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Health impacts of fine particles under climate change mitigation, air quality control, and demographic change in India

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Despite low per capita emissions, with over a billion population, India is pivotal for climate change mitigation globally, ranking as the third largest emitter of greenhouse gases. We linked a previously published multidimensional population projection with emission projections from an integrated assessment model to quantify the localised (i.e. state-level) health benefits from reduced ambient fine particulate matter in India under global climate change mitigation scenarios in line with the Paris Agreement targets and national scenarios for maximum feasible air quality control. We incorporated assumptions about future demographic, urbanisation and epidemiological trends and accounted for model feedbacks. Our results indicate that compared to a business-as-usual scenario, pursuit of aspirational climate change mitigation targets can avert up to 8.0 million premature deaths and add up to 0.7 years to life expectancy (LE) at birth due to cleaner air by 2050. Combining aggressive climate change mitigation efforts with maximum feasible air quality control can add 1.6 years to life expectancy. Holding demographic change constant, we find that climate change mitigation and air quality control will contribute slightly more to increases in LE in urban areas than in rural areas and in states with lower socio-economic development.

Keywords: co-benefits, India, particulate matter, climate change, projection, air pollution

List of abbreviations

Abbreviations	Full description
CO_2	Carbon Dioxide
GAINS	Greenhouse-Gas Air Pollution Interaction and Synergies
GBD	Global Burden of Disease
GEMM	Global Exposure Mortality Model
GHGs	Greenhouse Gases
NAAQ	Indian National Ambient Air Quality standard
INDC	Intended Nationally Determined Contributions
LE	Life Expectancy
LRIs	Lower Rrespiratory Infections
MFR	Maximum Feasible Reduction
NCDs	Noncommunicable Diseases
NPi	National Policy Implementation
$PM_{2.5}$	Fine Particulate Matter

1. Introduction

Socio-economic development in India has been accompanied by gains in life expectancy (LE) and improvements in a range of health outcomes over the past decades (KC *et al* 2018). However, these developments have occurred in parallel with growing environmental challenges, including rising CO_2 emissions and deterioration of air quality (GBD MAPS Working Group 2018, Dey *et al* 2012). Currently, 99.9 % of the Indian population lives in areas exceeding the World Health Organization's Air Quality Guideline for annual mean concentrations of ambient fine particulate matter ($PM_{2.5}$) of 10 µg/m^3 (Balakrishnan *et al* 2019), and the country hosts 13 out of 20 of the world´s most polluted cities (Purohit *et al* 2019).

$PM_{2.5}$ (particulate matter with diameter ≤ 2.5 µm) comprises a complex mixture of solid and liquid aerosols arising from natural sources (e.g. wind-blown dust, sea salt and biogenic sources) and anthropogenic activities (WHO 2016). Residential energy use has been identified as the dominant contributing sector in India (Purohit *et al* 2019, Conibear *et al* 2018a, Lelieveld *et al* 2015). Both short-term and long-term exposure to $PM_{2.5}$ have been associated with adverse health impacts that can occur even at very low levels (WHO 2016). In India, air pollution was ranked as the second most important contributor to mortality and morbidity in 2017, after malnutrition and dietary risks (IHME 2019) and $PM_{2.5}$ was estimated to account for 12.5 % of total deaths (Balakrishnan *et al* 2019). Estimates of the annual premature mortality burden from ambient $PM_{2.5}$ in India range between 392 thousand and 2.2 million (Conibear *et al* 2018a, Burnett *et al* 2018), with differences explained by variations in ambient $PM_{2.5}$ estimates, baseline health and population data, $PM_{2.5}$-mortality functions and methodological approaches.

Climate change and air quality have an important potential for co-control since emissions of CO_2 and many health-damaging air pollutants such as nitrogen oxides, sulphur dioxide and particulate matter are generated through many of the same combustion processes (Li *et al* 2018). While the health impacts from reductions in CO_2 emissions involve large uncertainties and occur over long-time horizons and on a global scale, those from improved air quality are more immediate and localized (Nemet *et al* 2010, West *et al* 2013). Thus, health co-benefits of climate change mitigation due to air pollution reduction can serve as a catalyst for more stringent climate policy and provide an incentive for stronger cooperation, especially from Low- and Middle-Income Countries, where air pollution levels and the associated benefits of improving air quality are high, but the perceived responsibility for climate action may be limited due to low current and past per capita emissions (Nemet *et al* 2010, The World Bank, 2020). In this respect, India is pivotal for climate change mitigation globally, being the third largest emitter of greenhouse gases (GHGs) (CarbonBrief 2019).

