Inequalities in air pollution exposure and attributable mortality in a low carbon future

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Abstract

Understanding the costs and benefits of climate change mitigation and adaptation options is crucial to justify and prioritise future decarbonisation pathways to achieve net zero. Here, we quantified the co-benefits of decarbonisation for air quality and public health under scenarios that aim to limit end-of-century warming to 2ºC and 1.5ºC. We estimated the mortality burden attributable to ambient $PM_{2.5}$ exposure using population attributable fractions of relative risk, incorporating projected changes in population demographics. We found that implementation of decarbonisation scenarios could produce substantial global reductions in population exposure to $PM_{2.5}$ pollution and associated premature mortality, with maximum health benefits achieved in Asia around mid-century. The stringent 1.5ºC-compliant decarbonisation scenario (SSP1-1.9) could reduce the $PM_{2.5}$-attributable mortality burden by 29% in 2050 relative to SSP2-4.5, averting around 2.9M annual deaths worldwide. While all income groups were found to benefit from improved air quality through decarbonisation, the smallest health benefits are experienced by the low-income population. The disparity in $PM_{2.5}$ exposure across income groups is projected to reduce by 2100, but a 30% disparity between high- and low- income groups persists even in the strongest mitigation scenario. Further, without additional and targeted air quality measures, low- and lower-middle-income populations (predominantly in Africa and Asia) will continue to experience $PM_{2.5}$ exposures that are over three times the World Health Organization (WHO) Air Quality Guideline.

Key Points:

- Decarbonisation has the potential to generate substantial health co-benefits by averting millions of premature deaths associated with $PM_{2.5}$ exposure across all income groups.
- The low-income population is predicted to experience the smallest health benefits of decarbonation and continue to be exposed to $PM_{2.5}$ concentrations that are over three times that of the WHO Air Quality Guideline.
- Under a decarbonisation future pathway, the global socioeconomic disparity in $PM_{2.5}$ exposure reduces but persists at around 30% by the end of the century.

Plain Language Summary

Implementation of decarbonisation strategies to mitigate future climate change can provide additional benefits or "co-benefits" through improved air quality and public health. Quantifying these benefits and how they manifest across different world regions and income groups is essential to incentivise climate action. In this work we have quantified the air pollution health co-benefits for three different possible future scenarios: one 'middle-of-the-road' scenario and two decarbonisation scenarios. We found that by following a future decarbonisation pathway instead of a 'middle-of-the-road' pathway, can generate substantial air quality and public health benefits worldwide, particularly in Asia around 2050. While all income groups were found to benefit from improved air quality through decarbonisation, the smallest health benefits are experienced by the low-income population. Inequalities in air pollution exposure between the lower-income and high-income groups were found to reduce rapidly under a decarbonisation pathway, but persist through to 2100 even under the strongest mitigation. Further, without additional and targeted air quality measures, low- and lower-middle-income populations (predominantly in Africa and Asia) will continue to experience air pollution levels that exceed the World Health Organization Air Quality Guideline.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment report confirmed the need for rapid reductions in both carbon dioxide emissions and in emissions of other greenhouse gases (GHGs) such as methane by 2030 (Riahi et al., 2022). These reductions towards a mid-century net zero target are the minimum necessary to satisfy the Paris Agreement temperature goals. At the same time actual policies are falling short (UNEP, 2022). Climate change mitigation can be incentivised by the realisation of co-benefits, such as improved health, wealth, air quality, water availability, and access to nature (IPCC, 2022). These benefits and where they fall are poorly quantified, leading to difficulties designing co-benefits into specific policies and interventions. Here we detail the quantification of one possible co-benefit of future decarbonisation: air quality health effects.

Long-term exposure to ambient fine particulate matter ($PM_{2.5}$) is associated with a range of negative health outcomes including cardiovascular diseases, respiratory diseases, lung cancer, and subsequent premature mortality (Yuan et al., 2019; Chen and Hoek, 2020; Yu et al., 2021; Zhu et al., 2021; Liu et al., 2021; Park et al., 2021). At present, exposure to ambient $PM_{2.5}$ pollution is the largest environmental risk factor for disease and premature death globally (GBD 2019 Risk Factor Collaborators, 2020). Previous studies have demonstrated that emissions from the combustion of fossil fuels (coal, oil, and natural gas) are a major contributor to the global premature mortality burden attributable to ambient $PM_{2.5}$ exposure (Lelieveld et al., 2019; McDuffie et al., 2021; Vohra et al., 2021). Emissions from residential combustion of coal or solid biofuel are a major contributer to regional ambient $PM_{2.5}$-attributable premature mortality, particularly across South and East Asia (Reddington et al., 2019) and West Africa (Gordon et al., 2023). Over recent decades, emission control efforts have delivered notable reductions in $PM_{2.5}$ exposure across some regions, such as North America (Butt et al., 2017) and Europe (Turnock et al., 2016), and more recently in China (e.g., Silver et al., 2020a,b; Conibear et al., 2022a). Despite the reductions across these regions, ambient $PM_{2.5}$ exposure has been increasing globally, with increases mainly occurring in countries with a low to middle socioeconomic status e.g., countries in South Asia, Southeast Asia, North Africa, West Africa, and the Middle East (GBD 2019 Risk Factor Collaborators, 2020). The increases in $PM_{2.5}$ exposure in these regions are likely to be linked to changes in anthropogenic air pollutant emissions (e.g., Koplitz et al., 2017; Xu et al., 2019; Shi et al., 2020; Ospiov et al., 2022), although other factors may play a role.

Ambient $PM_{2.5}$ pollution exposure is often greater in populations with a lower socioeconomic status compared to those with a high socioeconomic status (Hajat et al., 2015; Miao et al., 2015; Fairburn et al., 2019), with low- and middle-income countries in Asia and Africa experiencing some of the highest $PM_{2.5}$ concentrations globally (Shaddick et al., 2020; WHO, 2022). Sub-national $PM_{2.5}$ exposure inequalities are also observed in countries with a high level of income and overall health inequality such as the United States (Y. Wang et al., 2017; Colmer et al., 2020; Jbaily et al., 2022). These inequalities can be partly explained by the non-linear relationship between $PM_{2.5}$ exposure and socioeconomic development. Ambient $PM_{2.5}$ concentrations tend to increase with industrialisation and per-capita GDP, and then subsequently decrease as air quality control measures are introduced with increasing resources and awareness of the health implications (S. Wang et al., 2017; Lim et al., 2020). Futhermore, higher-income countries/regions have in some cases 'outsourced' their manufacturing (and associated air pollutant emissions) to lower-income countries/regions with less stringent air pollution controls (Zhang et al., 2017; Xia et al., 2018), which can exacerbate the disparities (Nansai et al., 2020). Additional drivers of inequality in ambient air pollution exposure arise from polluting activities that are predominantly undertaken by poorer communities (Reddington et al., 2021; Rao et al., 2021).

Inequities in $PM_{2.5}$ exposure can be compounded by other socioeconomic factors that increase the vulnerability and disease susceptibility of a population, such as poor healthcare and nutrition (O'Neill et al., 2003) and population ageing (Conibear et al., 2018a; Rafaj et al., 2021). Lower-income countries tend to suffer from reduced access to healthcare (O'Neill et al., 2003), while high-income countries tend to have older (more vulnerable) populations than low- and middle-income countries (United Nations, 2019). Overall, despite current differences in population vulnerability, 92% of the 2019 ambient $PM_{2.5}$-attributable mortality burden was in low- and middle-income countries (GBD Collaborative Network, 2020). Even accounting for differences in population size, the ambient $PM_{2.5}$-attributable mortality rates in middle-income countries were 2-3 times greater than in high-income countries (GBD Collaborative Network, 2020). Rapid increases in population age in the least developed countries may increase this disparity, with two-thirds of the global population aged 60 years and over expected to live in lower- and middle-income countries by 2050 (United Nations, 2019). The extent to which socioeconomic disparities in ambient $PM_{2.5}$ pollution exposure and health impacts will continue in the future, as low- and middle-income populations develop economically and address their air quality problems, has not yet been examined.

