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REPORT

Local mortality impacts due to future air pollution under global climate change scenarios

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Abstract

Global governance arrangements play a critical role in climate change mitigation, although the health impacts of global mitigation efforts will affect local populations differently. We aimed to quantify the local health impacts due to fine particles ($PM_{2.5}$) under the governance arrangements embedded in the Shared Socioeconomic Pathways (SSPs1-5) under two greenhouse gas concentration scenarios (RCPs 2.6 and 8.5). We focus on three populations (Manhiça, Mozambique, Vadu, India, Barcelona, Spain) to investigate vulnerability due to stage of economic development. We considered climate change scenarios specified by combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) and estimated $PM_{2.5}$ concentrations for the period of 2010-2050 for each SSP-RCP scenario using the Global Change Analysis Model linked to The Fast Scenario Screening Tool (TM5-FASST). We used comparative risk assessment methods to estimate attributable premature deaths due to $PM_{2.5}$ through 2050 under each SSP-RCP scenario by linking local population and mortality data with $PM_{2.5}$–mortality relationships from the literature. Holding population change constant, variation in $PM_{2.5}$ attributable deaths across SSP-RCP scenarios was small in Manhiça (a range of 5 deaths per 100,000 in RCP2.6 to 4 in RCP8.6) and Barcelona (7 in RCP2.6 to 14 in RCP8.6), compared to Vadu (46 in RCP2.6 to 39 in RCP8.6). In sensitivity analysis, future attributable mortality burden of $PM_{2.5}$ was highly sensitive to assumptions about how populations will change according to SSP. SSPs reflecting high challenges for adaptation (SSPs 3 and 4) consistently resulted in the highest $PM_{2.5}$ attributable burdens in mid-century. Our analysis of local $PM_{2.5}$ attributable premature deaths under SSP-RCP scenarios in three case study populations highlights the importance of socioeconomic development and climate policy in reducing health burden from air pollution. Sensitivity of future $PM_{2.5}$ mortality burden to SSPS was particularly evident in low- and middle-income settings due to either high air pollution levels or dynamic populations.

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1. Introduction

The atmosphere is an essential part of the global environmental commons, which is being degraded through climate change and emissions of environment- and health-damaging air pollutants. Combustion of fossil fuels is not only the root cause of climate change, but also a source of a range of toxic air pollutants. There is increasing understanding that climate change will have profound, mostly harmful effects on human health and these effects will be distributed unequally (1). The largest health impacts will be borne by populations at increased vulnerability due to poverty, limited resources for adaptation, and weak public health and social protection infrastructure. Global governance arrangements play a critical role in climate change mitigation, although the health impacts of global mitigation efforts will affect local populations differently reflecting differences in population structures, underlying health status, and levels of environmental hazards (e.g. air pollution) affected by mitigation actions (2). Effective governance at national scales is critical to countries' future climate vulnerability and adaptive capacity. Institutions and governance are key determinants of long-term stability and sustainable development. Lack of institutional capacity is one of the most important constraints to adaptation across many sectors, including human health. Well-functioning institutions play key roles in implementation of adaptation strategies, and lack of institutional capacity has been identified as a critical constraint to adaptation across many sectors (e.g. human health) (3).

The Shared Socioeconomic Pathways (SSPs) are a scenario framework providing alternative futures of climate and society to facilitate integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (4). The pathways, which present alternative future societal developments, can be used across geographical scales (e.g. global, regional, national) to link climate change with other impacts (5). SSPs describe plausible global developments that combined would lead to different challenges for mitigation and adaptation to climate change and sustainable development more broadly. SSPs comprise both qualitative and quantitative components, where the qualitative description of broad trends in societal development are represented by the narratives: "Sustainability", "Regional Rivalry", "Inequality", "Fossil-fueled Development", and "Middle of the Road". These narratives provide a set of consistent, qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. These qualitative narratives can be combined with quantitative components of the SSPs through Integrated Assessment Models to describe the possible state of land use, energy and agricultural systems, and resulting emissions of greenhouse gases and air pollutants under different SSP and specific climate policy assumptions (6). SSPs can be combined with Representative Concentration Pathways (RCPs)(7), representing emissions and concentrations of greenhouse gases and their combined radiative forcing. For example, RCP 2.6 reflects radiative forcing levels roughly consistent with the Paris Agreement goal of warming of 2°C or below by end of century compared to preindustrial times. The matrix of SSPs and RCPs generate combined scenarios that span the range of different response options to climate change.