Global modeling studies based on the Representative Concentration Pathways and the Paris Agreement have demonstrated that India can reap some of the largest medium-term (i.e. by 2050) health co-benefits from lower $PM_{2.5}$ concentrations with ambitious climate change mitigation (Rafaj *et al* 2013, West et al., 2013, Silva et al., 2016; Vandyck et al., 2018) and these can fully compensate the mitigation costs even under most aspirational scenarios (Markandya *et al* 2018, Sampedro *et al* 2020). Chowdhury et al. (2018) projected reductions in premature mortality from $PM_{2.5}$ in India in 2050 compared to 2010 across a range of climate change and socio-economic scenarios and despite trends in population growth and aging. Studies focusing specifically on air quality policies in India project increases in $PM_{2.5}$ concentrations and associated premature mortality by 2050 under business-as-usual scenarios, while demonstrating a large scope for minimizing this burden under more stringent air quality control measures (Sanderson *et al* 2013, International Energy Agency 2016, Venkataraman *et al* 2017, Purohit *et al* 2019, Chowdhury *et al* 2018, Conibear *et al* 2018b, Limaye *et al* 2019). However, even under most aspirational scenarios several studies suggest the $PM_{2.5}$-mortality burden will not fall below present levels as a result of population growth and aging offsetting reductions in air pollution emissions (GBD MAPS Working Group 2018, International Energy Agency 2016, Conibear *et al* 2018b).While previous projection studies have considered demographic change, a major gap in the current literature is the failure to account for the feedback effects of changes in air pollution on future mortality rates and population, i.e. studies assume the same future mortality rate and population under alternative $PM_{2.5}$ scenarios. This can be misleading, especially for long-term projections in settings with high air pollution (Miller and Hurley 2003). Sanderson et. al (2013) incorporated the feedback effects of changes in air pollution on future mortality rates under different air quality control, but not mitigation, scenarios at the national level. A more comprehensive modeling framework is needed to quantify the health co-benefits of climate change mitigation at the sub-national level accounting for these feedbacks while also incorporating newly available epidemiological evidence and more advanced demographic projections.

We advance on previous studies in several ways by i) estimating future health co-benefits related to$PM_{2.5}$ dynamically by accounting for changes in population and mortality rates induced by changes in $PM_{2.5}$ levels; ii) calculating co-benefits from $PM_{2.5}$ reduction on LE and on avoidable premature mortality in the context of the Paris Agreement and at more spatially disaggregated levels (e.g. by state and urban and rural residence); and iii) exploring synergies between global climate change mitigation and national air quality control at the local level. The main contribution of this study is the consistent and dynamic integration of future trends in demographics, urbanization, and disease burdens in the health impact assessment, which allows us to isolate the impacts of air pollution on mortality from population aging effects and to account for the feedback effects of $PM_{2.5}$ exposure on population survival over time. As demographic change is a main determinant of future trajectories of exposure and vulnerability to environmental hazards, comprehensive modelling of the interplay of population dynamics and air pollution can support more realistic health impact assessments and better informed decision making.

The paper is organized as follows: section 2 describes the different models and datasets and how they are linked; sections 3.1 and 3.2 report the health co-benefits in terms of LE gains and avoided premature deaths across scenarios compared to the business-as-usual, and section 3.3 reports results according to region. In section 3.4, we show the implications of changing $PM_{2.5}$ exposure on population size. In section 4, we discuss the relevance and implications of our findings. We focus on $PM_{2.5}$ because of the well-established literature linking exposure to mortality, and because its mortality burden exceeds those of other major pollutants in India such as ozone (Balakrishnan *et al* 2019). We use the term premature mortality to refer to deaths brought forward in time due to air pollution exposure across all ages and avoidable premature mortality to refer to deaths that can be averted with respect to the business-as-usual scenario.

