Socio-demographic factors shaping the future global health burden from air pollution

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Abstract

Exposure to ambient particulate matter ($PM_{2.5}$) currently contributes to millions of global premature deaths every year. Here we assess the pollution and health futures in five 2015-2100 scenarios using an integrated modeling framework. Based on a global Earth System Model (GFDL-ESM4.1), we find lower ambient $PM_{2.5}$ concentrations, both globally and regionally, in future scenarios that are less fossil-dependent and with more stringent pollution controls. Across the five scenarios, the global cumulative $PM_{2.5}$-related deaths vary by a factor of two. However, the projected deaths are not necessarily lower in scenarios with less warming or cleaner air. This is because while reducing $PM_{2.5}$ pollution lowers the exposure level, increasing the size of vulnerable populations can significantly increase the $PM_{2.5}$-related deaths. For most countries, we find that changes in socio-demographic factors (e.g., aging and declining baseline mortality rates) play a more important role than the exposure level in shaping their future health burden.

Introduction

Exposure to ambient particulate matter ($PM_{2.5}$) is a major global health threat, causing 3-9 million worldwide premature deaths every year.[1–3] The health burden is unevenly distributed across countries and disproportionally borne by the Global South. At present, more than half of $PM_{2.5}$-related deaths occur in China and India, due to their heavy reliance on fossil fuels, insufficient pollution controls, as well as large size of affected population.[4,5] In fact, fossil fuel combustion alone contributes to about 4 million $PM_{2.5}$-related deaths globally, and its relative contribution is higher in lower-income regions.[6]

While managing air pollution is a widely acknowledged sustainability challenge, how the health impacts and the global distribution might evolve in the future remains poorly understood. A range of factors could play a role, such as pollution control policies, climate action and energy transition, as well as socio-demographic trends.[7–11] First, over the past few decades, strengthening air pollution control policies has been the key measure to clean up the air around the world. For instance, in China, the widespread installation of pollution control devices lowered the nationwide $PM_{2.5}$ concentration from coal power generation by 57% (or 8 $\mu g/m^3$) from 2005 to 2015.[12] Second, climate mitigation action can bring air quality and health co-benefits by curbing fossil energy use.[13–15] Studies have found that stabilizing the climate system could simultaneously lower the global annual air-pollution-related deaths by 2.2±0.8 million in 2100.[16] Finally, socio-demographic trends could alter the size and vulnerability of the exposed population, leading to complex implications on health burden. For instance, population aging may exacerbate the health burden by increasing the share of elderly people who are more vulnerable to air pollution.[17,18] Meanwhile, improvements in the healthcare system may lower the baseline mortality rate,[19] reducing the health impacts from all risk factors including those from air pollution exposure.

Despite a growing attention on the complex drivers for air pollution and health,[16,20,21] it remains unclear how these socioeconomic, technology, and policy factors might interact with each other and collectively shape the future landscape for pollution and health. Despite emerging evidence for a subset of countries (e.g., China,[18] India,[20] United States[17]), there is inadequate understanding of how the dominant factor might differ across countries (e.g., developing vs. developed countries) and evolve over time (e.g., current, 2050, or 2100).

The key objective of our study is to assess the relative contribution of various policy, technology, and socio-demographic drivers under a range of plausible futures. For 199 countries and regions, we use an integrated modeling framework to project future human activities and emissions, simulate the $PM_{2.5}$ concentrations, and assess the health impacts (Figure 1); we further decompose the total health effects into the contributions of four individual factors to identify key drivers that may vary across regions and time periods. By using coherent assumptions for health drivers, exposures, and outcomes, our modeling framework characterizes the complex processes and dynamics that influence future air quality and health. Identifying key determinants for $PM_{2.5}$-related health outcomes may also provide important insights to inform integrated policy decisions for energy, climate, and health.

Specifically, we consider five 2015-2100 scenarios that vary in two dimensions: i) socioeconomic pathways and air pollution control efforts (represented by different Shared Socioeconomic Pathways, SSPs), and ii) climate stabilization targets (represented by different Representative Concentration Pathways, RCPs). This SSP-RCP scenario framework has been the backbone of major global policy assessments by the Intergovernmental Panel on Climate Change (IPCC)[22] and is frequently used to evaluate global climate and sustainability challenges.[23,24] For each scenario, we then simulate the $PM_{2.5}$ concentration at 1° by 1.25° spatial resolution using a global Earth system model (GFDL-ESM4.1).[25–27] It allows a two-way feedback between aerosols and climate: a changing climate affects $PM_{2.5}$ formation and transport (e.g., through wind and rainfall), while the aerosols also influence the climate by absorbing or scattering radiation. Finally, we quantify the impacts on human health, measured by premature deaths, using country-level socio-demographic projections consistent with SSPs[28] and the state-of-the-art concentration-response relationships.[1,2,29–31]