Exposure to ambient fine particles (particulate matter <2.5 μm in diameters ($PM_{2.5}$)) is

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recognized as a major global health concern and linked to reduced life expectancy (8–10). Future levels of $PM_{2.5}$ will depend on how society develops (6) as well as the level of ambition of climate change mitigation (e.g. fossil fuel combustion). Previous studies of future air pollution health co-benefits of climate policy have neither considered the full range of SSPs and nor included assessment at local level and therefore provide limited insights into the influence of global governance arrangements and development trajectories on the range of possible future co-benefits on population health.

There is a clear need to inform global governance arrangements with health impact assessments to better understand drivers of vulnerability at local scales and to consider how different climate mitigation policies can maximize health co-benefits of mitigation and minimize negative trade-offs. To address the need for quantitative evidence regarding how global governance manifests as local health impacts, we aimed to quantify the local health impacts due to air pollution exposure under the specific governance arrangements embedded in the SSPs (1-5) under two greenhouse gas concentration scenarios (RCP2.6 and RCP8.5). We focus on health impacts in three case studies of local populations spanning low-, middle- and high-income countries, allowing for investigation of vulnerability due to the stage of economic development.

2. Methods

2.1 Study Area

We focused on three local populations selected to cover different levels of development based on low-, middle-, and high-income country categories from the World Bank (11). We selected local populations which had (1) demographic and mortality surveillance data allowing for projections of future health impacts; and (2) $PM_{2.5}$ ground-based measurements allowing for local calibration of global air quality models (TM5FASST). The three populations included:

- Manhiça District, Mozambique (low-income country) in southern Mozambique, is approximately 80km north of Maputo City (latitude 25°24’ south and longitude 32°48’ east) covering an area of 2.373 km^2. The Demographic and mortality surveillance for the entire district population is conducted through a Health and Demographic Surveillance System (HDSS); the HDSS covered a population of 93,473 in 2010 (12).
- Vadu HDSS, India (middle-income country) includes 22 villages of Shirur and Haveli Block (Tehsils) of Pune district in Maharashtra state. The population covered by routine demographic and mortality surveillance in 2010 was 73,446. Vadu HDSS (latitude 18°30 to 18°47N & longitude 73°58 to 74°12E) covers a geographical area of 232km^2 (13).
- Barcelona City, Spain (high-income country) is the second largest city in Spain is located on the north eastern coast of the Iberian Peninsula. Barcelona's climate is coastal Mediterranean (latitude 41°23 N and longitude 2°9 E); the total population was 1.619 million in 2010, and the city covers an area of 109.4km^2.

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2.2 Climate Change Scenarios

We included the five SSPs spanning the space of challenges to mitigation and adaptation to climate change, which are described briefly in Table 1. We considered scenarios based on paired SSPs with a set of mitigation scenarios (RCP2.6 and RCP8.5) for the period 2010 to 2050 (S-Figure 1). SSP1 (Sustainability) is not compatible with RCP8.5, which involves high greenhouse gas emissions; we therefore report results for nine SSP-RCP scenarios. We linked qualitative narratives of the SSPs with quantitative SSP components using emissions from the Global Change Analysis Model (GCAM) which specifies the behaviour of, and interactions between, the energy system, water, agriculture and land use, the economy, and the climate (http://www.globalchange.umd.edu/gcam/).

Table 1. Overview of SSPs and their links with governance and related factors.

