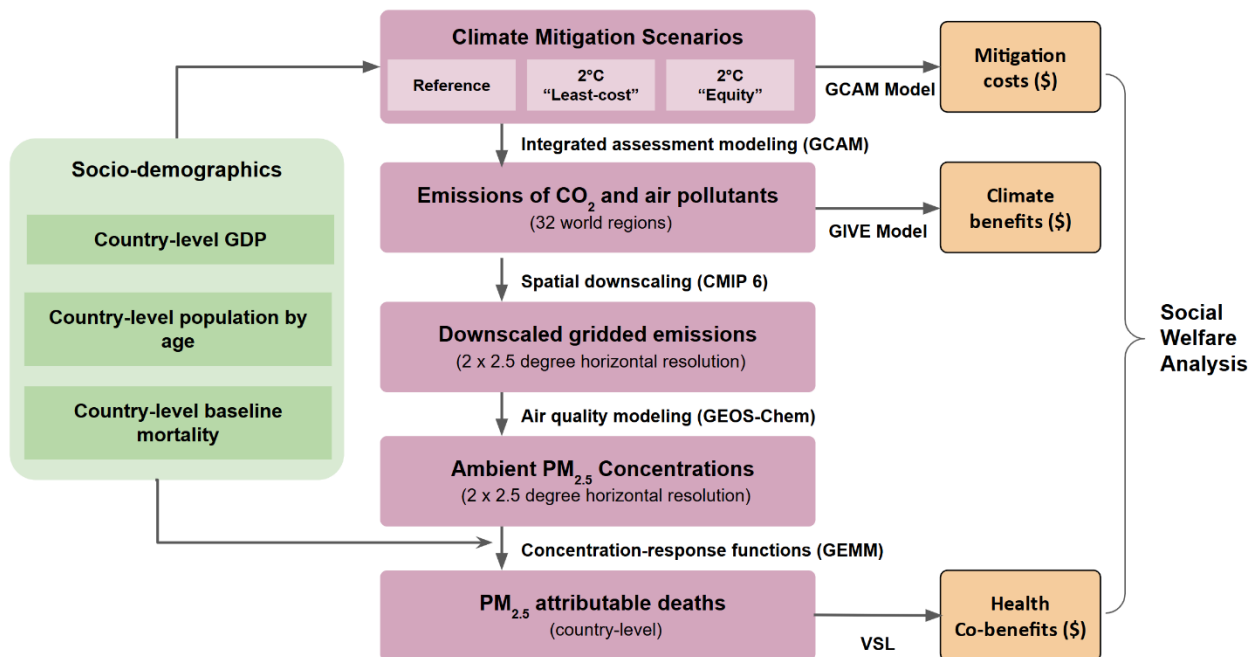
Here,  $D_{ct}$  represents the number of avoided deaths in country  $c$  at time  $t$ ,  $Dam_{ct}$  represents the non-mortality-related avoided climate harms,  $M_{ct}$  are the mitigation costs,  $y_{ct}$  denotes the GDP per-capita in

country  $c$  at time  $t$ ,  $y_t$  is the global GDP per-capita at time  $t$ , and  $r$  is the social discount rate. The discount rate is given by the Ramsey formula<sup>25</sup>:

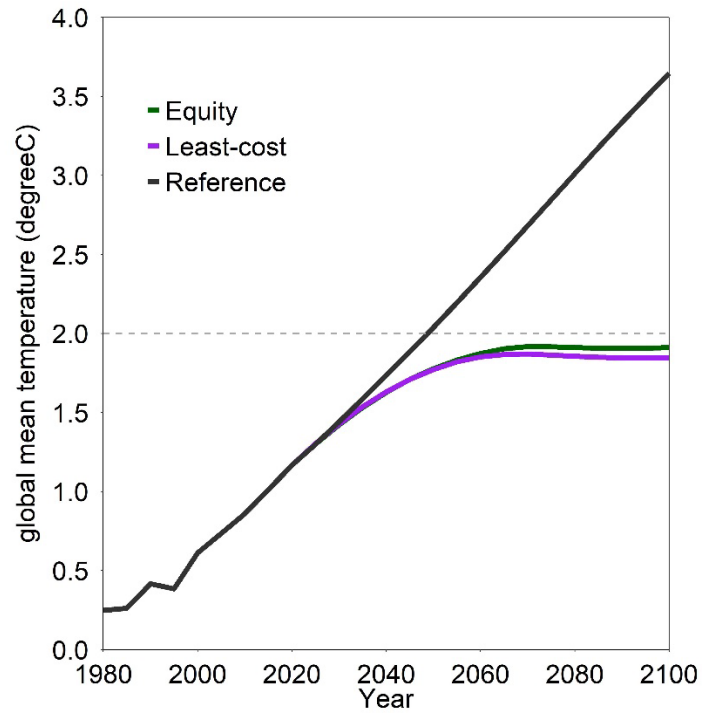
$$r = \rho + \eta g$$

The variable  $g$  represents the annual growth of global GDP per capita. The term  $\rho$  is the pure rate of time preference, which determines how much less wellbeing impacts to future generations are valued relative to today. The term  $\eta$  measures inequality aversion and it captures how much the value of a dollar declines with income. The larger  $\eta$ , the greater the societal concerns for impacts experienced by lower-income countries. Because of economic growth, the term  $\eta$  governs also inter-generational inequality aversion by discounting the costs and benefits affecting future (likely) richer generations.