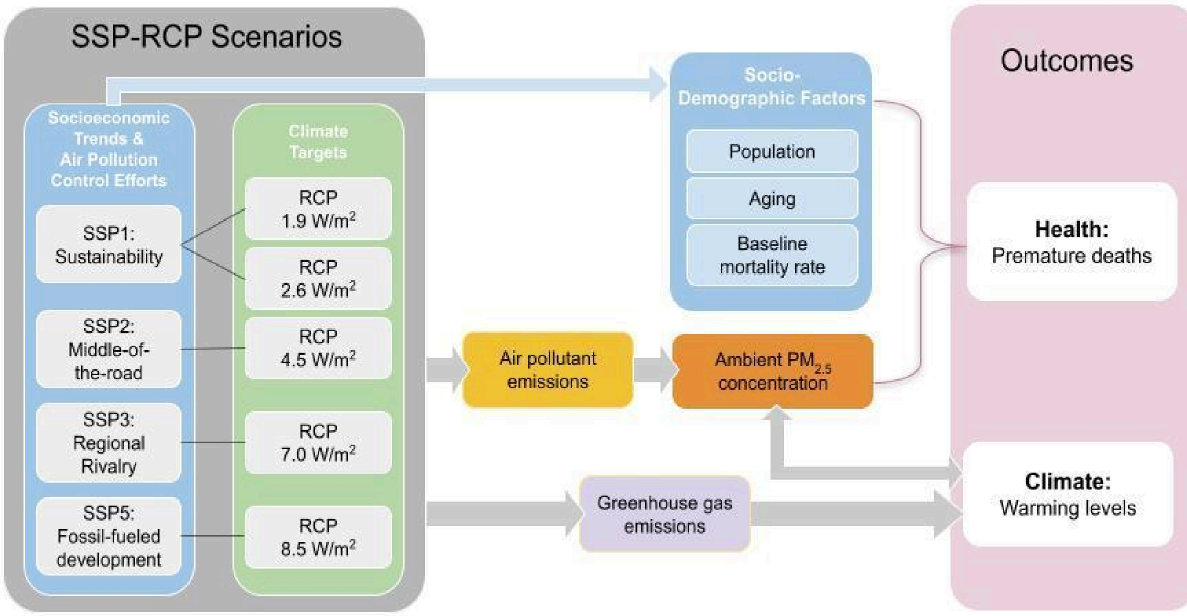

Figure 1. An integrated modeling framework to assess future warming levels and $PM_{2.5}$-related health burden. We consider five 2015-2100 scenarios which vary in socioeconomic trends, air pollution control efforts, and climate targets, namely SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP 3-7.0, and SSP 5-8.5. These five SSP-RCP scenarios are developed by the global integrated assessment models and utilized by major IPCC climate assessments including the Coupled Model Intercomparison Projects (CMIP).[32,33] Here the simulations of the future climate and ambient $PM_{2.5}$ concentrations are conducted by the GFDL-ESM4.1 model. More detailed descriptions of the scenarios and modeling methods are available in the Method section and in Supplementary Information Section 1.

Results

Global patterns for warming and $PM_{2.5}$-related premature deaths

Across the five scenarios, the end-of-century global average temperature is projected to be 1.2°C to 3.9°C higher than the pre-industrial level (see spatial distribution in Supplementary Figure S3). Over the course of this century, the warming levels are estimated to be 1.3-1.4°C in the near term (average of 2021-2040) and 1.4-2.1°C in the mid-term (average of 2041-2060) (Supplementary Table S2). Our climate projections based on GFDL-ESM4.1 are broadly consistent with the most recent IPCC findings.[22]

The substantial differences in warming levels across the five scenarios are driven by the variations in human activities and associated greenhouse gas and aerosol emissions (Figure

2a): based on the projections by the integrated assessment models, the cumulative 2015-2100 global CO_2 emissions vary by a factor of 20 across these scenarios, ranging from 0.40 Gton in SSP1-1.9 to 7.14 Gton in SSP5-8.5.

Globally, the cumulative $PM_{2.5}$-related premature deaths from 2015 to 2100 vary by a factor of two across the five scenarios (Figure 2b). The lowest burden is found in SSP1-1.9, the most sustainable scenario (central estimate and 95% confidence interval based on the relative risk functions: 460 million; CI 310-570 million). The highest burden is found in SSP3-7.0, the scenario assuming slow economic growth and continued fossil use (930 million; CI: 690-1,100 million). The annual average deaths over 2015 to 2100 are estimated to be between 5 and 11 million across the five scenarios. Compared to roughly 5 million $PM_{2.5}$-related deaths in 2019,[29] our results imply that the health damages from ambient $PM_{2.5}$ are expected to remain substantial in the coming decades and may exacerbate under some plausible futures.

Notably, $PM_{2.5}$-related health burden does not increase monotonically with warming level. The scenario with the most warming (i.e., SSP5-8.5) is associated with lower deaths than some other scenarios with less warming (e.g., SSP2-4.5 and SSP3-7.0). Although the fossil-intensive SSP5-8.5 scenario is becoming increasingly unlikely given recent energy trends[34] and climate commitments,[35] our findings suggest that climate mitigation efforts are not likely to be the most crucial determinant for the future $PM_{2.5}$-related health burden.

Further, the future distributions of $PM_{2.5}$ and health burden remain unequal across countries (Figures 2 and 3). Based on the five scenarios, 64-69% of the global cumulative deaths occur in only three regions: China, India, and Africa. Although $PM_{2.5}$ concentrations in these three regions are expected to go down in most scenarios (except for SSP3-7.0), the large size of exposed population and increasing population vulnerability due to aging make the future health burden substantial. This finding demonstrates that the global inequality in air pollution and health will likely persist in the future, as the Global South manages the interconnected challenges of growing economy, population, and energy demand.

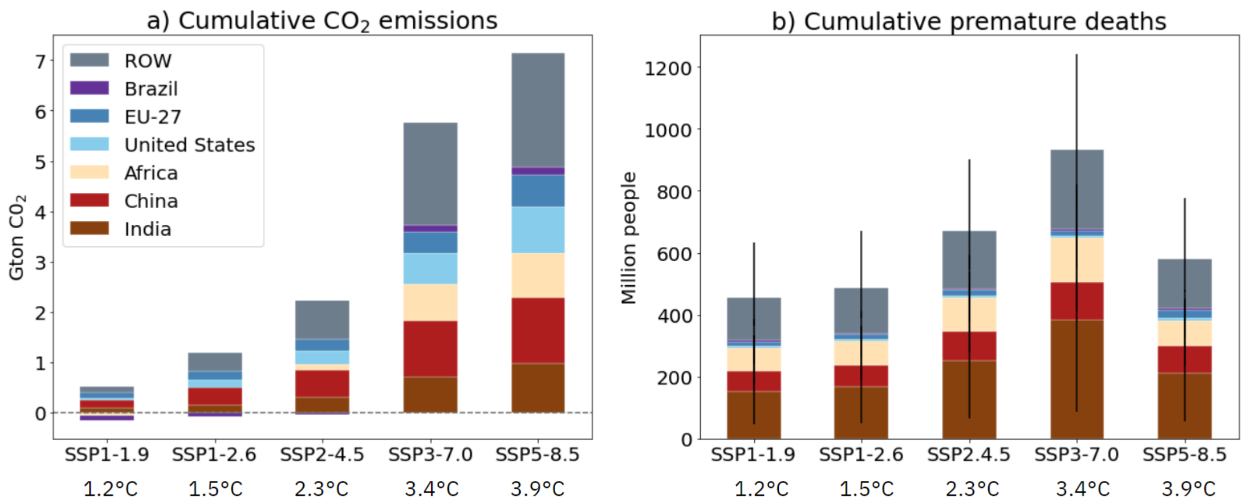

Figure 2. Cumulative CO_2 emissions (left panel) and $PM_{2.5}$-related premature deaths (right panel) from 2015 to 2100 in the five SSP-RCP scenarios. In both panels, the numbers below the scenario names show the projected long-term change (average of 2081-2100) in global average temperature relative to preindustrial times (1850-1900), based on simulations from the GFDL-ESM4 model output.[27] Different colors represent different world regions (ROW: rest of the world). In panel b), the error bars represent the deaths estimated based on the 95% confidence interval of the relative risk (RR) functions from the Global Burden of Disease (GBD) 2019 Study.[29,31] See sensitivity analyses on alternative RR functions and health metrics (e.g., years of life lost) in Supplementary Figures S11-14. For nearer-term impacts, see Supplementary Figure S2 for the cumulative impacts from 2015 to 2050.