2. Material and Methods

2.1 Scenario definition

Table 1 describes the modelled scenarios. These have been developed in the MESSAGEix-GLOBIOM global energy-economy framework (International Institute for Applied Systems Analysis 2019) as part of the CD-LINKS (Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing) project (CD-LINKS 2019). The National Policy Implementation (NPi), or business-as-usual scenario, specifies the implementation of currently announced targets for climate, energy, environment (air pollution) and development policies up to 2030 in all countries and equivalent effort to no climate policy beyond 2030 (based on a policy database for G20 countries with a cut-off year of 2015 (New Climate Institute 2020). The Intended Nationally Determined Contributions (INDC) scenario assumes that policy commitments specified in countries´ INDCs are implemented by 2030, but no further intensification of emission reduction commitments beyond this point is undertaken. The more aspirational scenarios of 2° and 1.5° are based on the NPi scenario. They stipulate implementation of national policies until 2020 and radical policy action for transitioning to global CO_2 budgets consistent with limiting global long-term temperature increases to 2°C and 1.5° C

Table 1 Scenario descriptions

Scenario	Description
NPi	National Policies until 2030, no climate policy after 2030
INDC	National Policies until 2020, after which implementation of Nationally Determined Contributions (NDCs) until 2025/2030
2° C	National Policies until 2020, after which mitigation measures in line with a >66% chance of staying below 2°C throughout 21st century

1.5° C	National Policies until 2020, after which mitigation measures in line with a >66% chance of staying below 1.5°C in 2100
INDC – MFR	Same as above, but combined with the implementation of measures for maximum feasible reduction of air pollution
2° C – MFR	
1.5°C – MFR	

thereafter (cumulative 2011-2100 global CO_2 budget of 1,000 $GtCO_2$ and 400 $GtCO_2$ for the 2° and 1.5° targets, respectively (McCollum *et al* 2018). These scenarios have been implemented in MESSAGE-GLOBIOM based on global cost-effective pathways for staying within the specified global CO_2 budgets as well as national objectives and capabilities for implementing mid-century emissions strategies. The NPi, INDC, 2° and 1.5° scenarios are combined in GAINS with a set of air pollution measures assuming a compliance with the current air pollution legislation in each country. The three additional scenarios correspond to the CO_2 emission mitigation pathways described above, but are complemented with implementation of explicit control measures for maximum feasible reduction of air pollutants in India, hereafter referred to as MFR (Purohit *et al* 2019, Rafaj *et al* 2018). The energy use by fuel type and the sector-specific $PM_{2.5}$ emissions under each scenario can be found in Fig. SI.1-2.

2.2 Ambient $PM_{2.5}$ concentrations

Projections of anthropogenic emissions, as well as historical and future (2010-2050) gridded annual ambient $PM_{2.5}$ concentrations (Fig. 1) under each modelled scenario for India were derived from the Greenhouse-Gas Air Pollution Interaction and Synergies (GAINS) model. These were based on regionalised economic activities of different types either developed in MESSAGEix-GLOBIOM (energy supply and demand, transport) or derived from the GAINS databases (industrial production, agriculture). To arrive at the $PM_{2.5}$ emissions in each scenario, a few hundred end-of-pipe national air quality control measures in the industry, power plant, household and agricultural sectors were applied in GAINS. For MFR variants these refer to the best available technical measures to capture SO_2, NO_x, VOCs, NH_3 and PM emissions at their sources before they enter the atmosphere and without structural changes in the economy or energy systems (see Table SI.1 for an illustrative list). Comparison of modelled concentrations against observational data shows relatively good agreement (Fig. SI. 3).

To determine population-weighted concentrations for urban and rural areas, the gridded $PM_{2.5}$ concentrations were intersected with urban polygon shapes from Global Rural-Urban Mapping Project (NASA 2020), gridded population data from the Joint Research Centre, and from WorldPop (WorldPop 2020). Urban regions were defined as towns and cities with >100,000 inhabitants and densities >1000 people/km^2 and the rest were classified as rural. The urban-rural distribution from the gridded data was adjusted to ensure consistency with percent rural area classification in the 2001 Indian census.