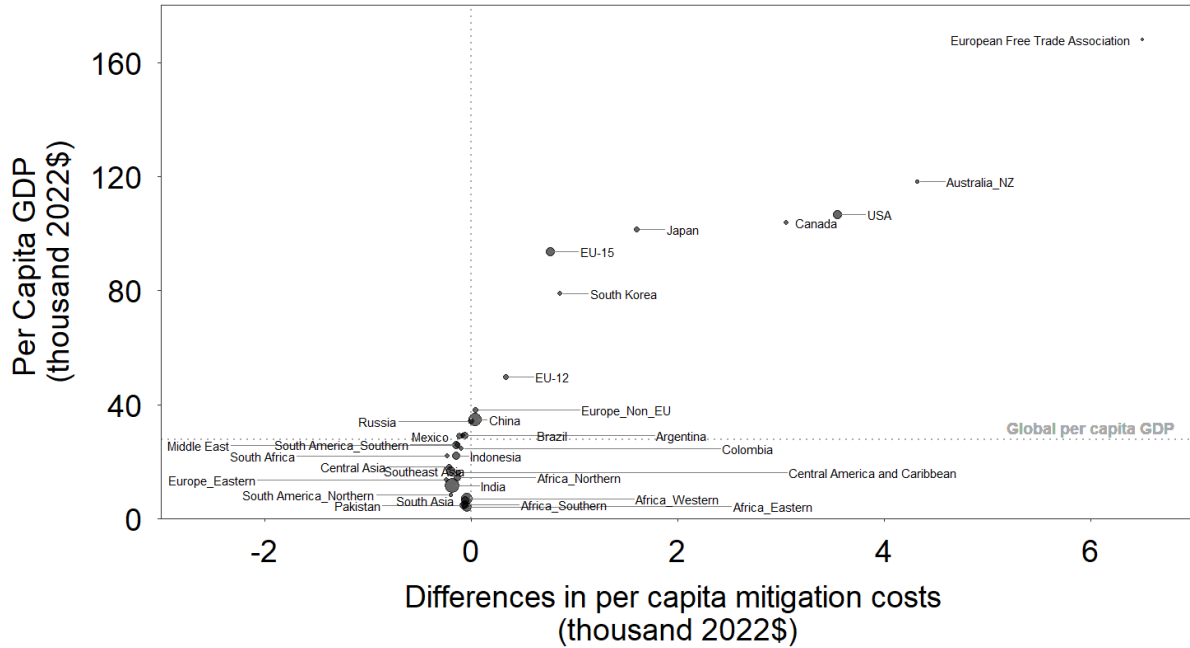
In our main results, we use parameter values of  $\rho=1\%$  and  $\eta=1.5$ . Both parameters can be viewed as a middle-of-the-road value, broadly in line with many governmental recommendations and academic writing.<sup>26,27</sup> For example, a widely-cited expert elicitation reported a mean value for  $\rho$  of 1.1, with a minimum of 0 and a maximum of 8, while for  $\eta$  the mean was 1.35, with a minimum of 0 and a maximum of 5.<sup>27</sup> To account for uncertainty in both parameters, we assess alternative values, but emphasize the  $\eta$  parameter, as a key focus of this paper is equity across countries at different levels of income. To help with interpretation of  $\eta$ , consider an average person in a poor country with an income of \$1,000 compared to one in a richer country with \$10,000. When  $\eta = 0$ , \$1 of benefits produces the same wellbeing for both people. When  $\eta = 1.5$ , \$1 of benefits produces a wellbeing gain roughly thirty times greater for the poorer person relative to the richer one. At  $\eta = 2$  it is roughly 100 times greater; higher values of  $\eta$  continue to increase the welfare gain for the poor compared to the rich. We note that the ranking of policies as a function of  $\eta$  is generally robust to lower values of  $\rho$ , including near-zero values advocated by many in the field (Supplementary Tables 6-7).<sup>28</sup>



