Science of the Total Environment 823 (2022) 153832

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

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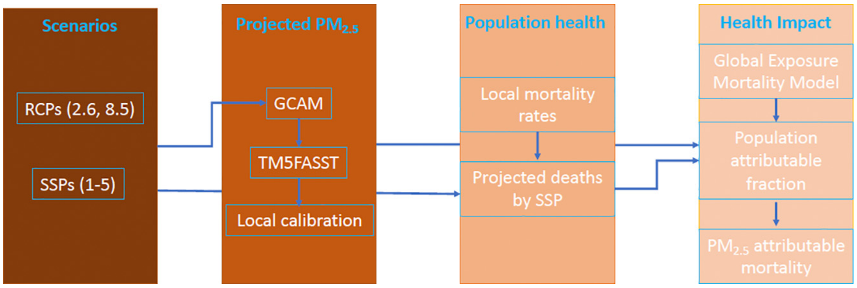
HIGHLIGHTS

- Local health and air pollution data used to explore vulnerability by development stage
- Influence of SSPs on $PM_{2.5}$ attributable deaths varied across populations.
- SSPs reflecting high challenges for adaptation had largest $PM_{2.5}$ attributable deaths.
- $PM_{2.5}$ attributable deaths highly sensitive to assumptions about population change under SSPs

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 November 2021
Received in revised form 27 January 2022
Accepted 8 February 2022
Available online 11 February 2022

Editor: Pavlos Kassomenos

Keywords:
Climate change mitigation
Shared socioeconomic pathways
Air pollution
Mortality
Health and Demographic Surveillance Systems

ABSTRACT

The health impacts of global climate change mitigation will affect local populations differently. However, most co-benefits analyses have been done at a global level, with relatively few studies providing local level results. 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 (Representative Concentration Pathways (RCPs) 2.6 and 8.5) in local populations of Mozambique, India, and Spain. We simulated the SSP-RCP scenarios using the Global Change Analysis Model, which was linked to the TM5-FASST model to estimate $PM_{2.5}$ levels. $PM_{2.5}$ levels were calibrated with local measurements. We used comparative risk assessment methods to estimate attributable premature deaths due to $PM_{2.5}$ linking local population and mortality data with $PM_{2.5}$–mortality relationships from the literature, and incorporating population projections under the SSPs. $PM_{2.5}$ attributable burdens in 2050 differed across SSP-RCP scenarios, and sensitivity of results across scenarios varied across populations. 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 mid-century. Our analysis of local $PM_{2.5}$ attributable premature deaths under SSP-RCP scenarios in three local populations highlights the importance of both socioeconomic development and climate policy in reducing the health burden from air pollution. Sensitivity of future $PM_{2.5}$ mortality burden to SSPs was particularly evident in low- and middle- income country settings due either to high air pollution levels or dynamic populations.

1. Introduction

The troposphere is an essential part of the global environmental commons, which is being degraded through climate change and emissions of

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http://dx.doi.org/10.1016/j.scitotenv.2022.153832

environment- and health-damaging air pollutants. Atmospheric pollutants, especially anthropogenic greenhouse gases, have the potential for impacting the health of distant populations (Roy et al., 2018). There is increasing understanding that climate change will have profound, mostly harmful effects on human health, and these effects will be distributed unequally. 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 (Coen et al., 2020), 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) among other factors.

Most health co-benefits studies have been done at a global level, with relatively few studies providing local (e.g. city) level analysis (Deng et al., 2017). Relative to other world regions, very few health co-benefits studies have specifically focused on African contexts (Deng et al., 2017). Translating insights from one location to another is challenging unless all underlying mechanisms are well understood. Information on the health co-benefits of climate change mitigation at the local-level can help support policy decisions for local communities as well as provide rationales for taking mitigation action that are more persuasive to particular sets of decision makers (Deng et al., 2017).

The Shared Socioeconomic Pathways (SSPs) are a scenario framework providing alternative futures of society to facilitate integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (O'Neill et al., 2017). 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 (Absar and Preston, 2015). 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, urbanization, human development (human and social capital), economy and lifestyle, policies and institutions, technology, and environment and natural resources (S-Table 1). These qualitative narratives have supported a range of quantitative extensions of the SSPs including projections from Integrated Assessment Models (O'Neill et al., 2020). These quantitative components are useful 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 (O'Neill et al., 2020; Riahi et al., 2017; KC and Lutz, 2017; Rao et al., 2017).