	SSP1	**SSP2**	**SSP3**	**SSP4**	**SSP5**
Label	Sustainability	Middle of the road	Regional rivalry	Inequality	Fossil-fueled development
Governance	Effective institutions, persistent international cooperation	Institutions are modestly effective and uneven	Ineffective, reduced support for international and development institutions	Stronger in high- income regions; in low-income regions, basic human development is neglected and policy implementation is likely to be unsuccessful due to weak governance	Assumes improved institutions and rapid human development, particularly for the currently disadvantaged populations
Income level	High	Medium	Very unequal between countries	Very unequal between and within countries	High
Level of attainment of higher education	High	Medium	Low	Unequal	High
Gender equality in education	High	Medium	Low	Unequal within regions	High
Population	Educational and health investments accelerate demographic transition, leading to low world population	Combination of medium fertility, mortality, and migration and education levels for all countries	Population growth is assumed to be high in developing countries and low in industrialized countries	Increasing stratification in education levels; high fertility in today's high fertility countries, high mortality in high fertility	High levels of education and low mortality for all countries. High fertility assumed for rich OECD countries and low fertility

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				countries, medium mortality and migration elsewhere	elsewhere

2.3 Integrated modelling framework

2.3.1 Air pollution exposure modelling

We combined an integrated assessment model (GCAM) with an air quality tool (TM5-FASST) to estimate emissions and concentrations for each of the nine SSP-RCP modelling scenarios (combination of 9 scenarios linking 5 SSPs and 2 RCPs) for 32 global regions. We used GCAM to estimate future emissions of main air pollutants, which were used as inputs into TM5-FASST. TM5-FASST calculates $PM_{2.5}$ concentrations using underlying parametrizations of meteorology and atmospheric chemistry drawn from more complex models. The combined use of these models is explained in more detail in Sampedro et al (15).

Application of $PM_{2.5}$ estimates from global models to local areas is highly uncertain without correction using ground-based measurements. We derived a site-specific correction factor comparing locally measured $PM_{2.5}$ levels to the corresponding TM5-FASST $PM_{2.5}$ concentrations estimated for the study areas for the same year as the measurements or a linear-interpolation between model years. We then applied the site-specific correction factor to TM5-FASST $PM_{2.5}$ for each time slice (e.g. 2030, 2050). Measured $PM_{2.5}$ concentrations were as follows:

- Manhica- 13.8 μg/m^3 annual average for 2015 (16)
- Vadu - 47.2 μg/m^3 five month average from 2019
- Barcelona- 16.1 μg/m^3 annual average for 2015 derived from background stations of air monitoring network(17).

2.3.2 Air Pollution and Health Impact Modelling

In our main analysis, we modelled health impacts among adults (age ≥ 25 years) for the 2010 population assuming population size, structure, and mortality rates remained constant through 2050. Population by age and sex in 2010 were based on observed data in each population. We used observed mortality data to estimate the average mortality rate between 2005-2015, which we used to estimate the mortality rate for 2010. Age-specific all-cause mortality rates were available from the Manhiça and Vadu HDSS; however, cause-specific mortality rates for these populations were not available. To estimate cause-specific mortality rates, we assumed the local population had the same proportion of total deaths due to non-communicable disease (NCDs) and lower respiratory infections (LRI) as the country (Mozambique) or state (Maharashtra, India) (18) reported in the Global Burden of Disease (GBD 2010). We used age- and cause-specific mortality data for Barcelona to calculate the percentage of deaths due to NCD+LRI based on data from Instituto Nacional de Estadística (INE), Spain. We assumed the

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cause-specific mortality rates estimated in 2010 were constant through 2050.

We estimated the total number of premature NCD+LRI deaths attributable to $PM_{2.5}$ under each SSP-RCP scenario using comparative risk assessment methodology combining data on population exposure levels under each scenario, age-specific mortality rates in 2010, age-specific percentage of deaths due to NCD+LRI, and age-specific $PM_{2.5}$-mortality relationships from the literature. By premature deaths, we refer to deaths at any age brought forward in time due to exposure. We applied the Global Exposure Mortality Model (GEMM) (8) to estimate the risk of death from NCD+LRI in relation to $PM_{2.5}$ exposures according to 5-year age groups. Hazard ratios in GEMM are based on observational epidemiological studies across a relatively wide range of exposure (2.4 μg/m^3 to 84 μg/m^3) (8). We estimated the number of NCD+LRI deaths due to $PM_{2.5}$ levels in each SSP-RCP scenario relative to the lowest observed exposure level in the studies used to develop GEMM (2.4 μg/m^3). For each five-year age group, we calculated the population attributable fraction as one minus the inverse of the age-specific hazard ratio: the ratio of the probability of death by a certain age given a specific exposure relative to the probability of death at that age assuming the lowest observed exposure level (2.4 μg/m^3) (8).