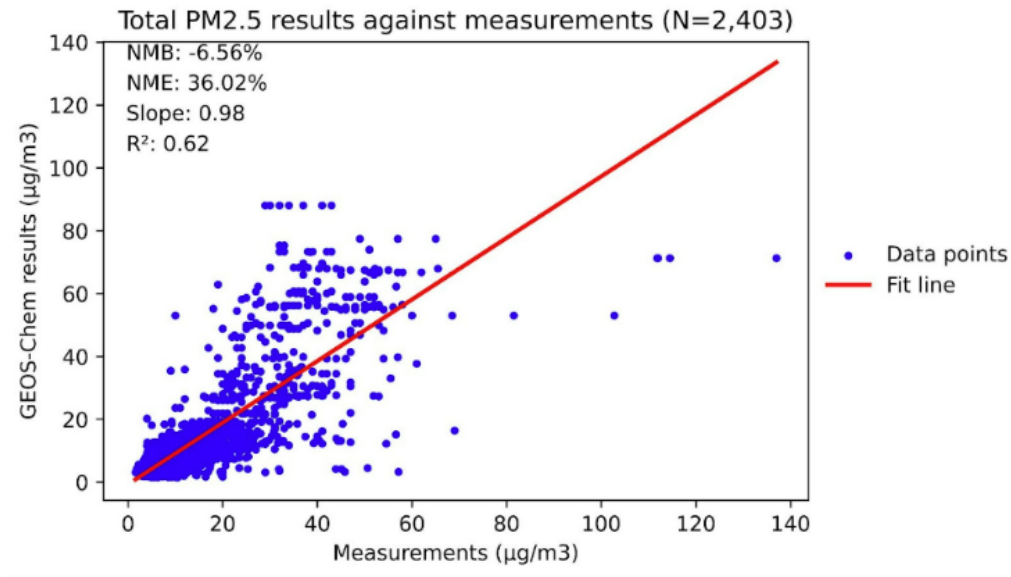
**Supplementary Figure 1. Summary of the modeling approach.** Note that for simplicity we only represent the three core scenarios. The fourth scenario (“Equity+AQ”) builds on the Equity scenario, but uses the GAINS model to add conventional end-of-pipe air quality policies to achieve the level of health co-benefits realized in the Least-cost policy.



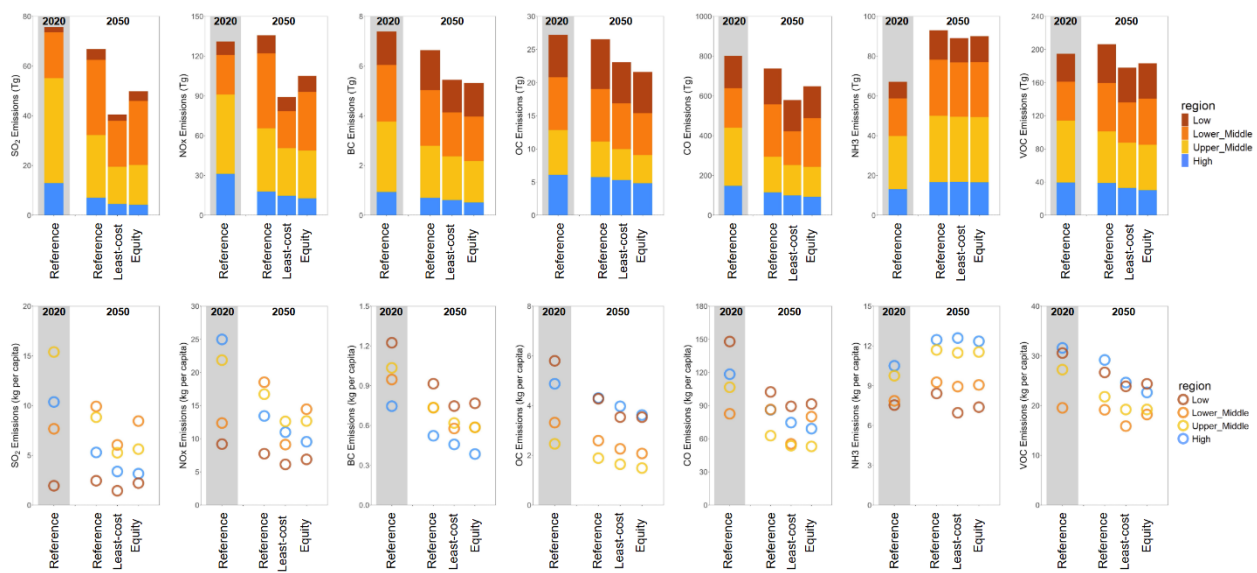
**Supplementary Figure 2: Global mean temperature across scenarios.** The minor differences between Least-cost and Equity are due to differences in non-CO<sub>2</sub> emissions.



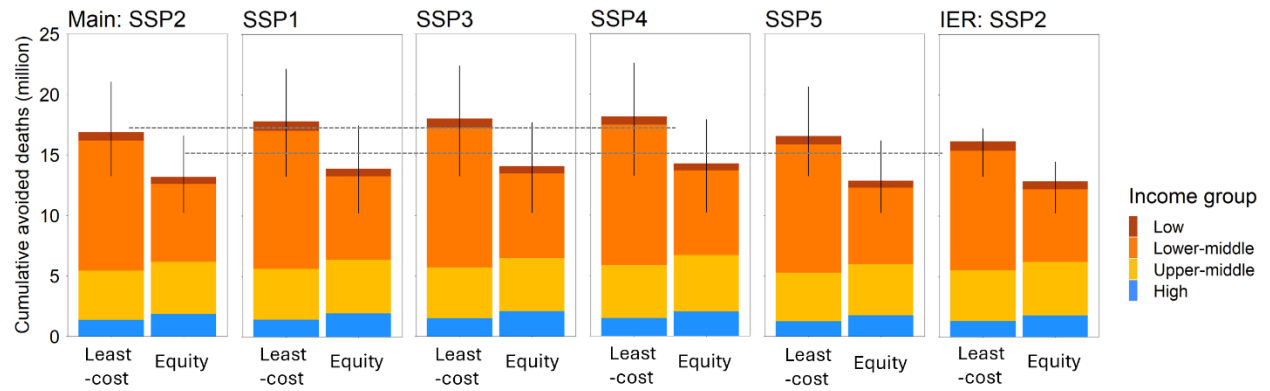
**Supplementary Figure 3. Difference in climate mitigation costs in the Equity compared to the Least-cost scenario in 2050 for each GCAM model region.** In general, regions above global average GDP (here in 2050) pay more in mitigation costs in Equity compared to Least-cost, and vice versa. The size of the dots corresponds to population size.