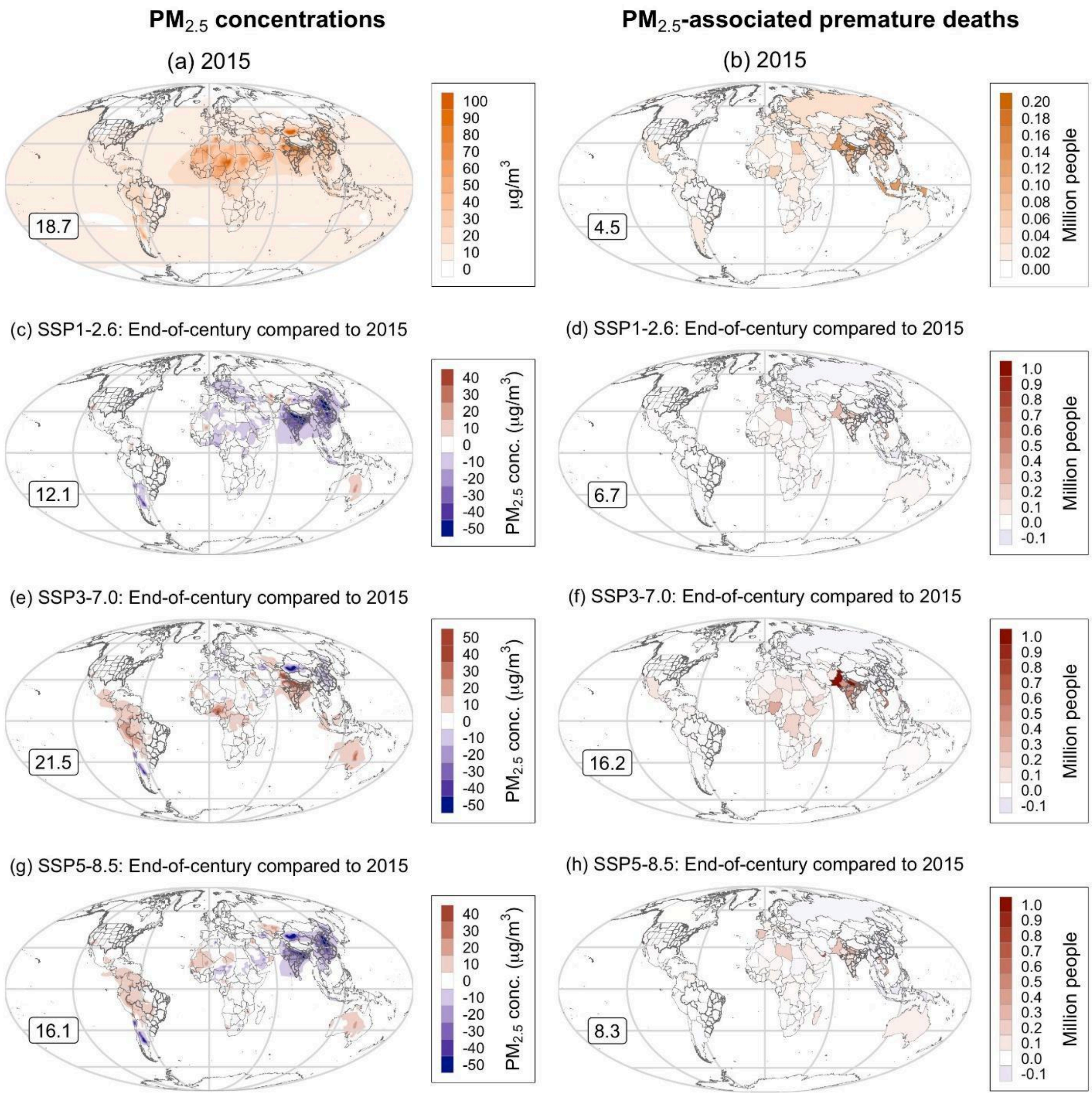

Figure 3. Current and future distribution of annual mean $PM_{2.5}$ concentrations (left column) and annual total premature deaths (right column). Panels a) and b) show the patterns in 2015. Panels c)-h) show the changes by the end of the century as compared to 2015. The $PM_{2.5}$ concentrations are simulated at 1° latitude by 1.25° longitude resolution. The premature deaths are calculated for 199 countries and regions, with subnational state-level assessments for four major countries (China, India, USA, and Brazil). The end-of-century values are calculated using the decadal averages from 2090 to 2100. The numbers in the text box show the population-weighted global mean $PM_{2.5}$ concentration (left column) and the global total premature deaths (right column). The patterns for the mid-century are shown in Supplementary Figure S6. To assess health risks, we also report the $PM_{2.5}$-related death rates in Supplementary Figures S7 and S8.

The determining role of socio-demographic factors

To explain the variations in health outcomes across regions and scenarios, we decompose the aggregate changes in premature deaths from 2015 to 2100 into the effects of four individual factors. First is the change in the exposure level to ambient $PM_{2.5}$ as a result of energy, air pollution and climate efforts. We then consider three socio-demographic factors that affect the size of the exposed population and their vulnerability: population growth, population aging, and changes in baseline mortality rate.

We find that socio-demographic factors, especially aging and changes in baseline mortality rate, play a dominant role in shaping the future health burden from ambient air pollution (Figure 4). In comparison, the effects of population growth and ambient $PM_{2.5}$ concentrations are small in most regions and scenarios (exceptions will be discussed in later sections). In particular, population aging would significantly exacerbate the future health burden: across the five scenarios, aging alone would increase the global $PM_{2.5}$-related deaths by a factor of 3 to 8 from 2015 to 2100. This is because, compared to younger age groups, the older age groups have a higher baseline death rate and are more vulnerable to almost all types of health risks including those from air pollution exposure.[36] In contrast, for scenarios that assume rapid economic growth and improved healthcare (e.g., SSP1-1.9, SSP1-2.6, and SSP5-8.5), the baseline mortality rates are projected to go down for all age groups, reflecting a general improvement of human health conditions, which also lowers the premature deaths from pollution exposure. For instance, from 2015 to 2100, the declining baseline mortality rate is expected to reduce global deaths by a factor of 6 in both SSP1-2.6 and SSP5-8.5. In net, from 2015 to 2100, the three socio-demographic factors contribute to an 80% to 290% increase in global premature deaths, across the five scenarios.