2.3.3 Sensitivity Analysis

In sensitivity analysis, we allowed the size and age structure of the population and all-cause mortality rate to change over time according to SSP. Because of lack of consistent projections of cause-specific mortality by SSP, we assumed the % of deaths due to NCD+LRI remained at 2010 levels through 2050. Population projections by age, sex, and SSP have been previously developed for each country based on assumptions about future fertility, mortality, migration, and educational transitions according to three groups of countries: high fertility, low fertility, and rich-OECD countries (19). Our three case study populations illustrate assumptions for each country group. We used data generated as part of the population projections included in the SSP Public Database (20), which modelled Mozambique as high fertility, India as low fertility, and Spain as a rich-OECD country. We used country-level deaths by age group under each SSP for each time slice, a component of the population projection (14) (projected deaths data provided by Samir KC) to capture differences in all-cause mortality rates and population changes according to SSPs. We assumed that the relative change in age-specific deaths from 2010 to each time slice at the country level was the same for our sub-national populations. All other steps in the health impact calculations were as in the main analysis.

3. Results

3.1 Projection of ambient PM2.5 exposures under modelling scenarios

Estimates of population exposure to $PM_{2.5}$ under each SSP-RCP scenario for the year 2050 for each case study population are presented in **Figure 1**. The SSP3-RCP8.6 scenario resulted in the highest levels of $PM_{2.5}$ in 2020-2050 for all three populations. In Manhiça,

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Mozambique, the highest $PM_{2.5}$ levels were projected under SSP3 and SSP4 scenarios for the Year 2020 in combination with RCP8.5 (8.4 μg/m^3 and 8.3 μg/m^3) and lowest among SSP1 and SSP5 under RCP2.6 (6.5 μg/m^3). Differences in $PM_{2.5}$ levels in Manhiça across scenarios were small. In Vadu, India, $PM_{2.5}$ in 2050 was estimated to be highest under SSP3-RCP8.6 (65.0 μg/m^3) and lowest under SSP1-RCP2.6 (24.5 μg/m^3). In Barcelona, Spain, the highest $PM_{2.5}$ level was under SSP3-RCP8.6 (15.1 μg/m^3) in the year 2020 and the lowest under SSP2-RCP2.6 (6.8 μg/m^3) in the year 2050. Of the three populations, differences in $PM_{2.5}$ levels across scenarios were largest in Vadu.

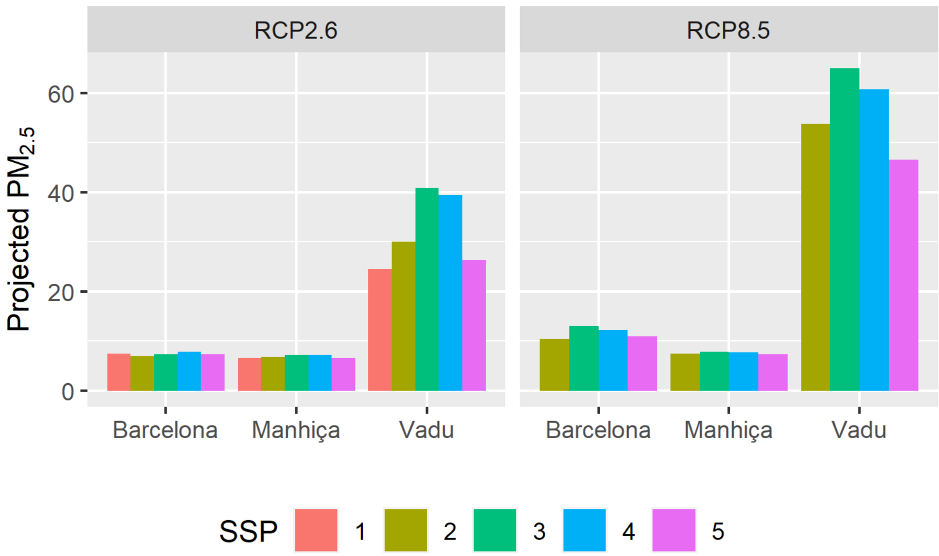

Figure 1. Projected levels of PM2.5 in μg/m3 in 2050 according to scenario for each case study population