**Supplementary Figure 4: GEOS-Chem model evaluation.** The observational data is taken from city-level data from the WHO Ambient Air Quality Database<sup>29</sup> (number of cities = 2,403). The GEOS-Chem results are taken for the respective grids where those cities are located. Here we show normalized mean bias (NMB), normalized mean error (NME), the slope and  $R^2$ .

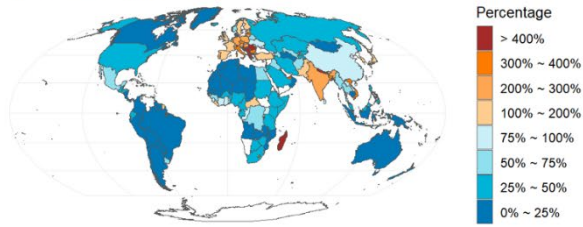


**Supplementary Figure 5: Emissions in 2020 and 2050 in the Reference and 2 °C scenarios, both in absolute (top) and per capita (bottom) terms.**

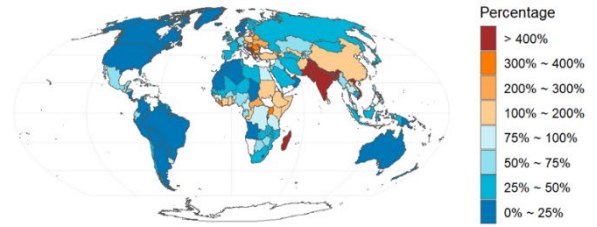


**Supplementary Figure 6. Global distribution of cumulative avoided deaths from air pollution for the main results (left panel), for different SSPs using the Global Exposure Mortality Model (middle four panels), and for SSP2 using the Integrated Exposure Response function (right panel).** Error bars reflect 95% confidence intervals in the concentration-response functions.