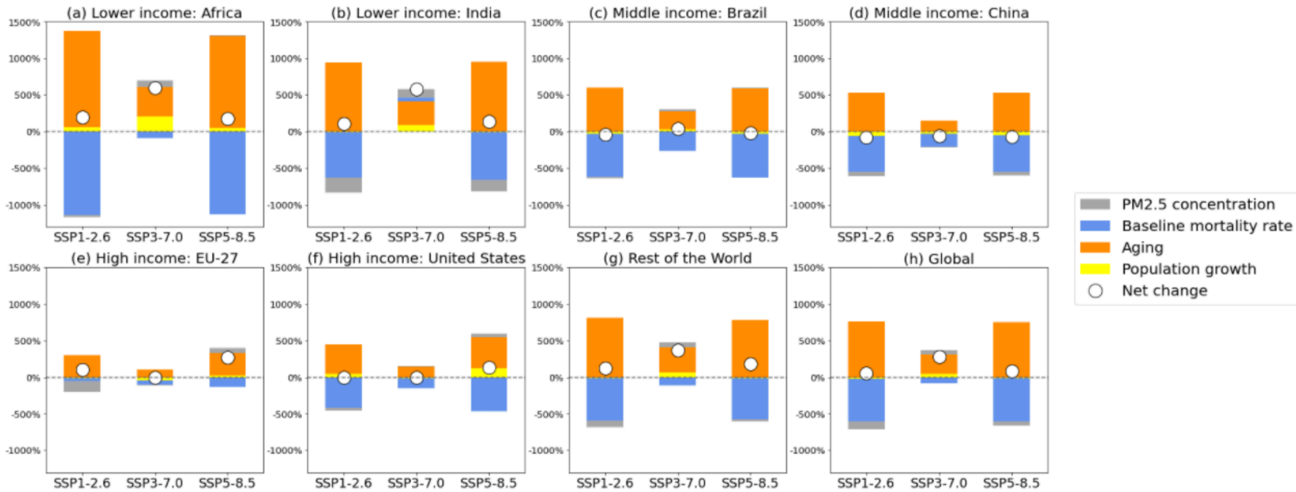

Figure 4. Relative contribution of four individual factors to the 2015-2100 changes in $PM_{2.5}$-related deaths: i) changes in $PM_{2.5}$ concentrations (grey), ii) baseline mortality rate (blue), iii) population aging (orange), and iv) population growth (yellow). Combining the effects of these four factors, the white dots represent the net changes in 2100 relative to 2015. Here we show three selected scenarios (SSP1-2.6, SSP3-7.0 and SSP5-8.5). The 2100 decomposition analysis results for the other two scenarios (i.e., SSP1-1.9 and SSP2-4.5) are represented in Supplementary Figure S10. The decomposition results for the mid-century are reported in Supplementary Figure S9.

For scenarios that assume rapid economic growth, two socio-demographic trends are projected to happen simultaneously: (1) population aging, which increases the size of vulnerable populations and hence increases the $PM_{2.5}$-related deaths from the same exposure level, and (2) declining baseline mortality rates, which reduces population vulnerability and hence lowers the $PM_{2.5}$-related deaths. For example, in SSP5-8.5, aging would raise $PM_{2.5}$-related global total premature deaths by a factor of 8 from 2015 to 2100, but the improved baseline mortality rate would reduce the deaths by a factor of 6; in net, despite the heavy dependence on fossil fuels in SSP5-8.5, the premature deaths in 2100 are only 88% greater than in 2015. The counteracting effect of aging and declining mortality rates on $PM_{2.5}$-related deaths is also a key feature of the sustainable development scenarios (e.g., SSP1-1.9 and SSP1-2.6). In contrast, another fossil-heavy scenario, SSP3-7.0, follows a "regional rivalry" narrative with much slower projected growth and relatively weak controls on air pollutant emissions (and as a result, high $PM_{2.5}$ concentrations). Despite a modest trend of population aging, the lack of improvement in baseline mortality rate in SSP3-7.0 significantly increases the health burden, which is further exacerbated by higher exposure level to $PM_{2.5}$ due to unsatisfying pollution controls. In net, we find 2.8 times more deaths in 2100 relative to 2015 in SSP3-7.0.

A large portion of the regional variations in health outcomes can be explained by differences in their projected socio-demographic patterns (Figure 5). Regarding aging, lower-income regions currently have relatively young populations: in 2015, people older than 65-years-old were only accounted for 4%, 5%, and 9% of the population in Africa, India and China, respectively, while the shares were 19% and 15% in EU-27 and USA, respectively. Despite a global trend of aging, the low- and middle-income countries are expected to age more rapidly in the future in most scenarios (except for SSP3-7.0 in which slow economic development is assumed). Under SSP1 and SSP5, for instance, by 2100, more than half of the population in China and India are projected to be older than 65 years, which is a higher ratio than the USA and EU. Regarding the baseline mortality rates, the current rates in China, India, and Africa are almost twice as high as those in EU-27 or USA. Such improvements in socioeconomic conditions could contribute to better health, by providing more resources for healthcare and healthier lifestyles (e.g., diet, rest).[37] Since the less developed countries are projected to grow faster, their baseline mortality rates would also decline faster, largely closing the cross-country gaps by 2100.