Improvements in air quality and public health can be achieved by implementing climate mitigation strategies that involve reductions of both GHG emissions and co-emitted air pollutants (West et al., 2013; Silva et al., 2016; Chowdhury et al., 2018; Shindell et al., 2018; Fujimori et al., 2020; Amann et al., 2020; Hamilton et al., 2021). The estimated global economic value of these air quality and health co-benefits could potentially offset the costs of climate change policy implementation and GHG reductions (West et al., 2013; Markandya et al., 2018; Vandyck et al., 2018; Scovronick et al., 2019; Sampedro et al., 2020; Aleluia Reis et al., 2022). However, it is important to note that proposed climate mitigation / net-zero measures can have a range of impacts on air quality (Royal Society, 2021). A number of specific measures that would likely yield the largest co-benefits for climate and air quality have been highlighted in recent reports (UNEP, 2019; Royal Society, 2021; UNESCAP, 2023). Overall, the greatest health benefits are likely to result from implementation of climate mitigation policies in combination with stringent air pollution control measures (Likhvar et al., 2015; Rao et al., 2016; Partanen et al., 2018; Amann et al., 2020; Harmsen et al., 2020; Rafaj et al., 2021; Shim et al., 2021; Conibear et al., 2022b).

The new Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014) combine a range of potential future climate policies with varying degrees of air pollution control (Rao et al., 2016). Recent studies have assessed the impacts of the SSPs on global air quality (Turnock et al., 2020; Allen et al., 2020; Shim et al., 2021) and public health in Africa (Shindell et al., 2022), China (Wang et al., 2022) and globally (Yang et al., 2023; Turnock et al., 2023), demonstrating that strong mitigation of both climate and air pollutants in the SSPs could yield large reductions in $PM_{2.5}$ concentrations across all world regions. Turnock et al. (2023) showed that there are potential penalties to the future air pollution health burden in some world regions due to a warming climate that could offset benefits from reductions in air pollutant emissions, highlighting the importance of mitigating both climate and anthropogenic air pollution sources simultaneously.

Here, we examine and quantify the air quality and health co-benefits of future decarbonisation pathways that were designed with the aim of meeting the Paris Agreement temperature targets of 2°C and 1.5°C by the end of the century. This is the first multi-model quantification of future global $PM_{2.5}$-attributable health impacts of the 2°C- and 1.5°C-compliant SSP1 scenarios using the current generation of Earth system models, which account for changes in both emissions and climate and simulate non-linear impacts of climate change on $PM_{2.5}$ concentrations. We examine how $PM_{2.5}$ exposure and associated health outcomes under different decarbonisation scenarios vary with socioeconomic status, and we make the first quantification of future socioeconomic disparities in $PM_{2.5}$-exposure and health.

2 Data and Methods

Here we briefly describe the emission scenarios, models, and health impact assessment methodology used. The methods are described in further detail in the supplementary material (see Sect. S1). Our results are reported for six continental regions (shown in Fig. S1) and for four socioeconomic groups (see Sect. 2.4).

2.1 Future baseline and decarbonisation scenarios

We used existing model data from experiments conducted as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) by the latest generation of Earth system and climate models. The CMIP6 model simulations were driven by prescribed GHG concentrations based on future scenarios that combine a particular climate mitigation target (in terms of an anthropogenic radiative forcing reached by 2100) and the range of emission mitigation measures necessary to achieve it, within the social, economic, and environmental developments of the individual SSP (O'Neill et al., 2014; 2016; Riahi et al., 2017). We selected three future scenarios (SSP2-4.5, SSP1-2.6, and SSP1-1.9) used in the future experiments conducted as part of the Scenario Model Intercomparison Project (ScenarioMIP; O'Neill et al. 2016), a sub-MIP of CMIP6. The scenario selected to be our future baseline, SSP2-4.5, combines the "Middle-of-the-Road" socioeconomic development of SSP2, with a medium radiative forcing target of 4.5 W m^{-2} by 2100. The mitigation (decarbonisation) scenarios used in this study combine the "Sustainable development" pathway of SSP1 with the lower end of the range of future forcing pathways aimed to limit warming to either well below 2°C (with a radiative forcing target of 2.6 W m^{-2}; SSP1-2.6) or below 1.5°C (with a radiative forcing target of 1.9 W m^{-2}; SSP1-1.9) by 2100.

The underlying SSP storylines include varying degrees of air pollution emission controls, with the implementation and strength of the controls linked to socioeconomic development (Rao et al., 2017). The SSP associated with our future baseline scenario SSP2-4.5 includes "medium strength" air pollution controls, which means that the implementation of air pollution controls is assumed to continue along current national trajectories with some 'catch-up' assumed for lower-income countries, where emission controls are achieved at lower income levels than when higher-income countries began controls (Rao et al., 2017). Over the 21st century, it assumed that air pollution concentration targets become more ambitious, and the enforcement of these targets becomes increasingly effective (Rao et al., 2017). The combination of medium strength air pollution controls and climate mitigation in SSP2-4.5 results in an eventual decrease in global air pollutant emissions (Gidden et al., 2019). The SSP associated with the decarbonisation scenarios SSP1-1.9 and SSP1-2.6, includes "strong" air pollution controls, which means that ambitious and stringent air pollution controls are assumed to be implemented rapidly across high-income countries, with successful achievement air pollutant targets that go beyond current legislation in the medium to long term (Rao et al., 2017). Lower-income countries are assumed to catch-up relatively quickly with high-income countries (Rao et al., 2017). The combination of strong air pollution controls and stringent climate mitigation in SSP1-1.9 and SSP1-2.6 results in relatively rapid reductions in global air pollutant emissions (Gidden et al., 2019).

2.2 CMIP6 model simulations

To investigate future changes in $PM_{2.5}$ pollution between 2015 and 2100, we calculated global surface distributions of $PM_{2.5}$ concentrations using data from five CMIP6 models (see Table S1) with data available for the SSP2-4.5, SSP1-2.6, and SSP1-1.9 experiments. Simulated surface $PM_{2.5}$ concentrations were calculated at the native model grid and then re-gridded to a consistent horizontal grid, before generating multi-model means for five-year time intervals between 2015 and 2100. To improve the representation of real-world ambient $PM_{2.5}$ concentrations for the health impact assessment, the present-day CMIP6-simulated $PM_{2.5}$ data were corrected to observation-based estimates of $PM_{2.5}$ concentrations from van Donkelaar et al.

(2021). The steps involved in processing and observationally-correcting the data are described in Sect. S1.1 and shown in Fig. S2. The sensitivity of including additional aerosol components in the calculation of future changes in multi-model mean $PM_{2.5}$ concentrations is explored in Sect. S2.

2.3 Health impact assessment

We performed an air pollution health impact assessment to estimate the future premature mortality burden attributable to long-term exposure to ambient $PM_{2.5}$ concentrations under the different model scenarios, using population attributable fractions of relative risk following Conibear et al. (2022b). The relative risk for a specific $PM_{2.5}$ exposure and population age group was estimated using the Global Exposure Mortality Model (GEMM) (Burnett et al., 2018). Long-term $PM_{2.5}$ exposure was calculated as the population-weighted five-year mean $PM_{2.5}$ concentrations from the observationally-corrected CMIP6 multi-model mean data (at 0.125° × 0.125° resoultion). We used the GEMM for non-accidental mortality (non-communicable disease (NCD) plus lower respiratory infections (LRI)) for adults over 25 years of age, with age-specific risk function parameters for each 5-year age group between 25 and 80+ years (Burnett et al., 2018). The uncertainty range in our $PM_{2.5}$-attributable premature mortality estimates was calculated based on the derived uncertainty intervals at the 95% confidence level from the GEMM exposure-outcome association (Burnett et al., 2018). Henceforth in the paper we refer to the $PM_{2.5}$-attributable premature mortality burden as the $PM_{2.5}$-attributable mortality burden. Futher details on the health impact assessment calculation can be found in Sect. S1.2.