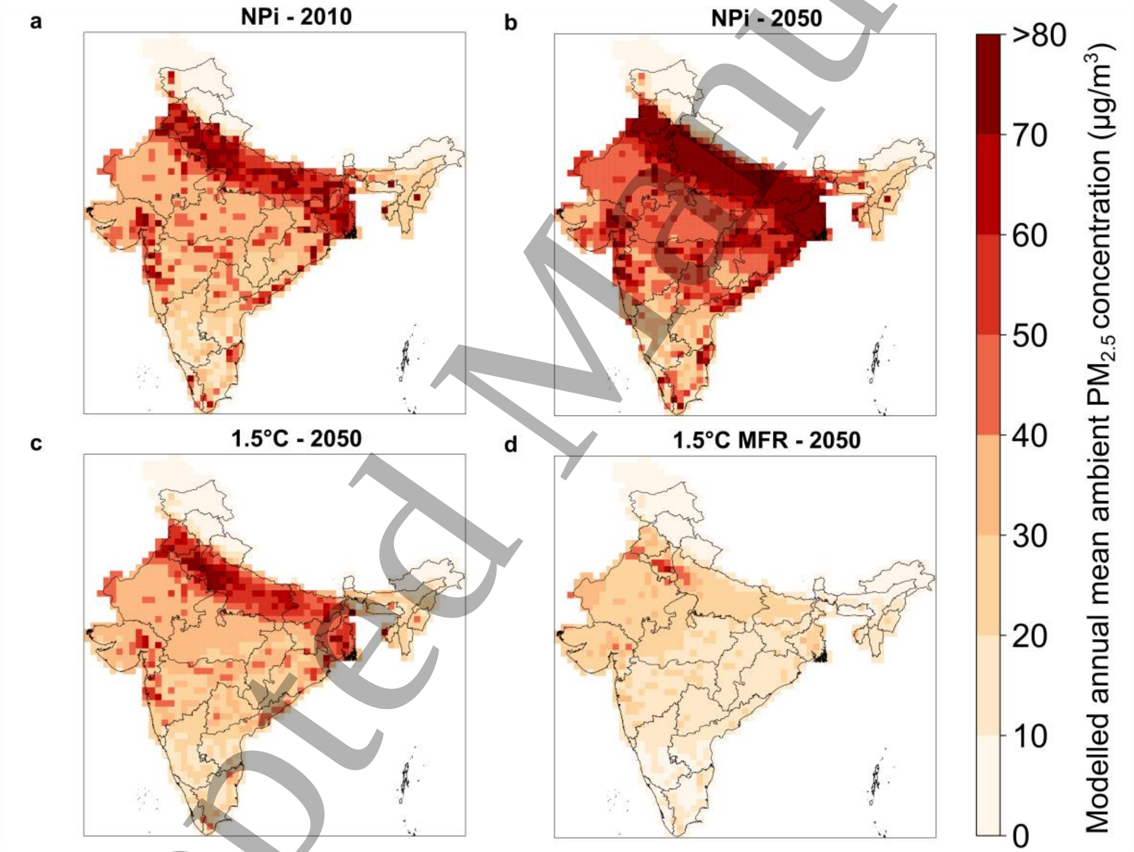

Fig. 1 Modelled annual mean ambient $PM_{2.5}$ concentrations (μg/m^3) over the Indian landmass for scenario (a) NPi, 2010, (b) NPi, 2050, (c) 1.5°C, 2050 and (d) 1.5°C - MFR, 2050

The projected $PM_{2.5}$ exposures under each scenario can be found in Fig. SI.4 and more details on the methods — in section S1.1 of the Supplementary Material.

2.3 Demographic projection

To estimate how changes in air pollution will affect future LE, age-specific mortality, as well as the structure and size of the population, we used the five-dimensional population projection for India developed by KC et. al (2018), which projects India´s population by state, urban/rural place of residence, age, sex and level of education, using sub-group specific fertility, mortality, education and migration rates. The initial data for the population projection has been derived from the two most recent Indian censuses (2001 and 2011) and vital rates from the India Sample Vital Registration System (1999-2013). The urban-rural designation applied in the population projection differs from the one used for the exposure assessment described above as it also considers population density and share of employment in non-agricultural work (Census India 2011). Further explanation of the method and data sources used in the population projection can be found in the Supplementary Material (section S1.2) and in the Appendix of KC et. al (2018).