3.2 Projection of premature mortality burden attributable to PM2.5

The magnitude of the burden of and patterns over time in projected premature deaths per population differed across SSP-RCP scenarios and case study populations (**Figure 2**). In all case study populations, increasing stringency of warming limits reflected in the RCP2.6 scenarios resulted in lower burden of $PM_{2.5}$ attributable mortality compared to RCP8.6 scenarios. Key results for each case study population (Manhiça, Vadu and Barcelona) follow:

3.2.1 Manhiça, Mozambique

$PM_{2.5}$ attributable deaths in Manhiça decreases under all SSP-RCP scenarios between 2020 and 2050 (**Figure 2**). For each SSP, $PM_{2.5}$ attributable mortality was lower under RCP2.6 compared to RCP8.5. Among the RCP2.6 scenarios, SSPs reflecting sustainability (SSP1) and fossil-fueled development (SSP5) pathways had the lowest $PM_{2.5}$ attributable mortality in

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2050, whereas the pathway with high global inequalities and challenges to adaptation (SSP4) resulted in the highest attributable mortality.

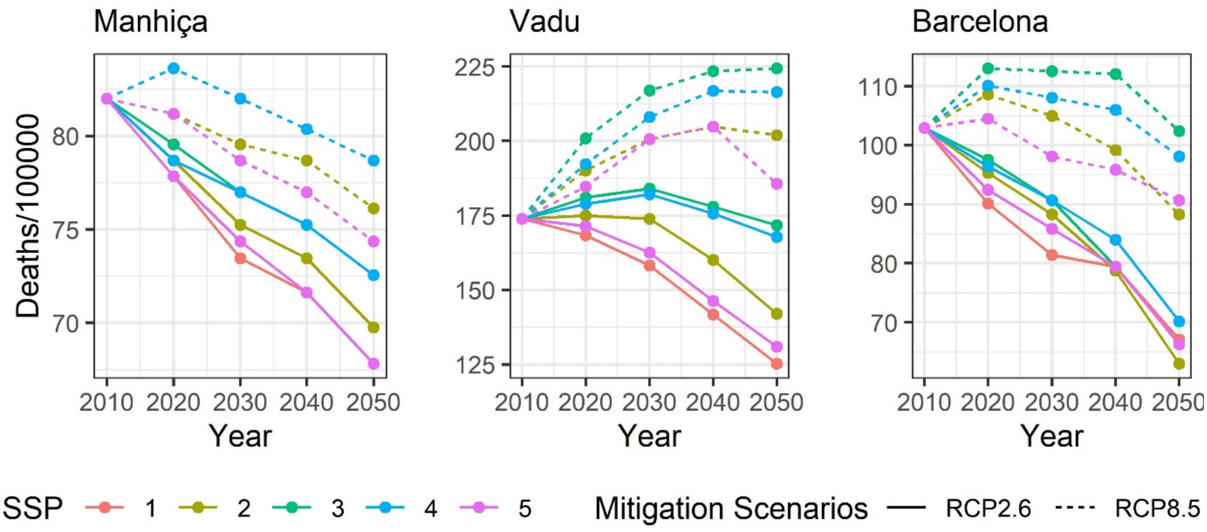

Figure 2. Projected premature deaths from non-communicable disease + lower respiratory infections (per 100,000 population) among adults due to PM2.5 across SSP-RCP scenarios in Manhiça, Mozambique, Vadu, India, and Barcelona, Spain assuming population constant at 2010 levels.