We chose to use the GEMM in our health impact assessment framework as it is based only on cohort studies of exposure to ambient $PM_{2.5}$ concentrations and has been used in several recent studies to quantify future $PM_{2.5}$-attributable mortality burdens under different scenarios (Conibear et al., 2022b; Shindell et al., 2022; Wang et al., 2022; Yang et al., 2023; Turnock et al., 2023). For completeness, the results calculated in this study using the GEMM are compared with those calculated using the recent function from Weichenthal et al. (2022) (combined with the Fusion function from Burnett et al. (2022)) in Sect. S3.

For each country, current and future cause-specific (NCD and LRI) baseline mortality rates and population age structure were taken from International Futures (IFs) for adults aged 25 to 80 years in 5-year age intervals and for 80 years plus (Frederick S. Pardee Center for International Futures, 2021). Current and future global gridded population count at a resolution of 0.125° × 0.125° was taken from Jones and O'Neill (2016; 2020). Future changes in global population count follow the SSP2 pathway (Jones and O'Neill 2016; 2020; Fig. S3) to be consistent with our baseline scenario (SSP2-4.5). Future changes in baseline mortality rates and population age structure follow the IFs "Base Case" (or "Current Path") scenario (Turner et al., 2017)), which is closest to SSP2 of all the SSPs in terms of storyline (Hughes and Narayan, 2021), but is slightly more pessimistic in terms of projections of some outcomes (Hughes et al., 2019; Burgess et al., 2023). We assumed that the current and future population (count and age structure) and baseline mortality rates were kept the same for all three scenarios (SSP1-1.9, SSP1-2.6, and SSP2-4.5) in order to isolate the effects of the differences in projected air pollutant emissions and simulated $PM_{2.5}$ concentrations on future $PM_{2.5}$ exposure and attributable mortality.

2.4 Income groups

We grouped the global population into four socioeconomic groups (low-, lower-middle-, upper-middle-, and high-income; Fig. S4) based on population-weighted per-capita gross domestic product (GDP), following the method of Alizadeh et al. (2022). We advance the method of Alizadeh et al. (2022) by using future projected GDP data for the years of 2020 to 2100 in 10-year intervals, rather than fixed values for 2015. We used global gridded, spatially downscaled GDP data at the 1/12-degree grid scale from Murakami et al. (2021), which accounts for sub-national (population-level) variability in GDP. We selected GDP data that develop in line with economic development of the SSP2 pathway, with moderate economic growth projected for existing major cities, to be consistent with our baseline scenario (SSP2-4.5) and the population and health datasets (Sect. 2.3). We assumed that the global SSP2 GDP data stays fixed for each 10-year period, so for the intermediate five-year time intervals (i.e., 2015-2019, 2025-2029, 2035-2039,… etc.) we used the GDP data from the starting year of the following decade (i.e., 2020, 2030, 2040,… etc.).

To calculate GDP per capita, the gridded GDP dataset was regridded to match the grid resolution of the population data (0.125° x 0.125°) and divided by the SSP2 population count for the corresponding time period. As in Alizadeh et al. (2022), the weight for each grid cell was calculated by normalising its population count by the total global population count. The boundaries of the income groups were calculated for each 10-year time period as the population-weighted 25th, 50th,, and 75th quantiles of the per-capita GDP distribution, which meant that the population count was similar across the income groups for each time period. In simple terms, the low-income population group (referred to as a "region" in our results following Alizadeh et al. (2022)) represents the population with the lowest-quartile per-capita GDP globally.

We note that the identification of the socioeconomic status of a region or population is complex (Hajat et al., 2021) and the measure used here to classify income groups is one of many different measures used in the air pollution health literature. Our estimated population-weighted country-level income classifications for 2020 are comparable to those assigned by the World Bank based on national values of gross national income (GNI) per capita in 2020 (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups).

3 Results

3.1 Future air pollution exposure

Global $PM_{2.5}$ exposure is projected to reduce considerably during the 21st century under both the baseline scenario (SSP2-4.5) and the decarbonisation scenarios (SSP1-2.6, SSP1-1.9). Under SSP2-4.5, global $PM_{2.5}$ exposure reduces from 28.5 μg m^{-3} in 2015-2019 to 16.9 μg m^{-3} in 2095-2099. Relative to SSP2-4.5, the decarbonisation scenarios consistently produce greater reductions in global $PM_{2.5}$ exposure: by 22% (SSP1-2.6) and 26% (SSP1-1.9) on average across the 21st century. Several factors are responsible for the model-simulated changes in global $PM_{2.5}$ concentrations, including future changes in anthropogenic emissions, natural emissions, and climate. However, the predicted reductions in $PM_{2.5}$ in the decarbonisation scenarios are likely to be driven mainly by the projected reductions in primary anthropogenic emissions of organic carbon (Fig. S5), black carbon, and sulphur dioxide, resulting from the implementation of stringent air pollution controls and climate change mitigation policies. The CMIP6 models include changes in natural aerosol, such as mineral dust and biogenic SOA, in response to changes in climate, which likely drive the diversity in model estimates of $PM_{2.5}$ exposure in some regions (e.g., Shindell et al., 2022). We note that the projected future changes in $PM_{2.5}$ exposure shown in our results do not include simulated future changes in nitrate and ammonium aerosol concentrations, which likely results in an underestimation in the overall simulated changes in $PM_{2.5}$ exposure in each scenario (see Sect. S2).

The magnitude, timing, and rate of reductions in $PM_{2.5}$ exposure vary strongly between the different scenarios and between different regions of the world. Figure 1 shows the variation in simulated $PM_{2.5}$ exposure, calculated as population-weighted five-year mean $PM_{2.5}$ concentration, in six continental regions (Fig. S1) under the three scenarios between 2015 and 2100. In the Americas and Asia, the decarbonisation scenarios produce consistent reductions in $PM_{2.5}$ exposures relative to the baseline across the 21st century, with average reductions between 2015 and 2100 of 13-16% in South & Central America, 20-24% in North America, and 26-32% in Asia. In Europe, $PM_{2.5}$ exposure is similar in all three scenarios up to around 2030, after which we see the additional air quality benefits from decarbonisation. Hence, over the course of the 21st century overall, the decarbonisation scenarios produce average reductions of 16% and 19% relative to the baseline across Europe. In Africa, the decarbonisation scenarios lead to an air quality penalty towards the end of the century, where the baseline $PM_{2.5}$ exposure decreases beyond the levels predicted by SSP1-2.6 and SSP1-1.9 (as a result of the projected changes in anthropogenic aerosol emissions; Fig. S5). However, the decarbonisation scenarios predict strong reductions in $PM_{2.5}$ exposure relative to the baseline during mid-century, leading to overall average reductions of 13-15%. In Oceania, present-day $PM_{2.5}$ exposures are relatively low and are predicted to reduce by small amounts towards 2100 under the decarbonisation scenarios, relative to the baseline (by 5% on average). Under SSP1-1.9, $PM_{2.5}$ exposure in Oceania is projected to increase by ~1 μg m^{-3} between 2035 and 2045, which is driven by carbonaceous aerosol emissions from forest burning (see Figs. S5f and S6; Gidden et al., 2019).