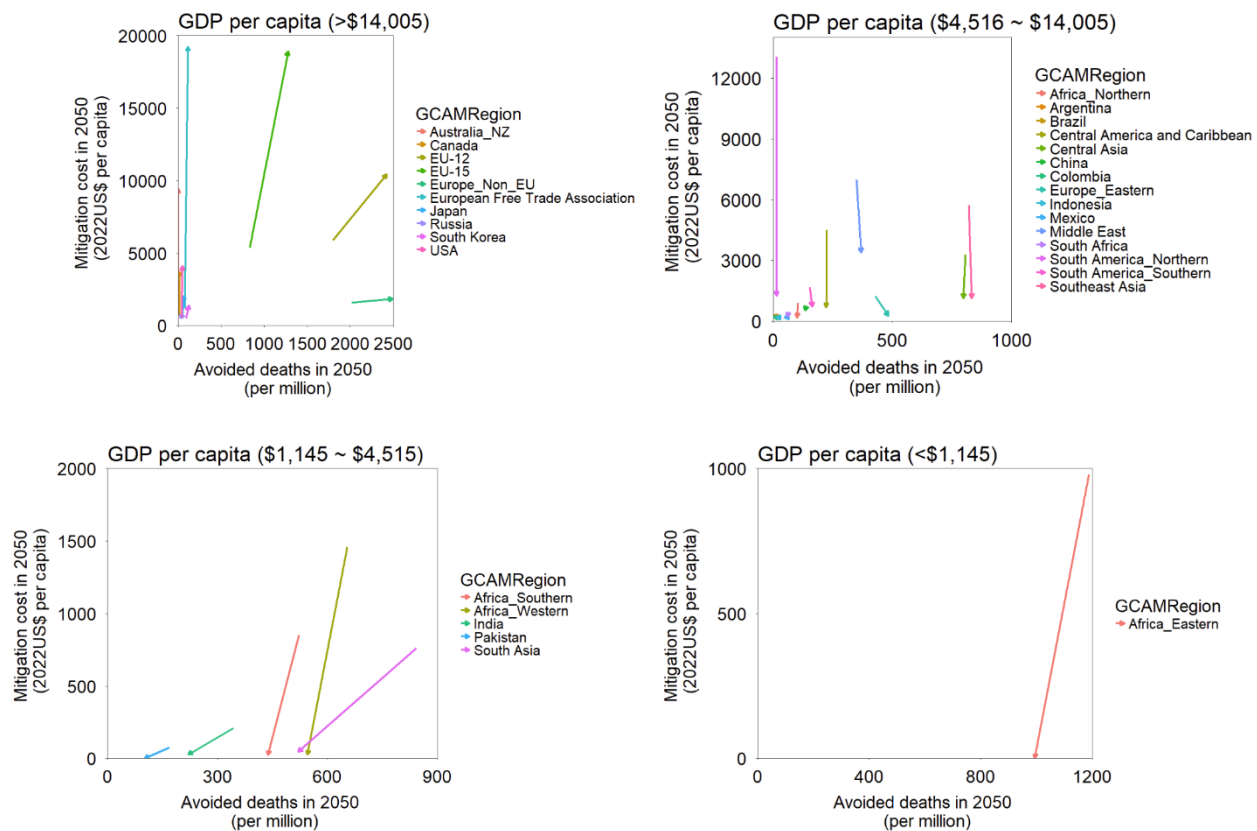
**Least-cost Scenario**



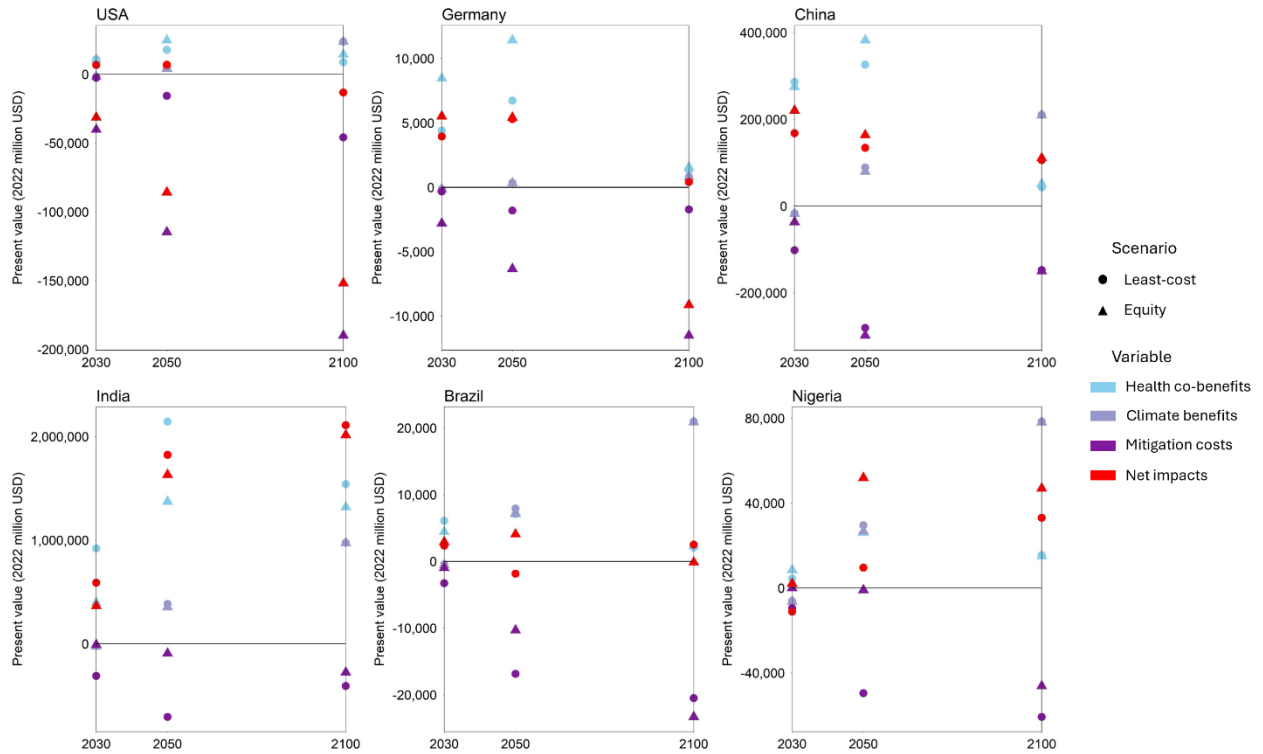
**Equity Scenario**



**Supplementary Figure 7. Percentage of climate mitigation costs that are offset by monetized health co-benefits, 2030-2100.** Costs and benefits are discounted according to the approach outlined in the Methods.

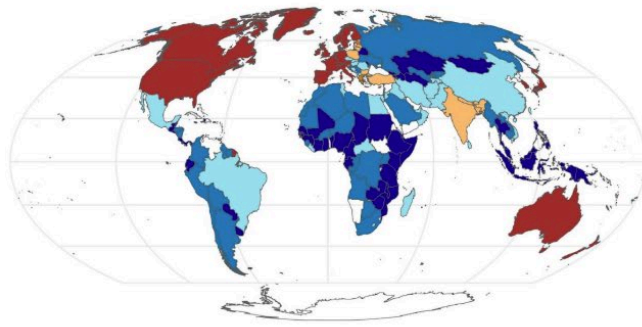


**Supplementary Figure 8. Change in avoided deaths and climate mitigation costs when moving from the Least-cost to the Equity scenario, by current income, for all GCAM model regions.**

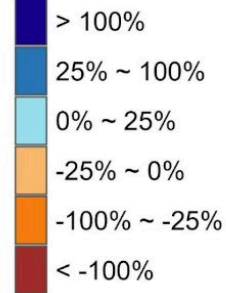


**Supplementary Figure 9. Present value of the different impacts, and the net impact, for select countries in 2030, 2050 and 2100.** The figure illustrates that the evolution of the impacts differs; for example, the present value of the health co-benefits tends to decline after 2050, whereas climate benefits generally increase.