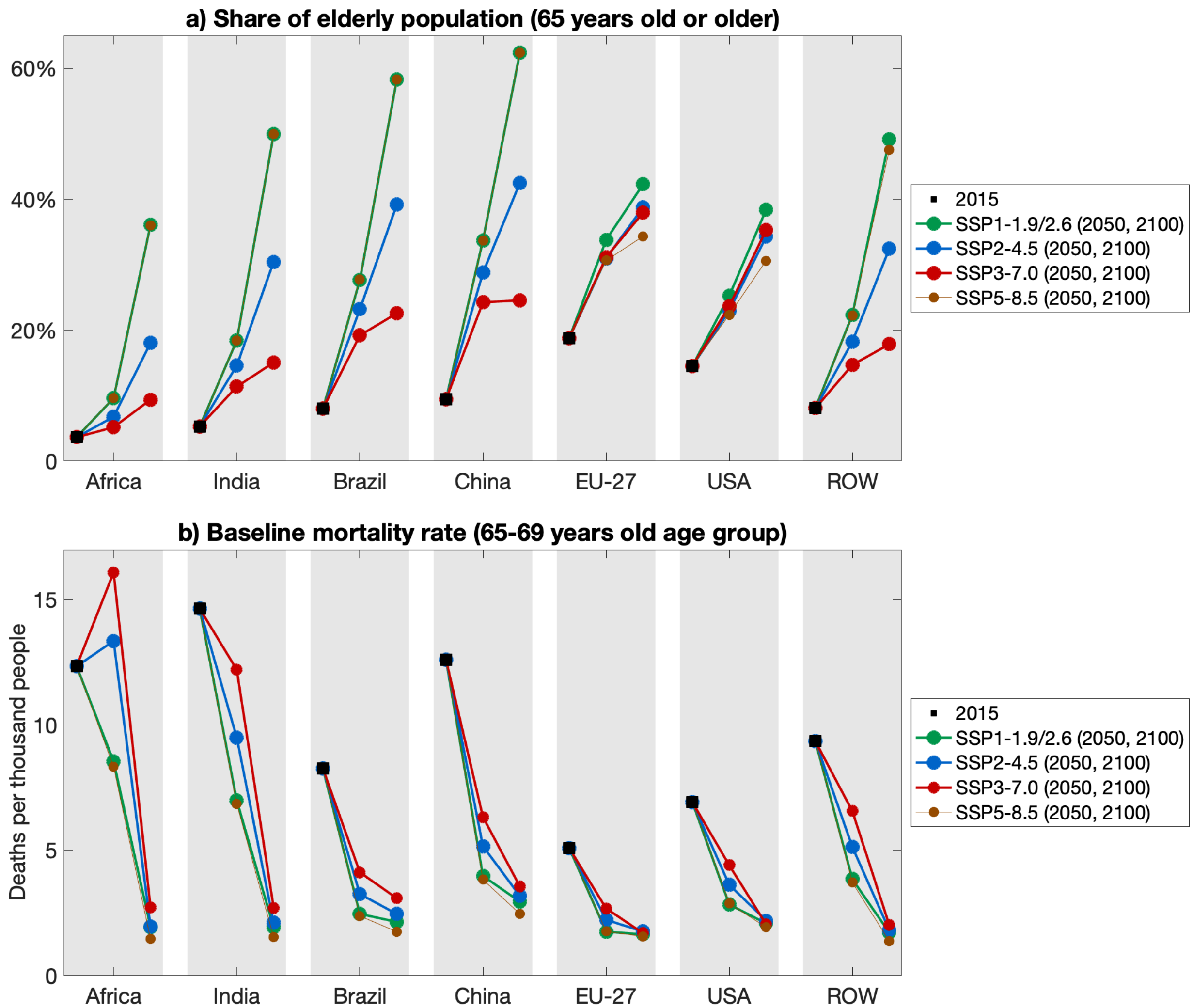

Figure 5. Aging pattern (panel a) and baseline mortality rates (panel b) in 2015 and under all five scenarios (SSP1-1.9/2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). From left to right, the world regions are ranked by increasing per capita income level in 2015 (ROW stands for the rest of the world). For each region, the black rectangles on the left represent the values in 2015, whereas the dots in the middle and on the right are the values projected for 2050 and 2100, respectively. For panel b), the 65-69 years old age group is selected as an example group to show the baseline mortality rate that varies by age. The projections for the aging patterns are taken from the IIASA SSP population dataset.[38,39] The projections for the baseline mortality rates are based on the predicted rates for five types of diseases from the International Futures (IFs) model and mapped to the six diseases considered in this study (see more in Method).[28]

Changes in energy use and $PM_{2.5}$ concentrations

Despite the dominating role of socioeconomic factors in determining the health burden, changes in $PM_{2.5}$ concentrations remain important, especially for emerging markets and developing countries, where the air is highly polluted at present and the future pollution level could vary significantly depending on energy choices, climate action, and air pollution control efforts.

We highlight two important trends. First, as mitigating climate change enables a drastic shift away from fossil fuels (Figure 6a), it brings the co-benefits of improved air quality (Figure 6b). In SSP1-2.6, for instance, the share of fossil fuels in the global energy system is projected to decrease from 85% at present to only 19% in 2100. Along with deep cuts in carbon emissions, the ambient $PM_{2.5}$ concentrations go down simultaneously. The largest reductions are expected in India and China which suffer from the worst air quality and heaviest death tolls at present. From 2015 to 2100, the median pollution levels across provinces reduce from 45 to 20 μg/m^3 in India (a factor of 2.25 decline) and from 36 to 10 μg/m^3 in China (a factor of 3.6 decline). The much lower pollution level and health damages in the climate stabilization scenarios confirm potentially large air quality co-benefits from climate action.

However, it is possible to clean up the air without transitioning away from fossil fuels. Strengthening air pollution control efforts using existing technologies can significantly lower the pollution level. For instance, both SSP3-7.0 and SSP5-8.5 assume a continued dependence on fossil fuels. Yet the projected pollution levels are much lower in the latter, especially in the developing world. This is because, compared to SSP3-7.0, SSP5-8.5 assumes faster economic growth and an acceleration of pollution control efforts in the future. This trend largely reflects the empirical evidence on the Environmental Kuznets Curve that economic development initially worsens the environment but later leads to improvement.[40] In fact, there is already evidence of the decoupling of fossil energy use and air pollution: while India has the highest pollution level, its energy mix is less fossil-intensive than other more developed regions. The 2015 share of fossil energy in primary energy mix was 76% in India, as compared to 89%, 91%, and 84% in China, USA, and EU-27, respectively (Figure 6a). This is partly because residential biomass use and waste burning are also major contributors to air pollution in India.[41] It highlights the complexity of air pollution sources and the need for economy-wide mitigation strategies.