2.4 Exposure response function

To quantify the mortality impacts of exposure to outdoor $PM_{2.5}$ due to Noncommunicable Diseases (NCDs) and Lower Respiratory Infections (LRIs), we apply the Global Exposure Mortality Model (GEMM) (Burnett *et al* 2018) (Fig. SI.5):

$$HR(z) = \exp\left\{\frac{\theta \log\left(\frac{z}{\alpha}+1\right)}{1+\exp\left\{-\frac{(z-\mu)}{\nu}\right\}}\right\},$$

where HR denotes the mortality hazard ratio (relative risk of mortality at any concentration compared to the counterfactual of $2.4\mu g/m^3$) for a specific annual exposure to $PM_{2.5,}$ z is population-weighted $PM_{2.5}$ exposure ($z = \mathrm{maxsurePM}_{2.5} - 2.4\mu g/m^3$) and θ, z, α, μ are age-specific and disease-specific parameters. The counterfactual was selected as the lowest observed concentration in any of the 41 observational studies, included in the GEMM development; below the counterfactual, GEMM assumes no change in the hazard ratio.

2.5 Projection of future disease burden

To account for future trends in disease patterns in India, we modelled the burden of NCDs and LRIs deaths based on the projected changes in LE at birth from the demographic projection. We used sex- and age-specific (5-years age groups) data on the percentage of all deaths due to NCDs and LRIs for 31 of the states and union territories in India for 2015-2017 from the GBD project (Indian Council of Medical Research, Public Health Foundation of India 2017). We assumed that if a state reached the LE at birth in 2050 that another state had in 2015, it will also have the same age- and sex-specific percentage of deaths due to NCDs and LRIs as the other state in 2015. Thus, for each state and sex, we matched projected LE at birth in the year 2050 with the state with the closest LE at birth in 2015 (within 3 years band) and assigned the 2050 NCDs and LRIs mortality burden accordingly. The values for all the years in-between were interpolated. States with the highest LE at birth that could not be matched with past LE in any state were matched to other countries in Southern Asia with similar LE at birth (Table SI.2).

2.6 Health impact estimation

We linked all models described above in an integrated framework, using a dynamic health impact assessment approach (see Fig. 2 and Fig. SI.6). Firstly, we presume that the future mortality assumptions in the demographic projection reflect only future socio-economic prospects, but not the impact of changes in air pollution (Miller & Hurley, 2003). We then re-ran the population projection for each emission scenario, adjusting age-specific mortality rates for each state and urban/rural residence at every five-year period from 2010 to 2050 to the changes in risk of mortality associated with the changing $PM_{2.5}$ concentrations over time:

$$m_{a,r,s}^{scen}(t) = m_{a,r,s}^{base}(t) * Share_{NCD+LRI} \frac{HR_{a,r,s}(t)}{HR_{a,r,s}(2010)} + m_{a,r,s}^{base}(t) * \left(1 - m_{a,r,s}^{base}(t) * Share_{NCD+LRI}\right)$$

$$a = age, r = residence, s = state$$

where $m_{a,r,s}^{scen}$ indicates the age-, urban/rural residence- and state-specific mortality rate in the respective emission scenario and $m_{a,r,s}^{base}$ in the population projection. $Share_{NCD+LRI}$ is the projected age-, sex- and state-specific share of NCDs and LRIs in all-cause mortality. $HR_{a,r,s}$ denotes the age-specific hazard ratio associated with the $PM_{2.5}$ exposure in each domain (urban/rural residence and state). Rescaling the mortality rates in this way, without changing any other demographic drivers in the projection (i.e. fertility, migration), entails distinct LEs, number of deaths, and population size under each scenario that can be attributed to the differences in $PM_{2.5}$ exposure levels.