3.2.2 Vadu, India

$PM_{2.5}$ attributable deaths in Vadu increase in nearly all RCP8.5 scenarios between 2020 and 2050 (**Figure 2**). Under RCP8.5, the fossil-fueled development (SSP5) pathway leads to an increase in attributable deaths between 2020 and 2040, after which levels return to those of 2020. Only for RCP2.6 under the sustainability (SSP1) and fossil-fueled development (SSP5) pathways are there consistent decreases in attributable deaths between 2020 and 2050. Similar to Manhiça, the lowest mortality burden projected under RCP2.6 is under the sustainability (SSP1) and fossil-fueled (SSP5) development pathways.

3.2.3 Barcelona, Spain

There were consistent decreases in $PM_{2.5}$ attributable deaths in Barcelona between 2020 and 2050 under RCP2.6 scenarios (**Figure 2**). Under RCP8.5, decreases between 2020 and 2040 were modest for pathways characterized by regional rivalry (SSP3) and high levels of inequality (SSP4). Under RCP8.5, $PM_{2.5}$ attributable deaths per 100,000 populations in 2050 ranged from 88 (SSP2) to 102 (SSP3) across SSPs. Under RCP2.6, $PM_{2.5}$ attributable deaths under different SSPs started to converge in 2040; by 2050 all SSPs had similar values of around 66 attributable deaths per 100,000.

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3.2.4 Sensitivity Analysis Results

Differences in premature mortality across scenarios in the main analysis reflected differences in $PM_{2.5}$ exposures. In the sensitivity analysis however, differences across SSPs also included the influence of changes in population size, structure, and mortality rates, for this reason results are not reported per population (**Figure 3**). Incorporating information on the projected population, the number of $PM_{2.5}$ attributable deaths in Manhiça increased between 2010 and 2050 considerably in all scenarios. Number of attributable premature deaths in 2050 was driven more by SSP than by RCP. $PM_{2.5}$ attributable deaths in 2050 ranged between 49 (SSP5) and 75 (SSP3) within RCP8.5 and between 44 (SSP5) and 69 (SSP3) for RCP2.6. Within SSP differences by RCP were relatively modest. The largest number of attributable deaths was projected in 2050 for the pathways characterized by regional rivalry (SSP3) and inequality (SSP4) paired with RCP8.5. Values for SSP1 and SSP5 paired with RCP2.6 yielded very similar number of attributable premature deaths in 2050. In Vadu, $PM_{2.5}$ attributable deaths in 2050 ranged between 114 (SSP5) and 194 (SSP3) within RCP8.5 and between 77 (SSP1) and 148 (SSP3) for RCP2.6. In Barcelona, the influence of population changes across SSPs determined whether $PM_{2.5}$ attributable deaths increased or decreased between 2010 and 2050. Steady decreasing trends in $PM_{2.5}$ attributable deaths were projected for SSPs 1 and 5 under RCP2.6 whereas for SSP3, deaths increased before returning to 2010 levels. Steady increased in $PM_{2.5}$ attributable deaths between 2010 and 2050 were projected for SSP3 under RCP8.5. $PM_{2.5}$ attributable deaths in 2050 ranged between 1548 (SSP5) and 2293 (SSP3) within RCP8.5 and between 1141 and 1134 (SSPs1 and 5) and 1488 (SSP3) for RCP2.6.