SSPs can be combined with Representative Concentration Pathways (RCPs) (O'Neill et al., 2020; van Vuuren et al., 2011), representing emissions and concentrations of greenhouse gases and their combined radiative forcing. For example, RCP2.6 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 (S-Fig. 1) (van Vuuren et al., 2014). Air pollution emissions are projected to change according to both the specific RCP and SSP scenario, reflecting the influence of societal futures as well as climate change mitigation. Richer detail on how populations will evolve under the SSPs better reflects vulnerability to climate change induced hazards (O'Neill et al., 2020).

Exposure to ambient fine particles (particulate matter <2.5 μm in diameters ($PM_{2.5}$)) is a major global health concern and is linked to reduced life expectancy (Burnett et al., 2018; Apte et al., 2015; Cohen et al., 2017). Future levels of $PM_{2.5}$ will depend on how society develops (Rao et al., 2017), demographic change (ageing), as well as the level of ambition of climate change mitigation due to shared sources of emissions of greenhouse gases and air pollutants (e.g. fossil fuel combustion). Health co-benefits of climate change mitigation through reduced air pollution have been quantified in many previous studies (Karlsson et al., 2020). However, previous studies of future health co-benefits due to reduced air pollution have considered either RCPs alone (Silva et al., 2016; West et al., 2013), or a limited set of SSPs (Chowdhury et al., 2018; Kim et al., 2020), and have not assessed health impacts at local levels, therefore providing limited insights into the influence of global governance arrangements and development trajectories on the range of possible co-benefits across local contexts (Orru et al., 2017).

There is a clear need 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 tradeoffs. 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 leveraged local ground-based measurements, demographic, and health data in three local populations spanning low-, middle- and high-income countries, allowing for investigation of vulnerability for populations at different stages of economic development and urbanization.

2. Methods

2.1. Study settings

Our scenario-based health impact modelling study 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 (2020). We selected local populations which had (1) demographic and mortality surveillance data allowing for projections of future health impacts under our scenarios; and (2) $PM_{2.5}$ ground-based measurements allowing for local calibration of global air quality models. The three populations included:

- Manhiça District, Mozambique (low-income country): The district of Manhiça in southern Mozambique is approximately 80 km north of Maputo City (latitude 25°24′ south and longitude 32°48′ east) covering an area of 2373 km^2. 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 (Nhacolo et al., 2021).
- Pune District, India (middle-income country): The Vadu HDSS includes 22 communities of Shirur and Haveli Block (Tehsils) of Pune district in Maharashtra, India. 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 (Patil et al., 2019).
- Barcelona City, Spain (high-income country): Barcelona, the second largest city in Spain is located on the northeastern coast of the Iberian Peninsula. Barcelona's climate is coastal Mediterranean (latitude 41°23 N and longitude 2°9 E) and the total population was 1.6 million in 2010 and covers a geographical area of 101km^2.

2.2. Scenarios

We included five SSPs spanning the space of challenges to mitigation and adaptation to climate change, which are described briefly in S-Table 1. We considered scenarios based on paired SSPs with greenhouse gas concentration scenarios (RCP2.6 and RCP8.5), which imply mitigation pathways, for the period 2010 to 2050 (S-Fig. 1). SSP1 (Sustainability) is not compatible with RCP8.5, which involves high greenhouse gas emissions. We therefore report results for nine SSP-RCP scenarios for 2050, although by 2100, RCP8.5 is likely to be incompatible with all SSPs other than SSP5 (fossil-fueled development) (O'Neill et al., 2020). We linked qualitative narratives of the SSPs with quantitative SSP components using emissions from the Global Change Analysis Model (GCAM), which specifies the behavior of, and interactions between, the energy system, water, agriculture and land use, the economy, and the climate (Joint Global Change Research Institute, 2021). GCAM implements the SSP scenarios by using SSP-specific socioeconomic assumptions (population and GDP growth rates) in combination with technology assumptions derived from the SSP literature. More details on the SSP implementation in GCAM can be found in the dedicated documentation (Joint Global Change Research Institute, n.d.). RCPs are radiative forcing constraints which adjust carbon prices in order to find the least cost path to reaching the target.