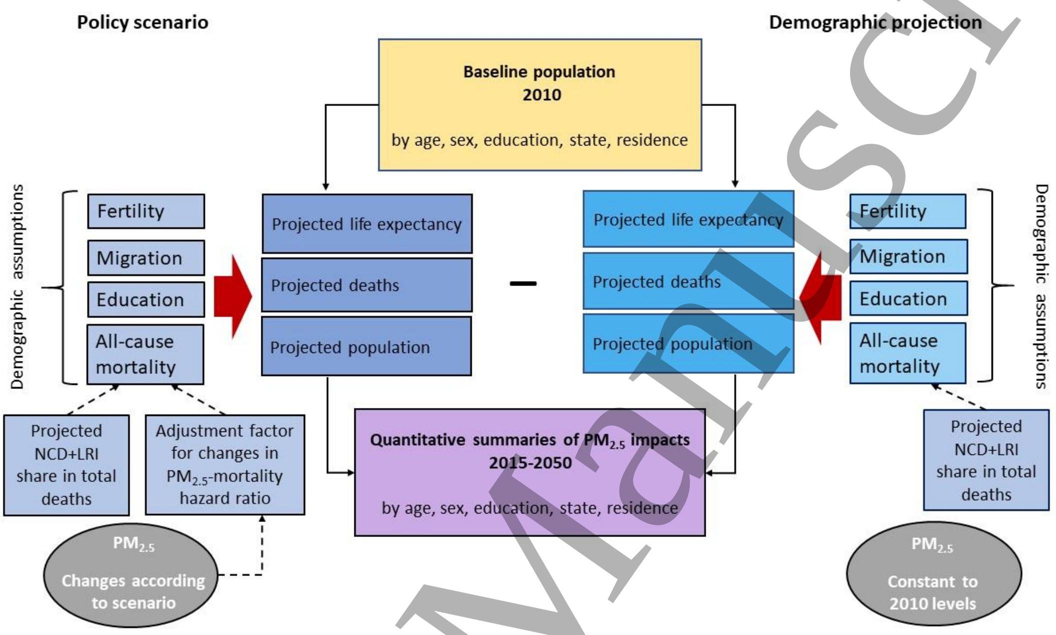

Fig. 2: Schematic model of the dynamic health impact assessment approach.

The health impact estimation was based on aggregated population-weighted concentrations for urban and rural areas in each state, respectively. The population projections under each scenario were implemented in R using version 0.0.4.1 of the MSDem (**M**ulti-**S**tate **D**emography) package (Marcus Wurzer, Samir KC 2018). In the following sections we compare the projected LE at birth, total number of deaths and population under each of the scenarios with those in the demographic projection that assumes 2010 constant $PM_{2.5}$ levels. We also draw comparison across scenarios to illustrate the potential health co-benefits of stricter climate change mitigation against the NPi.

3. Results

3.1 Gains in life expectancy

Fig. 3 and Table SI.4 show the projected gains in LE up to 2050 for each scenario. In the period 2010-2050 LE at birth for both females and males in India is projected to increase under all scenarios. These increases reflect the underlying assumption of improving LE in the demographic projection as well as the impacts of changing $PM_{2.5}$ levels. There are substantial differences in the projected LE trajectories across emission scenarios as a result of deaths being brought forward in time or delayed due to changes in $PM_{2.5}$ exposure. With continuation of current policy and no further efforts for mitigating climate change globally or addressing air pollution locally (NPi scenario), the increase in LE at birth between 2010 and 2050 is projected to be 9.1 years for females and 7.6 years for males (LE at birth in 2010 was 68.5 years for females and 65.1 for males). Pursuit of carbon emission targets can bring substantial health co-benefits through cleaner air by adding 0.4 (under 2°) or 0.7 (under 1.5°) years to the average (both sexes) projected LE in 2050. These LE gains account for 4.2 % and 7.4 % of the total increases in LE under each of these scenarios, respectively.