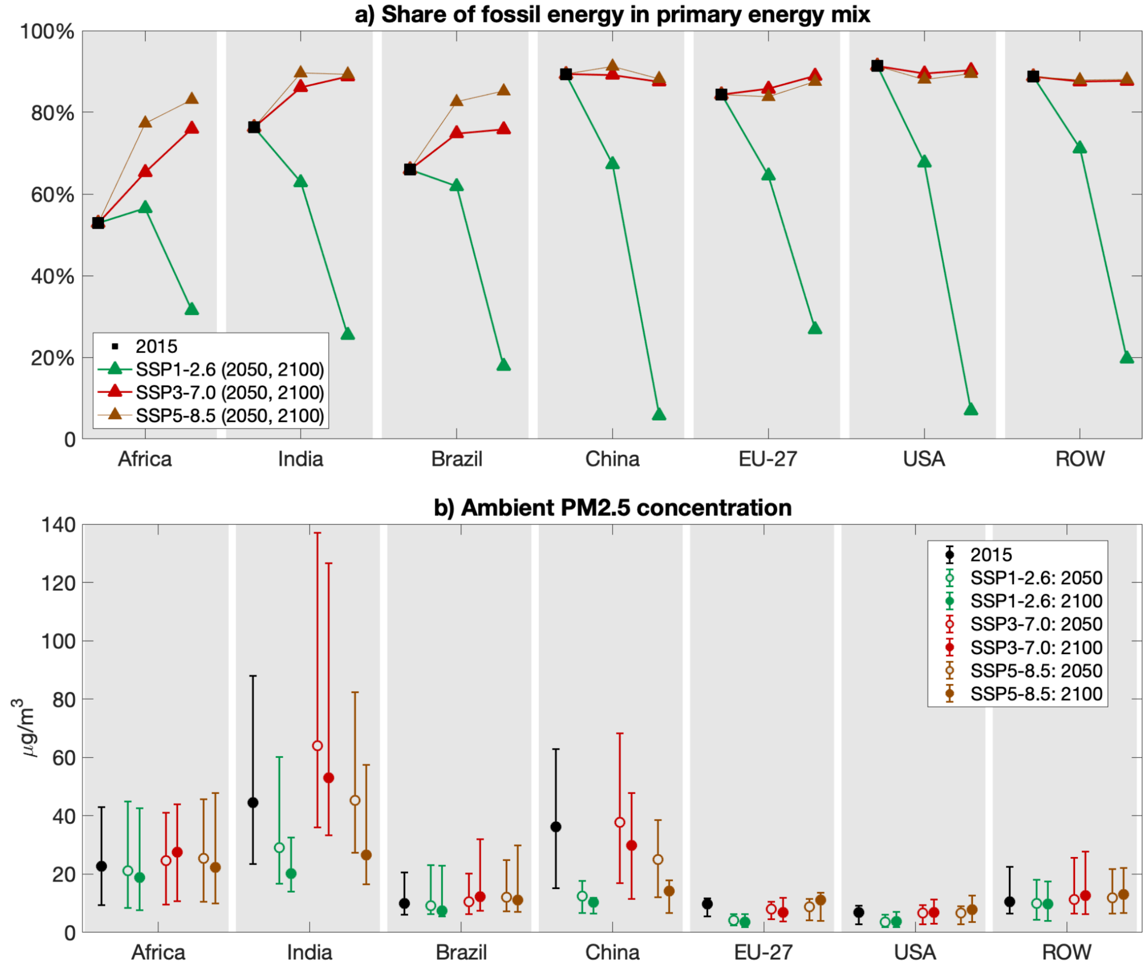

Figure 6. Energy mix (panel a) and $PM_{2.5}$ concentrations (panel b) in 2015, 2050 and 2100 under three selected scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5). From left to right, the world regions are ranked based on increasing per capita income levels in 2015 (ROW stands for rest of the world). The energy mix is based on the projections from a global integrated assessment model, Global Change Analysis Model, which covers 32 world regions including the country-level projections for the six countries/regions listed here.[38,42,43] The population-weighted $PM_{2.5}$ concentrations are calculated using the GFDL-ESM4 simulations[25,26] and gridded population projections.[39,44,45] To demonstrate the variations within each country/region, the dots in panel b represent the median and the error bars represent the range from the 10th to 90th percentile. The patterns for the simulated $PM_{2.5}$ concentrations in other two scenarios (i.e., SSP1-1.9 and SSP2-4.5) are presented in Supplementary Figure S5.

Additional insights from transitional pathways and nearer term impacts

Most trends about energy use, pollution level and socio-demographic patterns are consistent and continuous over time, leading to similar broad patterns for the mid-century and 2100 (e.g., comparing Supplementary Figure S2 to Figure 2). Here we highlight three potential differences.

First, the temporal paths of population and economic growth matter, especially in the less developed regions. For instance, in Africa, population growth is a much more important health driver for mid-century than in 2100 (see Supplementary Figure S9). Another example is the projection for the baseline mortality rate: In SSP3-7.0, the baseline mortality rate in Africa is projected to increase over the next few decades before it declines in the second half of the century, while the opposite temporal trends are found for India. These results highlight the particularly large uncertainties in future socio-demographic projections for the Global South.

Second, the relative contribution of $PM_{2.5}$ concentration to health burden is larger in 2050 than in 2100 for many world regions and in most scenarios (see Supplementary Figure S6). In particular, for a fossil-heavy pathway with rapid economic growth (e.g., SSP5-8.5), the pollution level is projected to decrease further in the second half of the century, thanks to accelerated pollution control efforts in conjunction with economic development. This underscores that air pollution could be a transient developmental issue that will be improved over time. Yet, the influence of socio-demographic factors on population vulnerability and health burden will likely have growing importance in the longer future.

Lastly, we observe time-varying patterns for the health disparities across age groups (see Supplementary Figure S4). Globally, the 75-79 age group currently suffers the most from premature deaths from ambient $PM_{2.5}$ exposure. With population aging and increased life expectancy, by mid-century all five scenarios project the greatest deaths occurring in the 80-84 age group. By the end of the century, for the two scenarios that assume rapid economic growth (SSP1-2.6 and SSP5-8.5), the greatest deaths are found in the 95+ age group. This is a combined effect of more people living past 95 years old and the much higher baseline mortality rate of this age group.

Discussion

Comparing five future scenarios with varying socioeconomic pathways, air pollution control efforts and climate mitigation, we find a twofold variation in the global $PM_{2.5}$-related deaths. Much of the variations across regions, time periods, and scenarios are driven by the differences in socio-demographic patterns, especially population aging and declining baseline mortality rate.

The net effects of these socio-demographic factors are often an increase in $PM_{2.5}$-related deaths in the future.

Our assessment also indicates that the air pollution-related health objective could largely be achieved without an energy system transformation (e.g., lower deaths in SSP5-8.5 in some other lower-warming scenarios). This is because installing end-of-pipe controls can already substantially clean up the air. Yet, a fossil-intensive future will result in a wide range of climate damages, from reduced agricultural yields to higher temperature-related mortality. This highlights the key challenge of tackling the interconnected societal problems on air pollution, climate, and health.

Notably, the regional inequalities in air pollution and health are likely to persist in the future and could even widen. Slower economic growth may delay efforts to strengthen air pollution control policies, leading to higher pollution levels. It may also result in slower improvement in baseline mortality rates, which exacerbates the health burden from pollution exposure. More generally, the transition towards a lower-carbon energy system requires capacity building in the less developed regions to facilitate leapfrogging towards cleaner, yet more expensive energy choices. Therefore, supporting growth in the Global South regions should remain a priority to reduce global inequality in air pollution, health, and economics.

We highlight four important areas for additional research. First, a more comprehensive impact assessment is critical for understanding the overall implications on health and wellbeing. This means combining the assessments of air pollution and health conducted in this study with the assessments of climate damages and other health effects from heat, diet, extreme events, etc. While the major regional and global climate assessments have tried to synthesize the literature findings in multi-dimensional impacts,[46,47] existing studies do not always use consistent assumptions and modeling frameworks, making a quantitative comparison challenging. More importantly, new modeling capabilities are needed to account for complex feedback. For instance, the energy and emission scenarios used in this study are constructed without the feedback loop that future climate damages could have negative impacts on socioeconomic development. This may lead to overestimation of future GDP growth and therefore improvement in baseline mortality rates in the warming scenarios (e.g., SSP3-7.0 and SSP5-8.5), resulting in underestimation of the health burden in these scenarios. Although it goes beyond the scope of our study to quantify this feedback, future studies should further evaluate these complex system dynamics to identify potential synergy and tradeoffs between competing societal goals.