2.3. Integrated modelling framework

2.3.1. Air pollution exposure modelling

We combined the GCAM integrated assessment model with an air quality tool (TM5-FASST) to estimate emissions and concentrations for each of the nine SSPs-RCPs combined 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, namely black carbon, organic carbon, carbon monoxide, non-methane volatile organic compounds, ammonia, nitrogen oxides, and sulphur dioxide. These emissions were used as inputs into TM5-FASST, which calculates $PM_{2.5}$ concentrations using underlying parameterizations of meteorology and atmospheric chemistry drawn from more complex models (Van Dingenen et al., 2018). The combined use of these models is explained in more detail in Sampedro et al. (2020).

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 (CF) 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 (S-Fig. 2): Manhiça- 13.8 μg/m^3 annual average for 2015 (Curto et al., 2019); Vadu – 62.0 μg/m^3 ten-month average from 2019 to 2021; and Barcelona- 16.1 μg/m^3 annual average for 2015 derived from background stations of air monitoring network (SVCAC S de V de C del A de C, 2020). Site-specific correction factors (corrected $PM_{2.5}$ = CF ∗ TM5-FASST $PM_{2.5}$) were: 2.6 for Manhiça; 3.1 for Vadu; and 1.8 for Barcelona.

2.3.2. Health impact modelling

In our main analysis, we allowed the size and age structure of the population and all-cause mortality rate to change over time according to SSP. 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 (KC and Lutz, 2017). Our three local populations illustrate assumptions for each country group. We used data generated as part of the population projections included in the SSP Public Database, which modeled 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 (projected deaths data provided by Samir KC), to capture differences in all-cause mortality rates and population changes according to SSPs (KC and Lutz, 2017). 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. Because of lack of consistent projections of cause-specific mortality by SSP at national or subnational levels, we assumed the % of deaths due to non-communicable diseases (NCDs) and lower respiratory infections (LRI) remained at 2010 levels through 2050.

Population by age and sex in 2010 was based on demographic surveillance or census data in each location. In order to suppress year-to-year variability, we used the average observed mortality rate between years 2005–2015 to estimate the baseline 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 NCDs and LRI as the country (Mozambique) or state (Maharashtra, India) reported in the Global Burden of Disease (Institute for Health Metrics and Evaluation (IHME), 2017). 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, Spain.

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 (Burnett et al., 2018). 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) (Burnett et al., 2018) to estimate the risk of death from NCD + LRI in relation to $PM_{2.5}$ exposure 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) (Burnett et al., 2018). 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) (Burnett et al., 2018).

In sensitivity analysis, we modeled health impacts among adults (age ≥ 25 years) for the 2010 population assuming population size, structure, and mortality rates remained constant through 2050. All other steps in the health impact calculations were as in the main analysis.

3. Results

3.1. Projected ambient $PM_{2.5}$ exposure under modelling scenarios

Projected population exposure to $PM_{2.5}$ under each SSP-RCP scenario for the year 2020 to 2050 for each population is presented in Fig. 1 and S-Tables 2–4. The SSP3-RCP8.5 scenario resulted in the highest levels of $PM_{2.5}$ in 2050 for all three populations. In Manhiça, Mozambique, the highest $PM_{2.5}$ levels were projected under the SSP3-RCP8.5 scenario in 2020 (14.4 μg/m^3) and lowest under SSP5-RCP2.6 (11.2 μg/m^3). Differences in $PM_{2.5}$ levels in Manhiça across scenarios were small. In Vadu, India, projected $PM_{2.5}$ was highest under SSP3-RCP8.5 (91.6 μg/m^3) in 2050 and lowest under SSP1-RCP2.6 (34.5 μg/m^3) in 2050. Of the three populations, differences in $PM_{2.5}$ levels across scenarios were largest in Vadu. In Barcelona, Spain, the highest projected $PM_{2.5}$ level was under SSP3-RCP8.5 (18.2 μg/m^3) in 2020 and the lowest under SSP2-RCP2.6 (8.2 μg/m^3) in 2050.