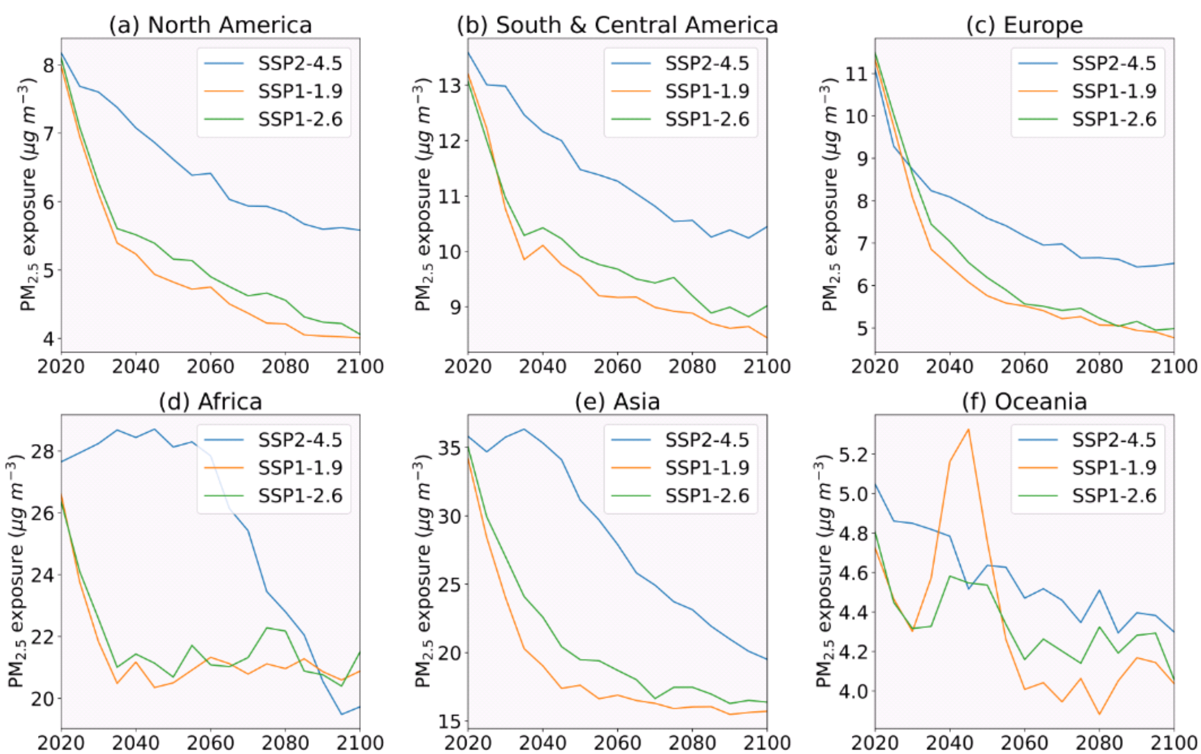

Figure 1. Variation in predicted $PM_{2.5}$ exposures between 2015 and 2100 under the baseline scenario, SSP2-4.5, and two decarbonisation scenarios, SSP1-2.6 and SSP1-1.9, in six continental regions. $PM_{2.5}$ exposure was calculated as the population-weighted five-year mean $PM_{2.5}$ concentration in each region from 2015-2019 to 2095-2099 (plotted as 2020 to 2100). $PM_{2.5}$ concentrations are from the observation-corrected multi-model mean CMIP6 data. The multi-model diversity in predicted $PM_{2.5}$ exposures is not shown in order to be able distinguish the multi-model mean values under each scenario more clearly.

3.2 Future air pollution exposure by income region

Relative to present day, $PM_{2.5}$ exposure is predicted to reduce across all four income regions (low, lower-middle, upper-middle, and high) by the end of the century, under the three future scenarios (Fig. 2). The predicted reduction in $PM_{2.5}$ exposure from present-day levels is largest in the lower-middle-income region (49-54%) and smallest in the high-income region (22-30%). However, populations in the high-income region are consistently exposed to the lowest $PM_{2.5}$ concentrations of all four socioeconomic groups across the century. The highest $PM_{2.5}$ exposures are experienced by populations in the low- and lower-middle-income regions.

In the baseline scenario (SSP2-4.5) the $PM_{2.5}$ exposures in the low and lower-middle income regions are predicted to increase initially towards 2040, and then decrease towards 2100. In the decarbonisation scenarios (SSP1-2.6, SSP1-1.9), all income regions experience relatively rapid reductions in $PM_{2.5}$ exposure up to around 2040. The predicted reductions in $PM_{2.5}$ exposure in the low-income region in SSP1-2.6 and SSP1-1.9 are not as strong as for the lower-middle-income region. Thus, during the latter half of the century the low-income region experiences the highest $PM_{2.5}$ exposure of all the socioeconomic groups. These projected changes in $PM_{2.5}$ exposure across the income groups remain consistent with the inclusion of future changes in nitrate and ammonium aerosol in the $PM_{2.5}$ calculation (see Sect. S2, Figs. S7 and S8).

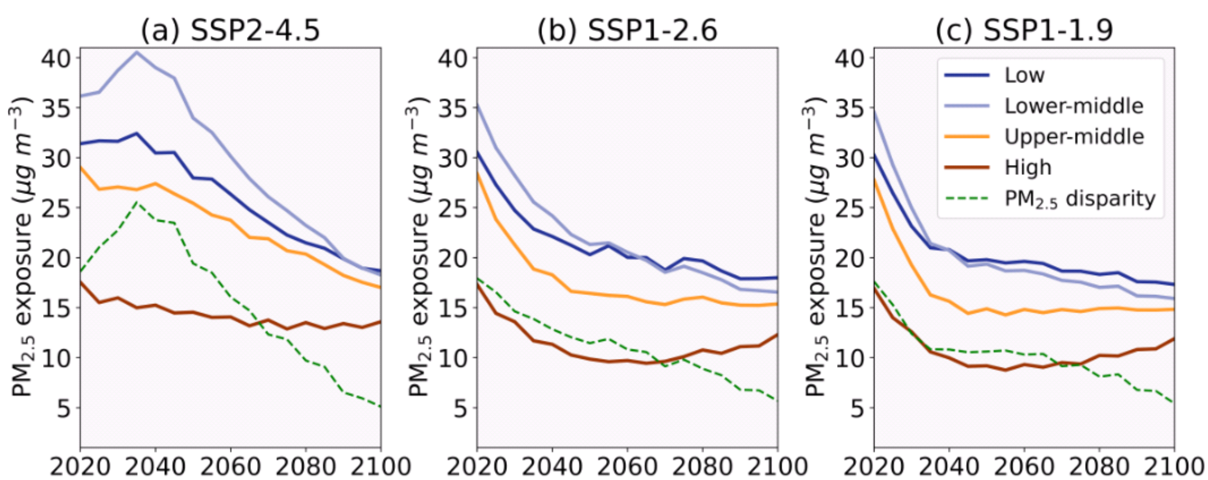

Figure 2. Variation in predicted $PM_{2.5}$ exposures in four income regions (low, lower-middle, upper-middle, and high) between 2015 and 2100 under the (a) baseline scenario, SSP2-4.5, and two decarbonisation scenarios, (b) SSP1-2.6 and (c) SSP1-1.9. The dashed line shows the "$PM_{2.5}$ disparity": the difference between the income regions with the greatest and lowest $PM_{2.5}$ exposures in each five-year interval. $PM_{2.5}$ exposure was calculated as the population-weighted five-year mean $PM_{2.5}$ concentration in each income region from 2015-2019 to 2095-2099 (plotted as 2020 to 2100). $PM_{2.5}$ concentrations are from the observation-corrected multi-model mean CMIP6 data. The income regions are calculated based on the population-weighted per-capita GDP. The projected population count and GDP data, and thus the regions within each socioeconomic group, vary with time in 10-year intervals.