Second, finer-scale assessments are important to better understand the distribution of the health effects and tackle environmental injustice. Methodological improvements are needed to project future spatial distribution of demographics, emissions, pollution levels, and health impacts. For instance, here we use downscaled air pollutant emissions from CMIP6 at 0.5° by 0.5° resolution following the spatial patterns in 2014.[48] Yet, the emission hotspots in the future may occur in different locations compared to today, as new urbanization trends emerge and low-carbon energy infrastructure replaces existing sources. In addition, our $PM_{2.5}$ simulations at 1° by 1.25° spatial resolution may not capture the subnational heterogeneity in pollution exposure levels. Here we also use the national-level projections of major socioeconomic trends, such as aging and baseline mortality rates. Yet, quantifying the health disparities across socio-demographic groups needs to rely on population-specific health information and projections.[49]

Third, incorporating insights from demography and the relevant social sciences could strengthen the modeling of interactions between socioeconomic drivers, environmental policies, energy choices, and health. A wide range of social, economic, and demographic factors can influence the health burden at present and in the future.[50,51] For instance, improvement in educational attainment could accelerate economic growth[52,53], leading to direct and indirect effects on key drivers for air pollution and health, including energy demand, policy efforts, and life expectancy. Further research should leverage these new social science findings and explore ways to quantitatively represent these linkages in the modeling of the coupled human-natural systems.[54]

Finally, we need improved representation of uncertainties to identify most important ones that may shape the air pollution and health futures. In this study we have assessed a few key uncertainties related to the health impact assessment, including using alternative relative risk functions from GBD 2017[30,31] and the Global Exposure Mortality Model (GEMM)[2] as well as different health metrics such as years of life lost (see Supplementary Figures S11-14). Our core insight – that socio-demographic factors dominate the projected health effects – remains robust under these uncertainties. To assess other types of uncertainties, future research needs to evaluate the effects of model uncertainties on simulating $PM_{2.5}$ exposure (e.g., leveraging the multi-model comparison effort from ScenarioMIP),[33] as well as how the deep future uncertainties in the socioeconomic and technical systems may influence precursor emissions and population vulnerabilities (e.g., leveraging large-scale scenario ensemble approach).[55]

Method

1) SSP-RCP scenarios

The SSP-RCP scenario framework is designed to explore plausible futures of human activities, emissions, and the changing climate. The Shared Socioeconomic Pathways (SSPs) include different narratives of future trends in socioeconomic drivers and environmental actions, particularly air pollution control efforts.[24,40] The Representative Concentration Pathways (RCPs) consider different targets for end-of-century climate forcing level to represent varying levels of climate mitigation efforts.[56] As such, the SSP-RCP integrated scenario architecture captures the central features of global socioeconomic trends, air pollution efforts, and climate policies through the end of the century.[57]

In our study, we select five scenarios that cover a range of SSPs and RCPs. We first include four Tier 1 scenarios from the Scenario Model Intercomparison Project (ScenarioMIP; see Supplementary Information Section 1.1 for more information),[33] a major activity to provide multi-model concentration-driven climate projections based on future emissions and land use trends:[33,58] SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. We also include one additional scenario, SSP1-1.9, which targets the end-of-century warming level to be below 1.9 W/m^2. More information is included in the Supplementary Information Section 1 and Figure S1.

The CO_2 emissions from these five scenarios are reported by the IIASA SSP database.[38,43] The projection for the energy structure is taken from one integrated assessment model, the Global Change Analysis Model, that include energy projections in 32 world regions including the representation of major countries of interest here (as shown in Figure 6a).

2) Simulations of ambient $PM_{2.5}$ concentrations

Using downscaled emissions (0.5° latitude x 0.5° longitude) consistent with the projections from the integrated assessment models,[48] we simulate the ambient $PM_{2.5}$ concentrations using the Earth System Model v4.1 developed by Geophysical Fluid Dynamics Laboratory (GFDL-ESM4.1).[26,27] The ESM4.1 model has comprehensive representations of Earth system interactions and coupled carbon chemistry. In particular, its atmospheric component, AM4.1,[25] has been developed for chemistry and air quality applications. AM4.1 includes representations of physics, dynamics, radiation, aerosol, and chemistry interactions via forcing inputs, well-mixed greenhouse gas mixing ratio inputs, precursor emissions inputs, land component, ocean-atmosphere physical and chemical interactions, and chemical processes that are calculated within the module. It has an improved set of chemical parameterizations reflecting consistency in presentation of various species and advances of the underlying science over the course of decades. The GFDL-ESM4.1 model indicates the substantial development of coupled carbon-climate and coupled chemistry-climate modeling for understanding the changing climate system; it is numerically efficient and demonstrates “fidelity to participate as a state of the art contribution”.[26] Evaluation of the simulated aerosol concentrations against observations is reported in prior publications, including surface $PM_{2.5}$ observations[59], as well as key aerosol components such as sulfate and nitrate[25,26]. These model evaluation efforts demonstrate satisfying model capabilities in predicting ambient aerosol concentrations (see more Supplementary Information Section 1.2).[25]

For each of the SSP-RCP scenarios, transient ESM4 simulations are conducted at ~100 km spatial resolution for the time period 2015–2100. We then calculate the monthly and annual mean concentrations for the health impact assessment in the following steps.

3) Health impact assessment

For each five-year age group from 0 to 95+, we calculate premature deaths in 199 countries and regions, as well as subnational states and provinces for four large countries – China, India, USA, and Brazil. These four countries currently account for 62% of global total $PM_{2.5}$-related deaths according to our assessment (Figure 2). We consider six diseases that have found to be associated with air pollution exposure: ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer, lower respiratory tract infection (LRI), and type-2 diabetes.