3.2. Projected premature mortality burden attributable to $PM_{2.5}$ incorporating demographic change

Incorporating information on projected population size, structure, and mortality rates, the number of $PM_{2.5}$ attributable deaths in Manhiça increased between 2010 and 2050 considerably in all scenarios (Fig. 2). The 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 (S-Table 5). 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 139 (SSP5) and 228 (SSP3) within RCP8.5 and between 95 (SSP1) and 181

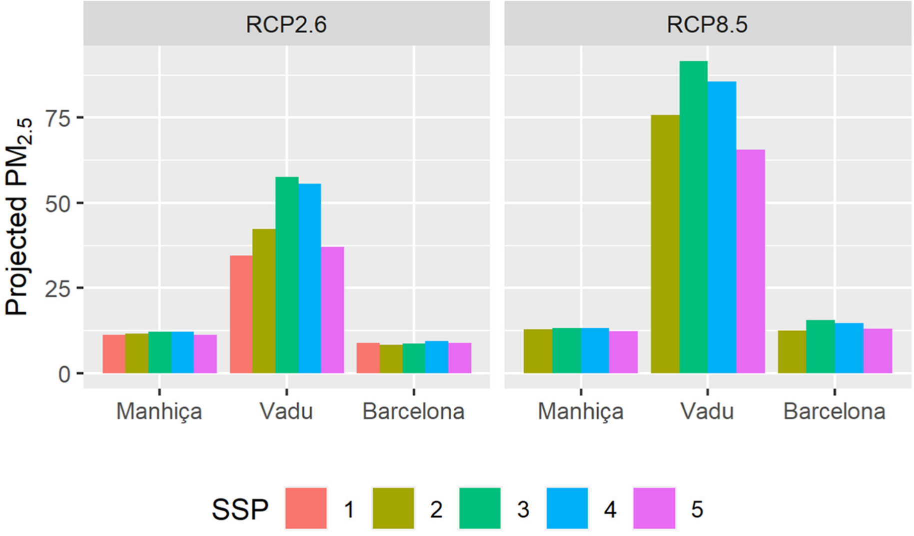

Fig. 1. Projections of $PM_{2.5}$ ($\mu g/m^3$) in 2050 according to scenario.

(SSP3) for RCP2.6 (S-Table 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 increases 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 1134 (SSP5) and 1488 (SSP3) for RCP2.6 (S-Table 7).

3.3. Projected premature mortality burden attributable to $PM_{2.5}$ assuming no demographic change

Differences in premature mortality across scenarios in the sensitivity analysis reflected only differences in $PM_{2.5}$ exposure. The magnitude of the burden of and patterns over time in projected premature deaths per population differed across SSP-RCP scenarios and local populations (Fig. 3 and S-Tables 8–10). In all local populations, RCP2.6 scenarios resulted in lower burden of $PM_{2.5}$ attributable mortality compared to RCP8.5 scenarios. Key results for each population (Manhiça, Vadu and Barcelona) follow:

$PM_{2.5}$ attributable deaths in Manhiça decreased under all SSP-RCP scenarios between 2010 and 2050 (attributable deaths per 100,000 population Fig. 3, per total population S-Table 8). Among the RCP2.6 scenarios, SSPs reflecting sustainability (SSP1) and fossil-fueled development (SSP5) pathways had the lowest $PM_{2.5}$ attributable mortality in 2050, whereas the pathways with high global inequalities and challenges to adaptation (SSPs 3 and 4) resulted in the highest attributable mortality.

$PM_{2.5}$ attributable deaths in Vadu increased in nearly all RCP8.5 scenarios between 2010 and 2050 (Fig. 3). Under RCP8.5, the fossil-fueled development (SSP5) pathway led to an increase in attributable deaths between 2020 and 2040, after which levels returned to those of 2020 (S-Table 9). Only for RCP2.6 under the sustainability (SSP1) and fossil-fueled development (SSP5) pathways were there consistent decreases in attributable deaths between 2010 and 2050. Similar to Manhiça, the lowest mortality