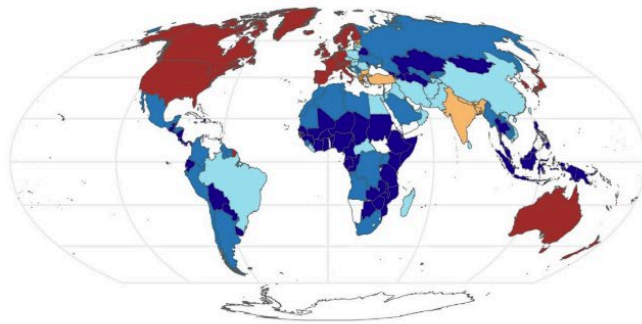
a)  $\eta = 1$



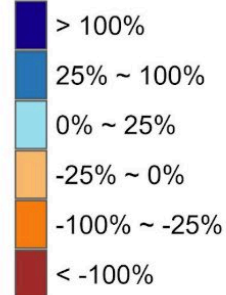
Percent Change



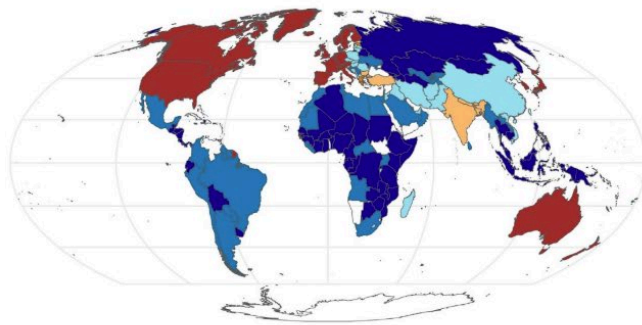
b)  $\eta = 1.5$



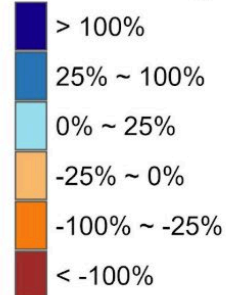
Percent Change



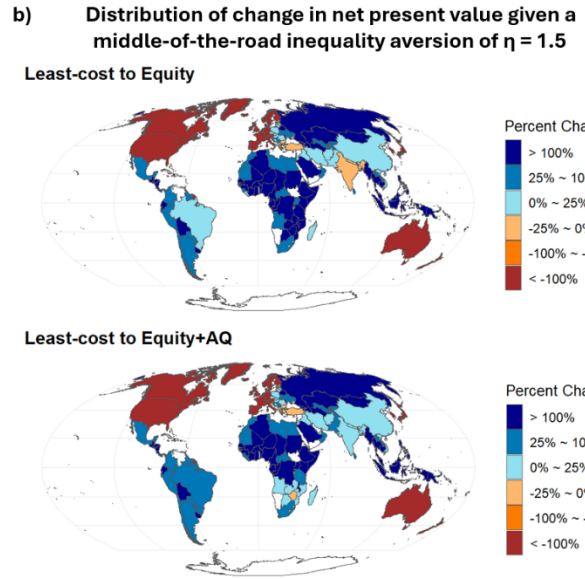
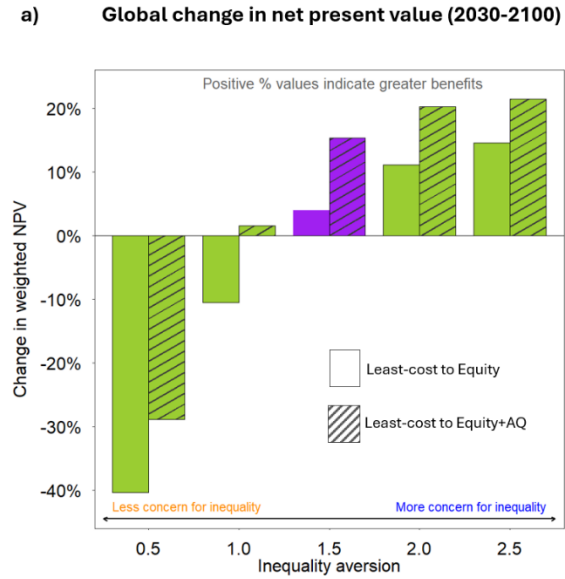
c)  $\eta = 2$