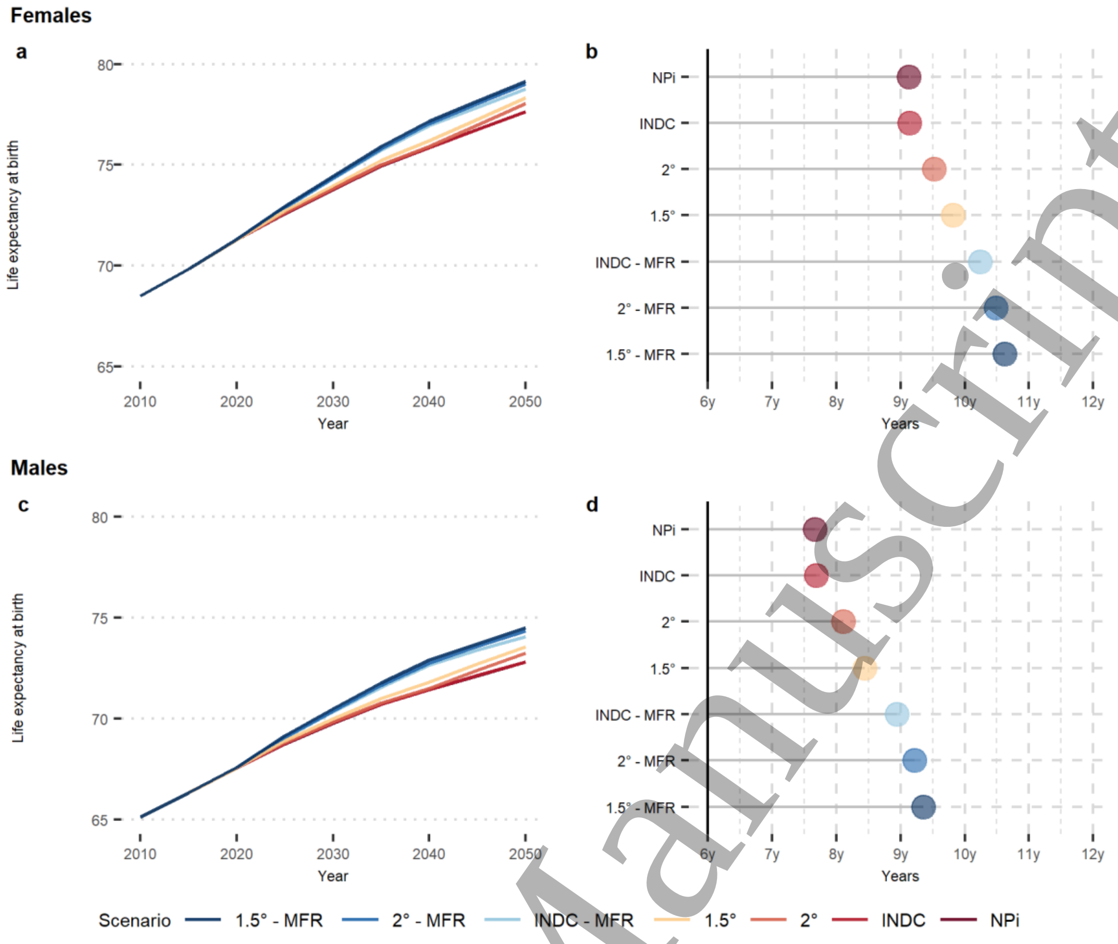

Fig. 3 Projected changes in LE at birth from 2010 to 2050 (**a** Females and **c** Males) and total gains in LE between 2010 and 2050 (**b** Females and **d** Males) under climate change mitigation and air quality control scenarios according to sex.

The results in Fig. 3 demonstrate that under the 1.5° – MFR scenario increases in LE at birth between 2010-2050 would be 1.6 years higher compared to the NPi scenario (15.5 % of the total increase in LE at birth between 2010 and 2050). There was essentially no difference in LE gains between the INDC and NPi scenarios.