Populations in Asia make up largest share of the total lower-middle- and upper-middle-income populations across the century (51-74%; Fig. S9), hence the magnitude and temporal pattern of $PM_{2.5}$ exposure for these income regions in Fig. 2 are comparable to Fig. 1e. While populations in Asia also make up a large proportion of the low-income region population (38-48%), populations in Africa make up the largest proportion (39-53%), which explains why the reduction in $PM_{2.5}$ exposure is weaker beyond ~2030 than for the lower-middle-income region under the decarbonisation scenarios (Figs. 2b and 2c), resembling Fig. 1d. The regional contribution to the high-income population is more mixed, with large contributions from Asia (45-54%), North America (14-22%), and Europe (12-24%) (Fig. S9). Towards the end of the century, there is an increasing contribution of populations in Africa (with relatively high $PM_{2.5}$ exposure) to the high-income population (up to 19%), which is why there is a small increase in $PM_{2.5}$ exposure beyond 2070 for this income region in Figs. 2b and 2c.

The global socioeconomic disparity in $PM_{2.5}$ exposure is predicted to reduce by the end of the century, but remain considerable, under all three scenarios (Fig. 2). Under SSP2-4.5, the difference in the 2015-2019 mean $PM_{2.5}$ exposure between the high-income region and the income region experiencing the greatest exposure (lower-middle) is 18.6 μg m^{-3} (51%), increasing up to 25.5 μg m^{-3} (63%) around 2035, and then reducing to 5.1 μg m^{-3} (27%) by the end of the century. Under the decarbonisation scenarios, the $PM_{2.5}$-exposure disparity continually decreases from present-day; going from 17.6 μg m^{-3} (51%) in 2015-2019 between the high- and lower-middle-income regions to 5.4 μg m^{-3} (31%) in 2095-2099 between the high- and low-income regions under SSP1-1.9. Overall, these results demonstrate that a range of future anthropogenic emission pathways could act to reduce the global inequality in $PM_{2.5}$ exposure by the end of the century. However, immediate reduction in the global $PM_{2.5}$ exposure inequalities in the near term, is only achieved under a decarbonisation scenario.

3.3 Future compliance with the WHO Air Quality Guideline

Across the 21st century, the decarbonisation scenarios consistently result in greater proportions of the global population moving into compliance with the WHO Air Quality Guideline (AQG) for $PM_{2.5}$ of 5 μg m^{-3} annual mean concentration (WHO, 2021), when compared to the baseline scenario. Figure 3a shows the fraction of the worlds' population exposed to ambient $PM_{2.5}$ concentrations within the AQG as predicted by the three scenarios for selected years. In 2095-2099, the decarbonisation scenarios produce a 52% (SSP1-2.6) and 61% (SSP1-1.9) increase in the population exposed to AQG-compliant $PM_{2.5}$ concentrations, relative to the baseline scenario. This suggests that by following a decarbonisation pathway, an additional 0.45-0.53 billion people could have a significantly reduced risk to acute and chronic health effects associated with $PM_{2.5}$ pollution by the end of the century. However, it is important to note that even with the strongest air pollution controls, as implemented in SSP1-1.9 and SS1-2.6, a large fraction of the worlds' population (~85%) remains exposed to concentrations above the AQG at the end of the 21^{st} century.

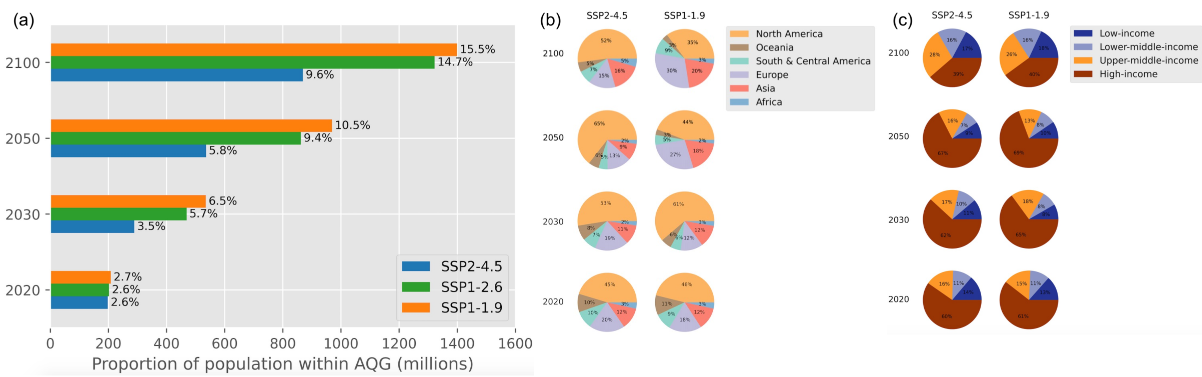

Figure 3. (a) Proportion of the global population exposed to $PM_{2.5}$ concentrations in compliance with the WHO Air Quality Guideline (AQG) for $PM_{2.5}$ (5 μg m^{-3}) as predicted by the baseline scenario (SSP2-4.5) and the decarbonisation scenarios (SSP1-2.6 and SSP1-1.9). **(b)** The relative contribution of six continental regions to the AQG-compliant population as predicted by scenarios SSP2-4.5 and SSP1-1.9. **(c)** The relative contribution of the four income regions (low, lower-middle, upper-middle, and high) to the AQG-compliant population as predicted by scenarios SSP2-4.5 and SSP1-1.9. Results are shown for selected time intervals: 2015-2019 (shown as 2020), 2025-2029 (shown as 2030), 2045-2049 (shown as 2050) and 2095-2099 (shown as 2100).

The North American population are predicted to make up the largest fraction (35-65%) of the population exposed to $PM_{2.5}$ concentrations within the AQG, under both the baseline and decarbonisation scenarios (Fig. 3b), despite making up only 7-8% of the total global population (see Fig. S3). The next largest fractions of the global AQG-compliant population are from Europe (12-30%; whilst making up 8-10% of the global population) and Asia (9-20%; whilst making up 49-60% of the global population), which increase under SSP1-1.9 towards 2100. The proportions of the populations *within* Europe and Asia that are compliant with the AQG increase strongly under SSP1-1.9 from 5% and <1% in 2015-2019 to 60% and 6% in 2095-2099, respectively (see Fig. S10). The fractional contributions of Oceania (3-11%) and South & Central America (5-10%) to the global AQG-compliant population are relatively small and decrease towards 2100 as the contributions from Europe and Asia increase (Fig. 3b). However, *within* South & Central America, the proportion of the AQG-compliant population increases strongly under SSP1-1.9 from 4% in 2015-2019 to 25% in 2095-2099 (Fig. S10). Oceania has the greatest proportion of its population in compliance with the AQG of all regions (Fig. S10; evident by the low exposures in Fig. 1f), which increases under both scenarios from 58-66% in 2015-2019 to 83-86% in 2095-2099. The African population make up the smallest fraction of the global AQG-compliant population under both scenarios (≤5%; Fig. 3b), despite a 16-29% contribution to the global population (Fig. S3), with little change across the century (decarbonisation generally reduces future $PM_{2.5}$ exposure in Africa (Fig. 1d), but not to levels below the AQG). Africa has the smallest proportion of its population in compliance with the AQG of all six regions, increasing from 0.6% in 2015-2019 to just 1.5% in 2095-2099 under SSP1-1.9 (Fig. S10).

Across the century, the high-income region accounts for the largest fraction of the global AQG-compliant population under all three scenarios, with low- and lower-middle-income regions accounting for the smallest fractions (Fig. 3c). In the middle of the century, 65-67% of the AQG-compliant population is in the high-income region, with only 8-9% in the low-income region and 7-8% in the lower-middle-income region. At the end of the century, the proportion of the AQG-compliant population in the high-income region is smaller (39-40%) but remains over twice that in the low-income region (17-18%) and the lower-middle-income region (16%).