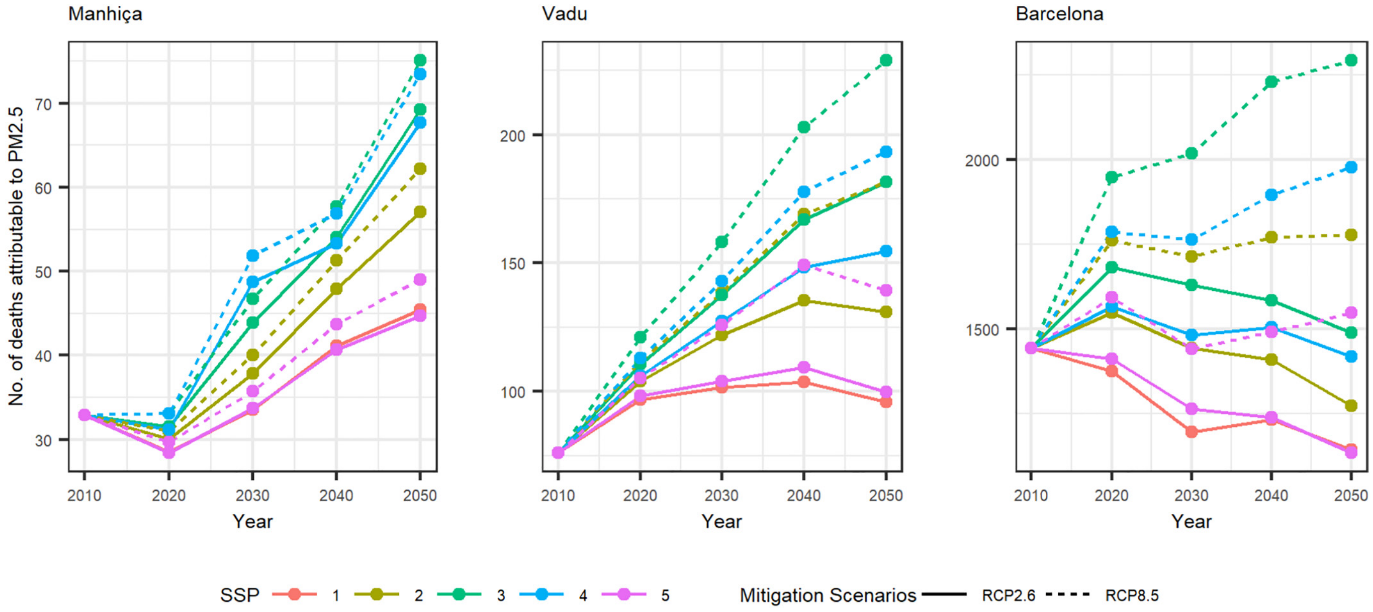

Fig. 2. Projected premature NCD + LRI deaths among adults due to $PM_{2.5}$ across SSP-RCP scenarios in Manhiça, Mozambique, Vadu, India, and Barcelona, Spain accounting for population changes by SSP.