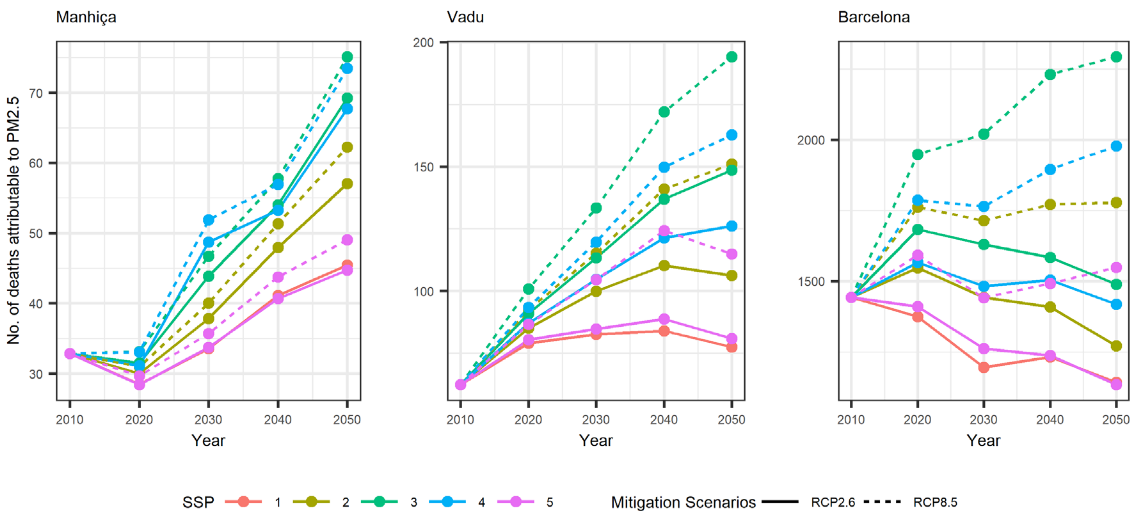

Figure 3. Projected premature deaths from non-communicable disease + lower respiratory infections among adults due to $PM_{2.5}$ across SSP-RCP scenarios in Manhiça, Mozambique, Vadu, India, and Barcelona, Spain accounting for population changes by SSP.

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4. Concluding Remarks

Our analysis highlights several important data and evidence gaps that should be targets for future research. These include: 1) better spatial resolution of current and projected air pollution emissions, particularly in global regions with high uncertainties (e.g. sub-Saharan Africa); 2) improved vital statistics and cause of death data in many world regions including India and sub-Saharan Africa: and 3) epidemiological evidence linking ambient $PM_{2.5}$ and mortality from a wider range of LMICs than was included in GEMM, which was limited to China.

In conclusion, our study of $PM_{2.5}$ attributable premature deaths under nine SSP-RCP scenarios in three local sites highlights the importance of socioeconomic development and climate policy in reducing health burden from air pollution, particularly in LMIC settings with dynamic populations (e.g. Mozambique) and/or high air pollution levels (e.g. India). Effective climate governance at global and national levels could critically influence the burden of health at the local level.

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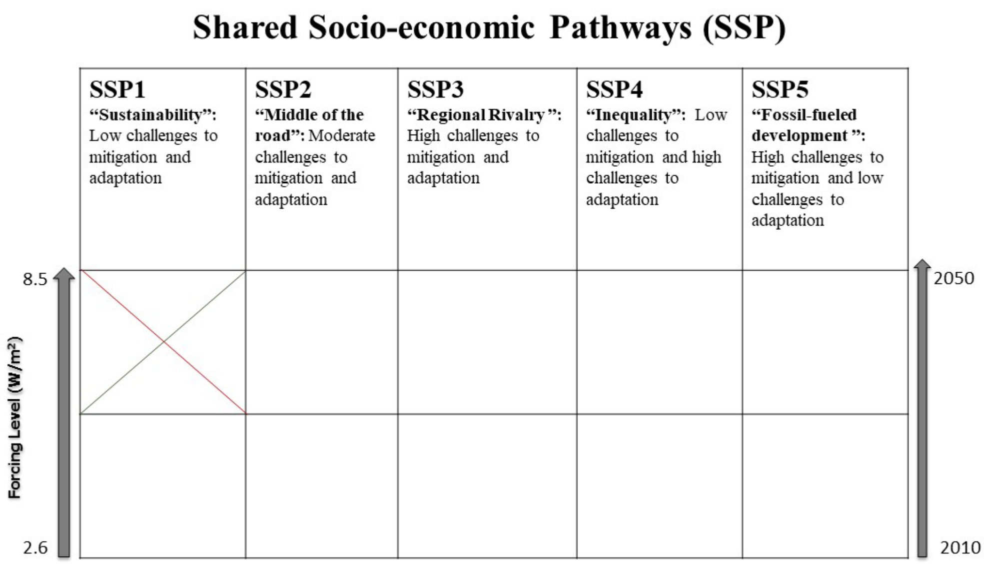

SFigure 1: The scenario matrix architecture combines different socio-economic reference assumptions as described by SSPs (1-5) with different future levels of climate forcing (2.6 and 8.5)(7) .

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