Across the century, low- and lower-middle-income populations consistently have greater proportions that remain exposed to $PM_{2.5}$ concentrations *above* the AQG than high-income populations. Under the decarbonisation scenarios, 89-91% of the low- and lower-middle-income populations remain exposed to $PM_{2.5}$ concentrations that are not in compliance with the AQG at the end of the century, compared to 75-76% of the high-income population. Therefore, although global $PM_{2.5}$ inequalities are projected to reduce in the future, they persist even under the strongest mitigation scenario.

3.4 Impacts of decarbonisation on future air pollution-associated mortality

We estimate the global $PM_{2.5}$-attributable mortality burden for 2015-2019 to be 6.61 (95% confidence interval (CI): 5.49 - 7.68) million annual premature deaths (see Table S2 and discussion in Sect. S3). Under the baseline scenario (SSP2-4.5), the global $PM_{2.5}$-attributable mortality burden is predicted to increase from present day towards 2075 (despite reductions in global $PM_{2.5}$ exposure) following projected increases in global population and population ageing, then decrease slowly towards the end of the century to 10.34 (95% CI: 8.53 – 12.10) million annual deaths. Projected changes in population demographics can have a strong influence on estimates of the future $PM_{2.5}$-attributable mortality burden (see Sect. S4 and Figs. S11-S13), as found in previous studies (Conibear et al., 2018a; 2022b; Rafaj et al., 2021; Turnock et al., 2023; Yang et al., 2023). In general, increasing population count and age act to increase the future $PM_{2.5}$-attributable mortality burden, while decreasing baseline mortality rates act to moderate this future increase, although there are interesting differences in these drivers across income regions (Fig. S11) and continental regions (Fig. S13).

Relative to the baseline scenario, the decarbonisation scenarios consistently produce reduced global annual $PM_{2.5}$-attributable mortality burdens across the 21st century (see the "all varying" line in Fig. S12). Figure 4 shows that the annual mortality burden that could be averted by following a decarbonisation scenario instead of the baseline scenario is greatest around mid-century (when decarbonisation is predicted to drive the largest reductions in $PM_{2.5}$ exposure; Fig. 1) and then decreases towards 2100 (see also Table S2). Following the SSP1-2.6 scenario could avert 2.48 (95% CI: 2.09-2.84) million annual premature deaths worldwide in 2045-2049, and 0.99 (95% CI: 0.82-1.15) million annual premature deaths in 2095-2099. Following the SSP1-1.9 scenario could avert 2.95 (95% CI: 2.48-3.38) million annual premature mortalities in 2045-2049, and 1.24 (95 CI: 1.03-1.44) million annual premature deaths in 2095-2099. We note that the magnitude of future changes in total and averted $PM_{2.5}$-attributable mortality burdens may be underestimated here due to the exclusion of simulated future changes in nitrate and ammonium aerosol concentrations (see Sect. S2).

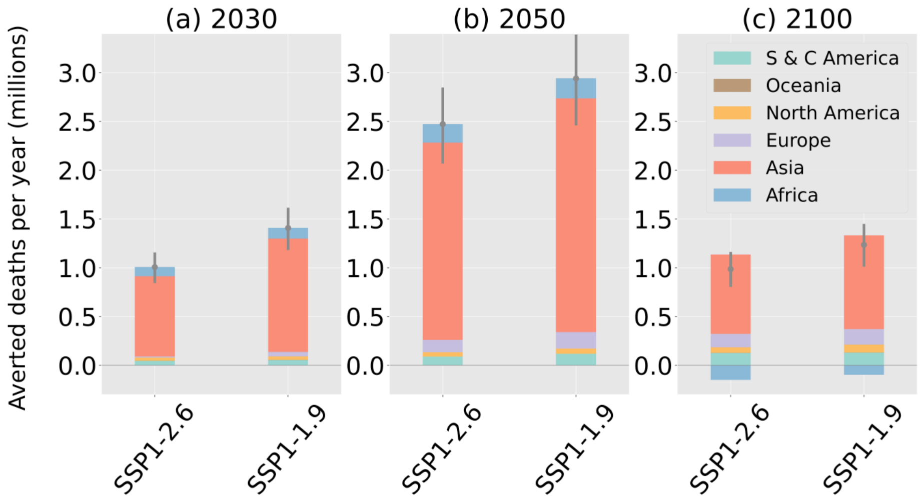

Figure 4. Global averted $PM_{2.5}$-attributable premature mortality burden that could be achieved by following the decarbonisation scenarios (SSP1-1.9 or SSP1-2.6) relative to the baseline scenario (SSP2-4.5) for (a) 2025-2029 shown as 2030, (b) 2045-2049 shown as 2050, and (c) 2095-2099 shown as 2100. The $PM_{2.5}$-attributable premature mortality burden was calculated for adults aged 25 years and older. Error bars represent the upper and lower mortality estimates (the 95% confidence interval) due to the uncertainty in the GEMM health function.

Across the 21st century, substantial public health benefits relative to the baseline scenario could be achieved in most continental regions by following either of the decarbonisation scenarios. Figure 5 shows the regional averted $PM_{2.5}$-attributable premature mortality per 100,000 head of total population of all ages (or "mortality rate"). The averted mortality rate depends on the $PM_{2.5}$ exposure levels predicted by the baseline and decarbonisation scenarios, in addition to projected changes in baseline mortality and population ageing. The mortality rate is not dependent on projected changes in future population count, allowing values to be more easily compared between continental regions.

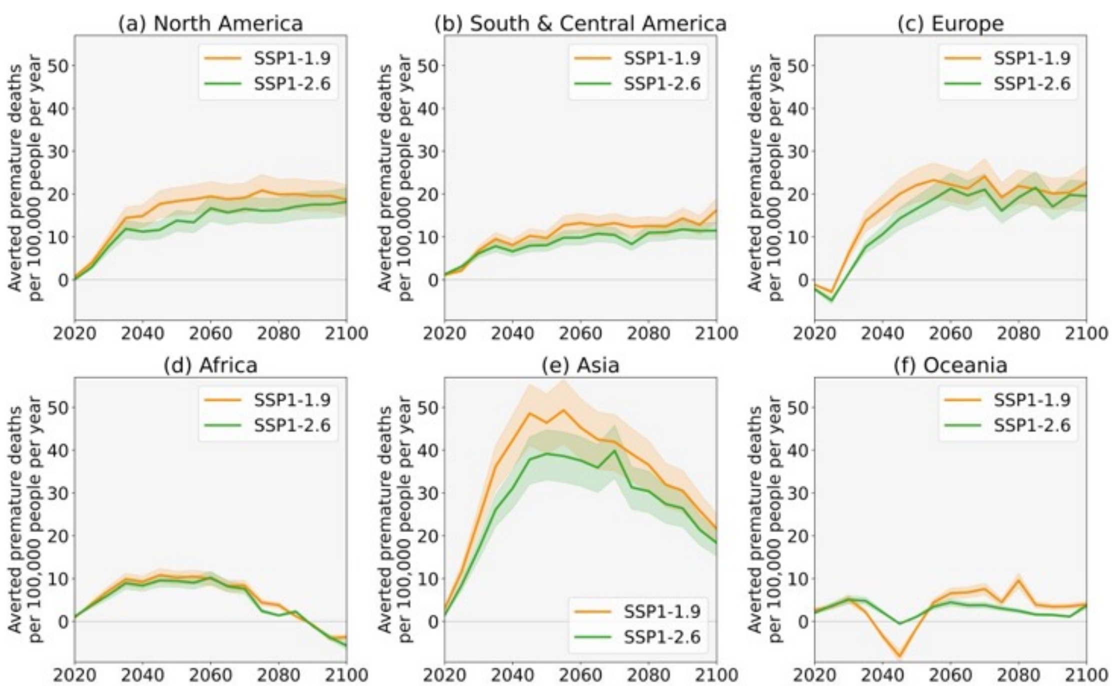

Figure 5. Averted annual $PM_{2.5}$-attributable premature mortality burden in continental regions over 2015–2100 that could be achieved by following the decarbonisation scenarios (SSP1-1.9 or SSP1-2.6) relative to the baseline scenario (SSP2-4.5). Results shown are the averted regional annual premature mortality rates (deaths per 100,000 head of total population of all ages) associated with $PM_{2.5}$ exposure in five-year intervals from 2015-2019 to 2095-2099 (plotted as 2020 to 2100). The $PM_{2.5}$-attributable premature mortality burden was calculated for adults aged 25 years and older. The shading represents the uncertainty in the mortality estimates (the 95% confidence interval) due to the uncertainty in the GEMM health function.