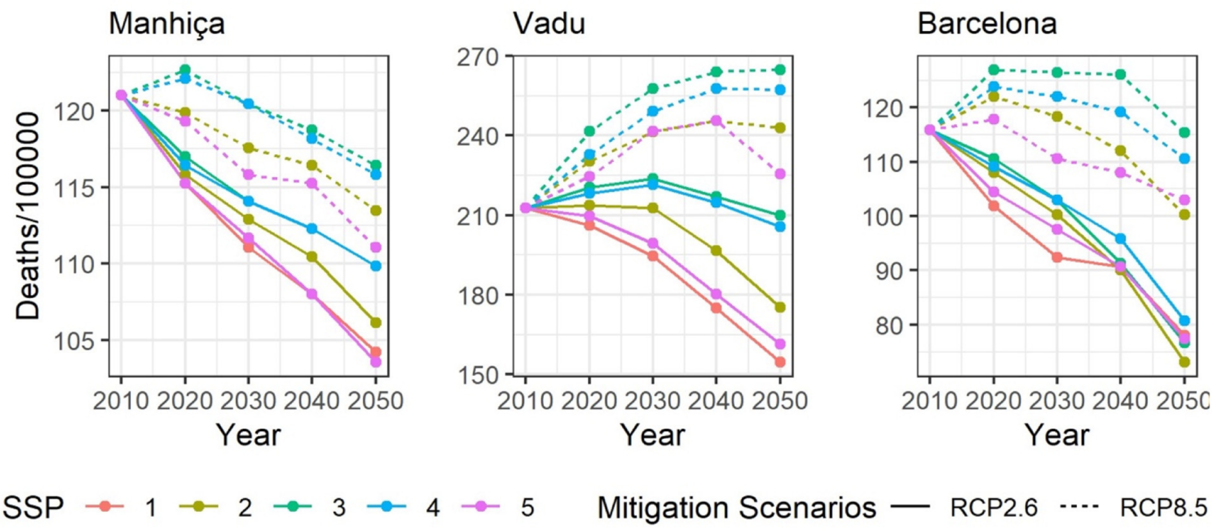

Fig. 3. Projected premature NCD + LRI deaths (per 100,000 population) among adults due to $PM_{2.5}$ across SSP-RCP scenarios in Manhiça, Mozambique, Vadu, India, and Barcelona, Spain assuming population constant at 2010 levels.

burden projected under RCP2.6 was under the sustainability (SSP1) and fossil-fueled (SSP5) development pathways.

There were consistent decreases in $PM_{2.5}$ attributable deaths in Barcelona between 2010 and 2050 under RCP2.6 scenarios (Fig. 3, S-Table 10). Under RCP8.5, decreases between 2020 and 2040 were projected to be 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 population in 2050 ranged from 100 (SSP2) to 115 (SSP3) across SSPs. Under RCP2.6, $PM_{2.5}$ attributable deaths under different SSPs started to converge in 2040.

4. Discussion

Our modelling study resulted in several relevant findings. First, global climate mitigation scenarios related to societal development pathways showed changes in local population exposure to air pollution and premature mortality. Second, the influence of the SSPs on $PM_{2.5}$ attributable deaths varied across the three local populations. Third, SSPs reflecting high challenges for adaptation caused by a combination of slow development, low education, high inequality, and weak institutions (SSPs 3 and 4) consistently resulted in the highest $PM_{2.5}$ attributable burdens mid-century across all populations. Four, mortality burden due to $PM_{2.5}$ was highly sensitive to assumptions about how populations will change according to different SSP narratives.

Results incorporating changes in population size, structure, and all-cause mortality in projections of $PM_{2.5}$ attributed mortality reflected the different assumptions about the multiple drivers of future population (e.g. fertility, mortality, migration, education) in the three populations (KC and Lutz, 2017). For example, SSPs1 and 5 resulted in similar numbers of $PM_{2.5}$ attributed deaths under RCP2.6 in all three populations despite different assumptions about population change across local populations. Since the impacts of future climate change depend heavily on the influence of socioeconomic development and population dynamics on future vulnerability and exposure to climate hazards, consideration of future health co-benefits of climate change mitigation should explicitly account for these influences.

Results in our sensitivity analysis, which held population constant, were largely consistent with the underlying characteristics of emissions specified under the SSPs. We observed the lowest levels of $PM_{2.5}$ and premature deaths under SSPs 1 and 5, which assume a faster rate of development of effective pollution control technologies compared to SSP2 (Rao et al., 2017). These SSPs achieve lower emissions by combining climate mitigation policy with energy access, however some densely populated regions (e.g., South Asia) are projected to face high levels of pollution in most scenarios (Rao et al., 2017). The higher levels of pollution and premature deaths in SSPs 3 and 4 across all local populations reflect the relatively weaker technological change and higher fossil fuel intensities in the energy system specified in those pathways (Rao et al., 2017). We observed relatively little variation across SSPs in the local $PM_{2.5}$ attributable deaths per population in the high-income country (Barcelona) population, but also in the low-income country (Manhiça) population, likely because of the relatively low levels of $PM_{2.5}$. In contrast, $PM_{2.5}$ attributable deaths in Vadu were much more sensitive to the SSPs, reflecting the higher levels of air pollution in Vadu compared to the other populations. Even under SSP1-RCP2.6, levels of $PM_{2.5}$ in Vadu in 2050 were more than six times the current WHO guideline for annual average $PM_{2.5}$ (5 $\mu g/m^3$). Our results, taken together with the broader literature, indicate that targeted air pollution control policies would be needed in addition to ambitious climate action and improved socioeconomic development to address the public health burden of air pollution in India (Dimitrova et al., 2021). India has been identified as a global region with some of the largest health co-benefits of climate change mitigation due to air pollution and where savings from health co-benefits consistently outweigh mitigation costs (Chowdhury et al., 2019; Markandya et al., 2018; Scovronick et al., 2021).