For each region, age group and disease type, the premature deaths associated with ambient $PM_{2.5}$ exposure are calculated using the following equation:

$$\Delta Mort = y_0 \times AF \times Pop,$$

where y_0 is the baseline mortality rate for the exposed population, AF is the attributable fraction, and Pop is the size of exposed population. In particular, AF is calculated as $AF = (RR - 1)/RR$, where RR is the relative risk attributable to ambient $PM_{2.5}$ exposure. Below we describe the data source and methods for each parameter.

a) Population (Pop)

Based on the population and economic projections from the integrated assessment models, we obtain age-specific population projections from two datasets. For country-level total population and age structure, we use the projections from the IIASA SSP population dataset,[38,39] which includes projections from 2020 to 2100 (with five-year intervals) for each five-year age group.[38,39] To match the spatial resolution of our air quality simulation and calculate population-weighted $PM_{2.5}$ concentrations, we downscale population to the subnational level using the NASA SEDAC gridded global population projections, from 2010 to 2100 with 10-year intervals and a 1/8-degree (7.5 arcminutes) resolution.[44,45]

b) Baseline Mortality Rates (y_0)

For 2015, we use the country-level baseline mortality rates, by age group and disease type, from the Global Burden of Disease study.[60] For future periods for each SSP, we use the age-specific baseline mortality rates for each country projected by the International Futures (IFs) model v7.45.[28]

The baseline mortality rates from IFs are projected based on primary drivers such as income, education and technology advance, combined with a range of other social and behavioral factors.[61] The projections are calibrated using the GBD 2004 data for cardiovascular diseases, diabetes, malignant neoplasms, respiratory diseases, and respiratory infections. To map IF-reported rates onto the six diseases considered in this study, for IHD and stroke, we use the rates for total cardiovascular disease from IF and multiply by the shares of IHD and stroke in total cardiovascular-disease-related deaths; for LC, we use the rates for malignant neoplasms; for COPD, we use the rates for respiratory disease; for LRI, we use the rates for respiratory infections; and for type-2 diabetes, we use the rates for diabetes. To cross-check the validity of this mapping method, we find that the 2015 baseline mortality rates calculated using our methods are comparable to the rates reported by the GBD study (see Supplementary Table S1).

c) Attributable Fractions (AF)

We apply age-specific concentration-response relationships from the GBD 2019 study to calculate the relative risks (RR) and attributable fractions (AF).[1,29] The RRs are derived from the Integrated Exposure–Response (IER) model for six types of diseases for the $PM_{2.5}$ exposure levels from 0 to 600μg/m^3. Reported with 95% Confidence Intervals (CI), the RRs are age-specific for IHD and stroke (from 25 to 95+ at five-year interval) and are for all age-groups for the other four diseases. To test the sensitivity of our results to the choice of RRs, we also consider the RR from GBD 2017[30,31] and GEMM;[2] we report the results of this sensitivity analysis in Supplementary Fig S11 and S12.

To obtain the long-term exposure level for RR calculation, we use annual average $PM_{2.5}$ concentrations from the GFDL-ESM4.1 simulations. Based on ArcGIS Pro geoprocessing tools, we match the $PM_{2.5}$ concentrations (1° latitude by 1.25° longitude) with the projected population (1/8-degree) to obtain population-weighted $PM_{2.5}$ exposure levels in each country and subnational region.

4) Decomposition analysis

For each country and subnational region, we calculate the percent contribution of four individual factors to the future changes in premature deaths: i) effect of population growth, ii) effect of the change in age structure (i.e., population aging), iii) effect of the change in exposure (measured as annual mean ambient $PM_{2.5}$ concentration), and iv) the effect of mortality rates independent of exposure to $PM_{2.5}$ (i.e., change in baseline mortality rate due to changes in access to care, treatment and other risk factors).

Here we follow the decomposition approach in GBD 2015.[62] For instance, to calculate the effect of each factor contributing to the changes in premature deaths in 2100 relative to 2015, we first estimate the total attributable burdens in 2015 and 2100 from the health impact assessment described in the previous section:

$$Total\ burden_{2015} = \sum_{a=1}^{95+} (Pop_{2015a} * y_{0_{2015a}} * AF_{2015a}) \quad (1)$$

$$Total\ burden_{2100} = \sum_{a=1}^{95+} (Pop_{2100a} * y_{0_{2100a}} * AF_{2100a}) \quad (2)$$

where y_0 = cause-specific mortality rate; AF = attributable fraction; Pop = population; a = age group at five-year intervals from 0 to 95+ (i.e., 0-4, 5-9, …, 90-94, 95+).

We then define:

$$A = \sum_{a=1}^{95+} Pop_{2100a} * \frac{\sum_{a=1}^{95+} (y_{0_{2015a}} * Pop_{2015a})}{\sum_{a=1}^{95+} Pop_{2015a}} * AF_{all,\,2015} \quad (3)$$

$$B = \sum_{a=1}^{95+} (Pop_{2100a} * y_{0_{2015a}} * AF_{2015a}) \quad (4)$$

$$C = \sum_{a=1}^{95+} (Pop_{2100a} * y_{0_{2100a}} * \frac{1-AF_{2100a}}{1-AF_{2015a}} * AF_{2015a}) \quad (5)$$

Based on equations (1) – (5), we calculate the percent contribution of each factor as follows:

- Population growth effect (%) = (A – total attributable burden in 2015) / total attributable burden in 2015
- Population aging effect (%) = (B – A) / total attributable burden in 2015
- Baseline mortality rate change effect (%) = (C – B) / total attributable burden in 2015
- Exposure change effect (%) = (total attributable burden in 2100 – C) / total attributable burden in 2015
- Total change (%) = (total attributable burden in 2100 – total attributable burden in 2015) / total attributable burden in 2015

In addition to a decomposition analysis for the changes in premature deaths in 2100 relative to 2015, we also conduct a similar analysis for 2050 (see Supplemental Figure S9).

Data Availability Statement

All the data being used in this study are publicly available, which can be downloaded from the following links. 1) Ambient $PM_{2.5}$ data: https://esgf-node.llnl.gov/search/cmip6/ (select Activity = 'ScenarioMIP', Institution ID = 'NOAA-GFDL', Variable = 'mmrpm2p5'). 2) Future population data (two links): https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10 and https://beta.sedac.ciesin.columbia.edu/data/set/popdynamics-pop-projection-ssp-2010-2100. 3) GCAM energy mix data: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10. 4)

Future baseline mortality rate projection: https://drupalwebsitepardee.s3-us-west-2.amazonaws.com/pardee/public/IFs+with+Pardee+7_45+Aug+22+2019.zip. 5) Future CO2 emissions data: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10.

Code Availability Statement

Projections on future baseline mortality rates were retrieved using the International Futures (v7.45) software. No other software was used to collect the data. Python, MATLAB, R were used for data analysis, as well as ArcGIS Pro (v2.5) and Microsoft Excel (v2022). Upon publication, all computer codes will be available at: https://doi.org/10.5281/zenodo.6558608**.**

Author Contributions

H.Y. and W.P. contributed equally to this work. H.Y. and W.P. conceived and designed the study. H.Y., W.P. and X.H. performed the analysis with data input from D.W. and L.H. H.Y. and W.P. wrote the manuscript with important input from all authors.

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