Both decarbonisation scenarios result in a similar temporal pattern of averted mortality rates over the 21st century in all regions except Oceania, with SSP1-1.9 generally producing greater values (Fig. 5). All continental regions experience a strong increase in averted mortality rates in the early part of the 21st century, from 2015 (from 2025 onwards in Europe) up to around 2035, reflecting the strong reductions in regional $PM_{2.5}$ exposure in the decarbonisation scenarios relative to the baseline over the same time period (Fig. 1). In the Americas and Europe, the positive trend in averted annual mortality rate flattens off beyond ~2035 but continues to increase at a slower rate towards the latter part of the century. In Asia and Africa, the averted annual mortality rates peak around mid-century and then begin to decrease towards 2100.

The greatest averted annual mortality rates of up to 49 (95% CI: 41-55) premature mortalities per 100,000 people are predicted to occur in Asia, around the middle of the 21st century (Fig. 5). The averted mortality rate in Asia decreases towards the end of the century but remains the largest of the six regions with 22 (95% CI: 18-25) averted premature mortalities per 100,000 people per year under the SSP1-1.9 scenario. In Europe, North America, and South & Central America, the greatest averted per-capita mortality burdens are achieved during the latter half of the century with up to 21 (95% CI: 18-25), 21 (95% CI: 17-25), and 16 (95% CI: 13-19) premature mortalities per 100,000 people per year, respectively. Beyond mid-century, the averted mortality rates in Europe and the Americas remain similar in magnitude year to year with small variability. In Africa, following either of the decarbonisation scenarios yields health benefits up to around 2085 (averting 1 – 12 premature mortalities per 100,000 people per year), but leads to health penalties in the latter part of the century relative to the baseline scenario (driven by the differences in predicted $PM_{2.5}$ exposures shown in Fig. 1d). In Oceania, the averted mortality rates are generally small relative to the other continents (up to 6 (95% CI: 5-7)) and fluctuate between health benefits and health penalties over the century due to small variations in predicted $PM_{2.5}$ exposure in this region (Fig. 1f).

3.5 Impacts of decarbonisation on future air pollution-associated mortality by income region

Figure 6 shows the global $PM_{2.5}$-attributable mortality burden for the four income regions that could be averted by following a decarbonisation pathway instead of the middle-of-the-road pathway. The greatest per-capita health benefits of reduced $PM_{2.5}$ pollution through decarbonisation are predicted to occur in the middle-income regions, with an average of 27 (95% CI: 22-31) averted premature mortalities per 100,000 people per year under SSP1-1.9 (Fig. 6a and 6b). Meanwhile, the smallest health benefits are predicted to occur in the low-income region (beyond ~2030), with an average of 14 (95% CI: 12-16) averted premature mortalities per 100,000 people per year under SSP1-1.9.

The proportion of the total annual $PM_{2.5}$-attributable mortality burden that could be averted through decarbonisation is greatest around mid-century in all income regions (Fig. 6c and 6d), with up to 34% of $PM_{2.5}$-attributable deaths averted in the lower-middle-income region under SSP1-1.9. For low- and lower-middle income regions, the peak in the averted fraction occurs slightly earlier (during 2040-2044) than for upper-middle- and high-income regions (between 2045 and 2070), particularly under SSP1-2.6. Beyond 2025, the proportion of deaths averted through decarbonisation in the low-income region (an average of 17% over 2025-2099 under SSP1-1.9) is noticeably smaller than in the other income regions (averages of 24-25%).

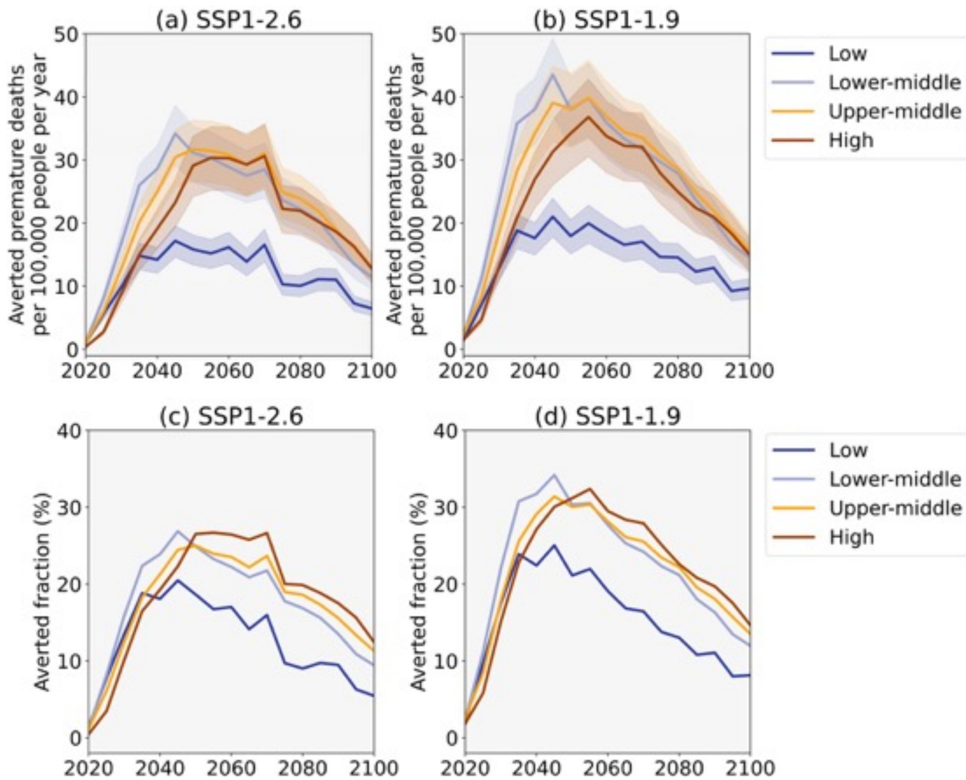

Figure 6. Averted annual $PM_{2.5}$-attributable premature mortality burden in four income regions (low, lower-middle, upper-middle, and high) between 2015 and 2100 that could be achieved by following the decarbonisation scenarios (SSP1-2.6 or SSP1-1.9) relative to the baseline scenario (SSP2-4.5). (a) and (b) show the averted annual premature mortality rates (deaths per 100,000 head of total population of all ages) associated with $PM_{2.5}$ exposure. The shading represents the uncertainty in the mortality estimates (the 95% confidence interval) due to the uncertainty in the GEMM health function. (c) and (d) show the percentage of the total $PM_{2.5}$-attributable premature mortality burden (under SSP2-4.5) averted under SSP1-2.6 or SSP1-1.9. The $PM_{2.5}$-attributable premature mortality burden was calculated for adults aged 25 years and older. All results are in five-year intervals from 2015-2019 to 2095-2099 (plotted as 2020 to 2100). The income regions are calculated based on the population-weighted per-capita GDP. The projected population count and GDP data, and thus the regions within each income region, vary with time in 10-year intervals.