Differences in scenarios and modelling assumptions make direct comparisons between our results and other studies challenging. One of the most comparable studies in regards to methodological approach was conducted for India, which considered $PM_{2.5}$ under RCP 4.5 and 8.5 (but not differences in emissions under the SSPs), in combination with demographic and socioeconomic conditions under the SSPs. Chowdhury and colleagues reported the lowest premature mortality burden for $PM_{2.5}$ in 2050 compared to a 2001–05 baseline for SSP5 (followed by SSP1) for all of India (Chowdhury et al., 2018). Under all SSP-RCP4.5 scenarios, $PM_{2.5}$ attributable mortality was projected to decrease over time relative to 2001–05, which the authors attributed to the projected fall in mortality rate in the future. In contrast, under the high emission scenario of SSP3-RCP8.5, there was practically no change in $PM_{2.5}$ attributable mortality between 2002–05 and 2050.

Which SSP-RCP scenario society follows beyond 2020 depends heavily on governance arrangements and levels of long-term, international cooperation. While air pollution health co-benefits can play an important role in motivating climate action, even in scenarios where countries act solely based on self-interest, global cooperation is required to prevent runaway temperatures (Scovronick et al., 2021). The resilience of future local populations to climate change depends critically on the implementation of policies, actions, and development strategies at the global and national-level.

Whether the future unfolds along a specific RCP scenario will be largely influenced by implementation of national-level commitments to reduce greenhouse gas emissions under international agreements, namely the United Nations Framework Convention on Climate Change. The SSPs provide useful elaboration of the nature of global development compatible with a given amount of warming, which depends on levels of international cooperation, the effectiveness of institutions, and other dimensions of governance. The broad SSP narratives have been further extended as quantitative governance indicators, which provide insight into how global development pathways play out in terms of national-level governance (Andrijevic et al., 2020). Indicators based on accountability, political stability, government effectiveness, regulatory quality, and control of corruption projected from socioeconomic variables used to characterize the SSPs, indicate that for high-income countries, the specific SSP made little difference to the quality of governance at the national-level, which remained high across all scenarios. In contrast, in less developed countries, the specific SSP had a much more pronounced impact on the quality of governance. Under SSP3, 30% of the global population in 2050 was projected to live in countries with weak governance, whereas under SSPs 1 and 5, weak governance had practically disappeared (Andrijevic et al., 2020).

4.1. Strengths and limitations of the study

The strengths of our study include modelling health impacts in low-and-middle income country (LMIC) settings by leveraging health surveillance data and ground-based $PM_{2.5}$ measurements. Well-performing national-level civil registry and vital statistics systems needed to estimate mortality rates is lacking in many LMICs, including India and Mozambique (Mikkelsen et al., 2015). We therefore focused our analysis on HDSS sites with well-established demographic and mortality surveillance (Sankoh and Byass, 2012). Lack of routine air pollution monitoring data is a major limitation to understanding population exposure to $PM_{2.5}$ and associated health effects in many LMICs, particularly in sub-Saharan Africa (Katoto et al., 2019). We used $PM_{2.5}$ measurements from the local populations to calibrate TM5-FASST model estimates, which substantially underestimated $PM_{2.5}$ in Vadu. While the results from these select local populations provide illustrative insights into how the SSP narratives and their quantitative extensions play out across levels of development, they should not be seen as representative of income groups as a whole.