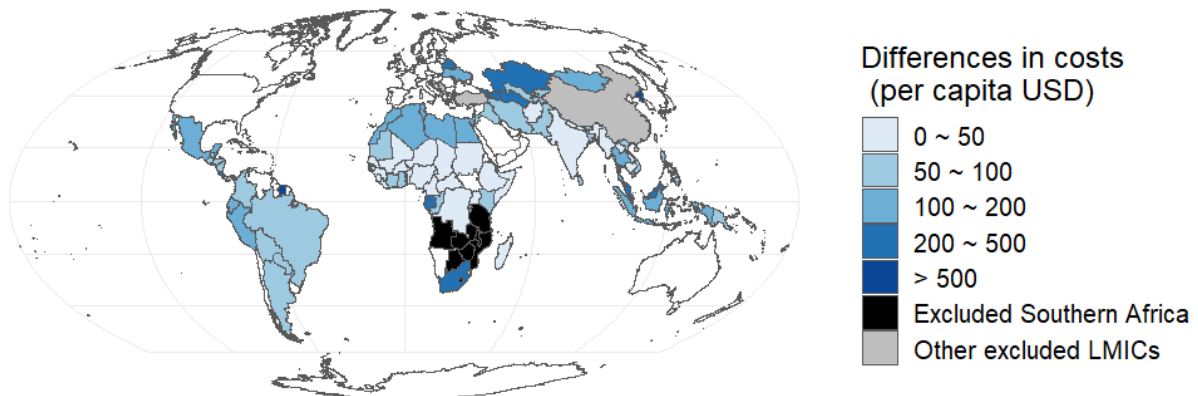
Percent Change



**Supplementary Figure 10. Change in Net Present Value when moving from the Least-cost to the Equity scenario (2030-2100) by country given different levels of inequality aversion ( $\eta$ ).** To help with the interpretation of  $\eta$ , consider an average person in a poor country with an income of \$1,000 compared to one in a richer country with \$10,000. When  $\eta = 1.5$ , \$1 of benefits produces a welfare gain roughly thirty times greater for the poorer person relative to the richer one. Increasing  $\eta$  weights the person in the poor country even more, and vice versa. Here the rate of pure time preference is set at 1% per year, but results with other values are reported in Supplementary Table 6.



**Supplementary Figure 11. Change in Net Present Value – a measure of wellbeing – when moving from the Least-cost to the Equity or Equity+AQ scenario (2030-2100) both (a) globally given different levels of inequality aversion, and (b,c) by country given a middle-of-the-road inequality aversion of  $\eta = 1.5$ .** A positive change in NPV means that the Equity scenario provides overall more net benefits than the Least-cost scenario. To help with the interpretation of  $\eta$ , consider an average person in a poor country with an income of \$1,000 compared to one in a richer country with \$10,000. When  $\eta = 1.5$ , \$1 of benefits produces a welfare gain roughly thirty times greater for the poorer person relative to the richer one. Increasing  $\eta$  (i.e. moving to the right along the x-axis) weights the person in the poor country even more, and vice versa. Here the rate of pure time preference is set at 1% per year, but results with other values are reported in Supplementary Tables 6-7.



**Supplementary Figure 12. Difference between the mitigation cost savings in Equity for LMICs and the air quality control costs needed to achieve the air pollution reductions in Least-cost in 2050.** Higher numbers indicate that there are greater cost savings in Equity+AQ to achieve the same air pollution reductions as in Least-cost. A small number of relatively high income LMICs (e.g., China, Turkey), represented in grey, are excluded because they have higher costs in the Equity scenario due to their income level. A small number of LMICs in Southern Africa were excluded because a uniquely large discrepancy between the GCAM and GAINS models renders the comparison unreliable for that specific model region.

**Supplementary Table 1. Regions in the GCAM model.**

<b>GCAM Region</b>	<b>Countries</b>
<b>Africa_Eastern</b>	<b>Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda</b>
<b>Africa_Northern</b>	<b>Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia</b>
<b>Africa_Southern</b>	<b>Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe</b>
<b>Africa_Western</b>	<b>Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo</b>
<b>Argentina</b>	<b>Argentina</b>
<b>Australia_NZ</b>	<b>Australia, New Zealand</b>
<b>Brazil</b>	<b>Brazil</b>
<b>Canada</b>	<b>Canada</b>
<b>Central America and the Caribbean</b>	<b>Aruba, Anguilla, Netherlands Antilles, Antigua &amp; Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines</b>
<b>Central Asia</b>	<b>Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan</b>
<b>China</b>	<b>China</b>
<b>Colombia</b>	<b>Colombia</b>
<b>EU-12</b>	<b>Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia</b>
<b>EU-15</b>	<b>Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom</b>
<b>Europe_Eastern</b>	<b>Belarus, Moldova, Ukraine</b>

<b>European Free Trade Association</b>	<b>Iceland, Norway, Switzerland</b>
<b>Europe_Non_EU</b>	<b>Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey</b>
<b>India</b>	<b>India</b>
<b>Indonesia</b>	<b>Indonesia</b>
<b>Japan</b>	<b>Japan</b>
<b>Mexico</b>	<b>Mexico</b>
<b>Middle East</b>	<b>United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen</b>
<b>Pakistan</b>	<b>Pakistan</b>
<b>Russia</b>	<b>Russia</b>
<b>South Africa</b>	<b>South Africa</b>
<b>South America_Northern</b>	<b>French Guiana, Guyana, Suriname, Venezuela</b>
<b>South America_Southern</b>	<b>Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay</b>
<b>South Asia</b>	<b>Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal</b>
<b>Southeast Asia</b>	<b>American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic Peoples Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa</b>
<b>South Korea</b>	<b>South Korea</b>
<b>Taiwan</b>	<b>Taiwan</b>
<b>USA</b>	<b>United States</b>



**Supplementary Table 2. CO<sub>2</sub> emissions in 2020 and 2050 by World Bank income groupings.**

Total emissions, in Gt CO<sub>2</sub> are outside parentheses, and per capita emissions, in t CO<sub>2</sub> are inside parentheses.