The greater number of averted mortalities in the middle-income regions (particularly between ~2030 and 2090) is largely due to the strong reductions in $PM_{2.5}$ exposure predicted by the decarbonisation scenarios relative to the baseline (29-30% on average across the century compared to 20% in the low-income region and 25% in the high-income region under SSP1-1.9). However, the averted mortality rate in each income region depends not only on the changes in $PM_{2.5}$ exposure between the decarbonisation scenarios and the baseline, but also on the absolute $PM_{2.5}$ concentrations (since the exposure-outcome association is non-linear) and on the underlying health data of the populations within each income region, all of which vary with time. Thus, in regions with higher $PM_{2.5}$ exposure and older populations there may be reduced health benefits per unit exposure decrease, compared to regions with lower $PM_{2.5}$ exposure and younger populations, depending on the baseline mortality rates in the different age groups. On average between 2015 and 2100, the relative reduction in the $PM_{2.5}$-attributable mortality burden per 1% reduction in $PM_{2.5}$ exposure between SSP2-4.5 and SSP1-1.9 is greater in high income regions (0.86%) compared to the low, lower-middle, and upper-middle income regions (0.73-0.79%). Inequalities in the underlying health data are projected to reduce by the end of the century (Fig. S14). Therefore, keeping population demographics fixed at 2020 values, the difference between income regions is more pronounced, with a 1% reduction in $PM_{2.5}$ exposure resulting in an average 0.71-0.77% reduction in $PM_{2.5}$-attributable mortality burden in low- and middle-income regions, compared to an average 1.00% reduction in high-income regions. These results show that although $PM_{2.5}$ exposure-health inequalities are predicted to remain throughout the 21st century under all three scenarios, projected reductions in $PM_{2.5}$ exposure and changes in population demographics are acting to reduce these inequalities over time.

4 Discussion and conclusions

In this study we used future projections of global $PM_{2.5}$ pollution under three different pathways; a middle-of-the-road baseline scenario (SSP2-4.5) and two decarbonisation scenarios with strong air pollution controls (SSP1-2.6 and SSP1-1.9), to explore the air quality and health inequalities of transitioning to a low carbon future.

We found that all three future scenarios predict reductions in global $PM_{2.5}$ exposure, relative to present-day. However, immediate reduction in global $PM_{2.5}$ exposure in the near term, is only achieved under a decarbonisation scenario. Moving from the SSP2-4.5 scenario to a decarbonisation scenario could further reduce future $PM_{2.5}$ exposure by 21-26% on average over the 21st century and will bring over a half a billion more people into compliance with the WHO Air Quality Guideline (AQG) by 2100. Projected changes in $PM_{2.5}$ exposure from decarbonisation vary strongly by world region, with the largest air quality benefits predicted to occur in Asia.

Despite strong reductions in global $PM_{2.5}$ exposure under the decarbonisation scenarios (which include stringent air pollution controls), a large fraction of the world's population (~85%) are projected to remain exposed to concentrations above the WHO AQG in 2100. Regional $PM_{2.5}$ exposures remain particularly high in Africa and Asia, with the $PM_{2.5}$ exposure remaining above the WHO AQG for over 94% of the populations in these regions in 2100. Our results are consistent with findings from previous studies that assessed the impact of removing all major anthropogenic sources on air quality in China (Conibear et al., 2022c) and globally (Pai et al., 2022). As anthropogenic aerosol emissions are reduced, natural or semi-natural aerosol, such as mineral dust, carbonaceous aerosol from wildfires, and biogenic SOA may make increasingly important contributions to regional $PM_{2.5}$ exposure in the future (Pai et al., 2022) particularly in a warming climate. Future work should seek to quantify the anthropogenic ("abatable") and natural contributions to future $PM_{2.5}$ exposure across the different income groups, particularly for lower-income populations with high $PM_{2.5}$ exposures. This future work should include the response of wildfire emissions to a warming climate and the subsequent impacts on air quality and public health, which was not considered here.

We found that substantial public health benefits could be achieved by following either of the decarbonisation scenarios relative to the baseline scenario. Moving from SSP2-4.5 to the more stringent decarbonisation scenario, SSP1-1.9, could substantially reduce the $PM_{2.5}$-

attributable mortality burden, averting 2.95 (95% CI: 2.48-3.38) million annual premature deaths globally in 2050. The largest per-capita health benefits of reduced $PM_{2.5}$ pollution through decarbonisation are predicted to occur in Asia around mid-century.

By grouping the global population into four income groups, using projections of per-capita GDP, we found that populations in low- and lower-middle-income regions (predominantly in Africa and Asia) consistently experience the highest $PM_{2.5}$ exposures across the 21st century in all three scenarios (SSP2-4.5, SSP1-2.6, and SSP1-1.9). The lowest $PM_{2.5}$ exposures consistently occur in the high-income region (predominantly populations in Europe, North America, and Asia). The proportion of the low- and lower-middle-income populations that remain exposed to $PM_{2.5}$ concentrations above the WHO AQG at the end of the century (89-91%) is considerably greater than the proportion of the high-income population (75-76%).

The number of averted $PM_{2.5}$-attributable deaths from decarbonisation is greatest in middle-income populations across the 21st century, with the fewest averted premature deaths in low-income populations. The magnitude of the averted $PM_{2.5}$-attributable mortality burden is largely driven by reductions in $PM_{2.5}$ exposure predicted by the decarbonisation scenarios relative to the baseline, but it can be influenced by other underlying differences between the income regions. The relative reduction in the $PM_{2.5}$-attributable mortality burden per unit reduction in $PM_{2.5}$ exposure is 8-15% less on average in low- and middle-income populations than in high-income populations due to differences in population demographics and the non-linearity of the exposure-outcome association at high exposures. Some studies show that associations between air pollution exposure and health outcomes may be stronger in groups with lower socioeconomic status (e.g., Bell et al. 2013; Rodriguez-Villamizar et al. 2016; Fuller et al. 2017), which has not been considered here and would therefore act to increase the disparity between high- and lower-income regions.

Despite the large number of deaths that could be avoided by following a decarbonisation pathway, particularly in middle-income regions, the total $PM_{2.5}$-attributable deaths at the end of the century are greatest in the low- and lower-middle-income regions (109 (95% CI: 89 – 126) annual deaths per 100,000 people under the SSP1-1.9 scenario). This means that although there are rapid and substantial health co-benefits of decarbonisation through improved air quality, it is the lower-income populations that are predicted to benefit the least from climate and air pollution mitigation; and continue to be exposed to $PM_{2.5}$ concentrations that are over three times that of the AQG. Overall, the $PM_{2.5}$ exposure inequality is predicted to reduce by 2100, but still remain even in the strongest mitigation scenario. In order to tackle inequalities in global $PM_{2.5}$ exposure and the associated health impacts, future climate change mitigation and air quality control measures should be better targeted towards lower-income regions with high $PM_{2.5}$ exposures.

This study has shown that although some co-benefits arise from decarbonisation, more could be done to improve non-climate outcomes, particularly in lower-income regions. To improve health outcomes, either additional air quality improvement measures could be introduced and/or health and other co-benefit metrics could be incorporated into net zero policies. The latter option will likely be more successful at minimising trade-offs and creating a just transformation.

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Open Research

The $PM_{2.5}$ concentration data used in this study was obtained from the CMIP6 data archive which is hosted at the Earth System Grid Federation (ESGF) and is freely available to download from https://esgf-node.llnl.gov/search/cmip6/. Future projections of global gridded population count following SSP2 are freely available to download from Jones and O'Neill (2020). Future projections of national baseline mortality rates and population age structures are freely available to download from Frederick S. Pardee Center for International Futures (2021). Future projections of global gridded GDP following SSP2 are freely available to download from Murakami et al. (2020).

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