Several limitations should be considered when interpreting our results. While it is broadly understood that socioeconomic development and climate action can have local health impacts, many assumptions are required to link quantitative models across global and local scales. We used the SSP-RCP set of common scenarios to facilitate comparisons with other studies of climate impacts and health co-benefits of mitigation. However, the emissions, land use changes, and levels of development embedded in these scenarios are resolved primarily at the regional or national level. The GCAM model captures regional, but not local, changes in land-use, energy systems, and emissions under the modelling scenarios. Projections of several factors that are likely to influence local air pollution emissions, adaptive capacity, and levels of development were not available and are not reflected in our estimates. Currently, there are no commonly agreed best practices for methods for downscaling global SSPs, a limitation that has been recently highlighted as a priority for future development within the SSP framework (O'Neill et al., 2020). We applied the same correction factor between ground-based measurements and the TM5-FASST estimates in 2030 and 2050. This is a strong assumption; however, our ability to incorporate trends in the correction factor was limited by lack of measurements to characterize long-term trends in $PM_{2.5}$ in Manhiça and Vadu.

There are several important sources of uncertainty in our analysis including emissions of air pollutants under the SSP-RCP scenarios and the evolution of population health in the future. Our main analysis indicates that projected changes in population size and structure reflecting assumptions about future fertility, all-cause mortality, migration, and access to education under the SSPs has a marked influence on the future health burden attributable to $PM_{2.5}$. We did not however include projections of changes in cause of death under the SSPs, which may be possible in future work as consistent projections of cause of death become available. A previous modelling study projecting cause of death under the SSPs indicated increasing proportion of deaths due to NCDs under more optimistic SSPs (e.g. SSP1), particularly in LMICS (Sellers, 2020). By not accounting for changes in cause of death, we are likely underestimating attributable deaths in LMICs for SSP1. More pessimistic SSPs (e.g. SSPs 3 and 4) resulted in continued high burden of preventable communicable diseases. In HIC settings, deaths continued to be primarily driven by NCDs and were relatively insensitive to specific SSPs (Sellers, 2020). We also assumed that the association between mortality and $PM_{2.5}$ remained constant over the study period, irrespective of change in composition of particles, health care access and burden of disease in the population, or other factors that might modify the relationship over time.

Our estimates of attributable deaths in Manhiça and Vadu are more uncertain than for Barcelona. This arises from greater uncertainty in cause of death in 2010 taken from the Global Burden of Disease, as well as from greater sensitivity of cause of death to the specific socioeconomic pathways, which is particularly high for sub-Saharan Africa (Sellers, 2020). While our analysis was based on observed mortality rates in the three populations, due to lack of data on cause-specific mortality in Manhiça and Vadu, we assumed these local areas had the same proportion of deaths due to NCDs and LRI as was modeled for the national level in the Global Burden of Disease. Efforts to compare cause specific mortality rates from HDSS sites similar to Manhiça and Vadu indicate good agreement with estimates from the Global Burden of Disease, particularly for NCDs and infections (Byass, 2016).

We did not include the mortality burden among individuals under 25 in our models due to the age range included in the cohorts underpinning the GEMM exposure-response function. Also, mortality rates for children under five for LRI are projected to decrease considerably, which resulted in small numbers of projected deaths in our local populations in future decades.

5. Conclusion

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 populations highlights the importance of socioeconomic development and climate policy in reducing the health burden from air pollution, particularly in LMIC settings with dynamic populations and/or high air pollution levels (e.g. India).

CRediT authorship contribution statement

Conceptualization (CT, JMA, XB, JB, AD); Data curation (VI, CS, SA, SJ, SR); Formal analysis (VI, AD, JS); Funding acquisition (CT, JMA, XB, JB); Writing (CT, VI); Review and editing (AD, JS, CS, SA, SJ, SR, PM, XB, JB, JMA).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Samir KC for data and technical assistance related to population projections according to SSP and Rita van Dingenen for providing access to the TM5-FASST model. JS is now affiliated with Pacific Northwest National Laboratory, Joint Global Change Research Institute, USA.

Funding

Funding for this work was provided by the European Commission H2020 GLOBE [822654]. CT was funded through a Ramón y Cajal fellowship [RYC-2015–17402] awarded by the Spanish Ministry of Economy and Competitiveness. VI, AD, XB, JB, JMA, CT acknowledge support from the Spanish State Research Agency and Ministry of Science and Innovation through the Centro de Excelencia Severo Ochoa 2019–2023 Program (CEX2018-000806-S), and support from the Generalitat de Catalunya through the CERCA Program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153832.

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