	<b>2020 Low</b>	<b>2020 Lower-middle</b>	<b>2020 Upper-middle</b>	<b>2020 High</b>	<b>2050 Low</b>	<b>2050 Lower-middle</b>	<b>2050 Upper-middle</b>	<b>2050 High</b>
<b>Reference</b>	0.53 (0.91)	5.78 (2.03)	20.24 (7.47)	14.42 (10.64)	0.94 (0.97)	13.28 (3.54)	24.15 (8.68)	17.00 (11.46)
<b>Least-cost</b>	-	-	-	-	-0.16 (-0.17)	3.99 (1.06)	8.03 (2.89)	6.14 (4.14)
<b>Equity</b>	-	-	-	-	0.31 (0.32)	9.09 (2.42)	10.99 (3.95)	-2.33 (-1.57)

**Supplementary Table 3. Population-weighted concentrations ( $\mu\text{g}/\text{m}^3$ ) of  $\text{PM}_{2.5}$  in 2020 and 2050 in each scenario for different country income groups.** LMIC = Low- and middle-income countries as a single group.

	<b>2020</b>	<b>2050 Reference</b>	<b>2050 Least-cost</b>	<b>2050 Equity</b>
High income	8.1	6.9	5.8	5.3
LMICs	23.2	23.8	17.6	19.1
Upper middle income	16.9	14.1	11.5	11.1
Lower middle income	31.0	33.2	23.3	26.5
Low income	14.4	15.2	13.0	13.4

**Supplementary Table 4. Point estimates and confidence bands for the net benefits by income group and scenario, in per capita net present value.**

	<b>Low-income</b>	<b>Lower-middle income</b>	<b>Upper-middle income</b>	<b>High income</b>	<b>Total</b>
<b>Least-cost</b>	94,511 (11,693 to 204,909)	54,223 (12,287 to 98,034)	4,722 (-5,910 to 20,663)	1,959 (-2,136 to 7,203)	31,283 (3,408 to 64,239)
<b>Equity</b>	115,627 (34,419 to 224,367)	54,802 (18,112 to 95, 010)	7,243 (-3,778 to 23, 512)	-8,639 (-13,309 to -2,857)	32,296 (6,393 to 63, 896)

**Supplementary Table 5. Ratio of net benefits from the Least-cost to the Equity scenarios using the GEMM concentration-response function and the IER concentration-response function.**

Positive values indicate that the Equity scenario is preferred, and negative values indicate that the Least Cost scenario is preferred.

	<b>Low-income</b>	<b>Lower-middle income</b>	<b>Upper-middle income</b>	<b>High income</b>
<b>GEMM</b>	1.223	1.011	1.534	-4.410
<b>IER</b>	1.211	1.044	1.512	-5.143

**Supplementary Table 6. Percent change in the global equity-weighted net present value when moving from the Least-cost to the Equity scenario given different values for inequality aversion ( $\eta$ ) and pure time preference ( $\rho$ ).** Positive values indicate that the Equity scenario provides greater benefits.

	$\rho=0.1\%$	$\rho=0.5\%$	$\rho=1.0\%$	$\rho=1.5\%$	$\rho=2.0\%$	$\rho=5.0\%$
$\eta=0.5$	-39.5	-39.8	-40.1	-40.3	-40.6	-41.3
$\eta=1$	-11.4	-11.1	-10.8	-10.5	-10.1	-6.9
$\eta=1.5$	2.1	2.6	3.2	3.9	4.7	9.8
$\eta=2$	8.2	8.9	10.0	11.1	12.2	20.0
$\eta=2.5$	10.6	11.6	13.0	14.5	16.1	27.2

**Supplementary Table 7. Percent change in global equity-weighted net present value when moving from the Least-cost (top) or Equity (bottom) scenario to the Equity + AQ scenario given different values for inequality aversion ( $\eta$ ) and pure time preference ( $\rho$ ). Positive values indicate that the Equity+AQ scenario provides greater benefits.**

	Move from Least-cost to Equity+AQ					
	$\rho=0.1\%$	$\rho=0.5\%$	$\rho=1.0\%$	$\rho=1.5\%$	$\rho=2.0\%$	$\rho=5.0\%$
$\eta=0.5$	-28.6	-28.7	-28.8	-28.9	-29.0	-29.3
$\eta=1$	0.0	0.4	0.9	1.5	2.1	5.9
$\eta=1.5$	12.5	13.2	14.2	15.3	16.3	22.7
$\eta=2$	16.1	17.2	18.6	20.2	21.8	31.9
$\eta=2.5$	16.1	17.4	19.3	21.4	23.5	38.3

	Move from Equity to Equity+AQ					
	$\rho=0.1\%$	$\rho=0.5\%$	$\rho=1.0\%$	$\rho=1.5\%$	$\rho=2.0\%$	$\rho=5.0\%$
$\eta=0.5$	18.1	18.4	18.8	19.2	19.5	20.4
$\eta=1$	12.8	13.0	13.2	13.4	13.6	13.8
$\eta=1.5$	10.2	10.4	10.6	10.9	11.1	11.7
$\eta=2$	7.3	7.6	7.9	8.2	8.5	9.9
$\eta=2.5$	4.9	5.2	5.6	6.0	6.4	8.7

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