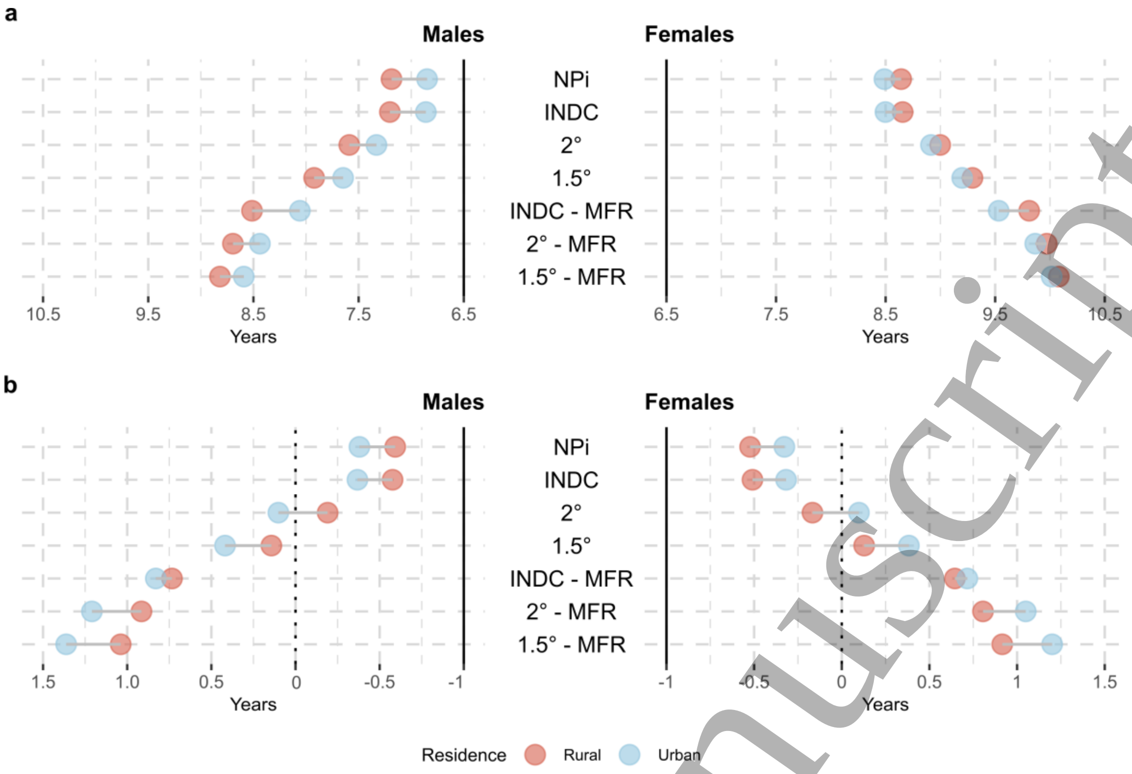

Fig. 4 Projected changes in LE at birth (from 2010 to 2050) in years under different climate change mitigation and air quality control scenarios according to sex and urban/rural residence (**a**) due to changes in demographic assumptions and changes in PM$_{2.5}$ concentrations and (**b**) only due to changes in PM$_{2.5}$ concentrations.

Under all scenarios total increases in LE between 2010 and 2050 are projected to be larger for women than for men and for rural residents than for urban (Fig. 4 a). Comparing LE changes across scenarios with those of the demographic projection allows us to isolate the impacts of changing PM$_{2.5}$ levels on LE from those of the underlying demographic assumption (Fig. 4 b). Holding demographic changes constant, the relative impact of climate change mitigation and air quality control is almost the same for men and women, which is expected considering that there are no sex-differentiated hazard ratios in GEMM. However, improvements in PM$_{2.5}$ levels associated with these measures contribute more to LE increases for urban residents.

3.2 Avoidable premature deaths due to PM$_{2.5}$ reductions

Our projections indicate that number of premature deaths due to PM$_{2.5}$ exposure will increase by 5.6 million and 5.3 million between 2010 and 2050 under the NPi and INDC scenarios, respectively (Fig.5 and Table SI.5). Taking ambitious action to prevent climate change can generate clear health co-benefits: under the 2° scenario we project the number of premature deaths from $PM_{2.5}$ in the period 2010-2050 to be 3.9 million lower compared to the NPi scenario and 8.0 million lower under the 1.5° scenario. Combining climate change mitigation efforts with measures targeting air pollution can bring the largest reduction in premature mortality due to $PM_{2.5}$ exposure: 2.6 to 4.8 times larger in magnitude than the avoided premature mortality through climate change mitigation alone. Compared to the NPi scenarios, aggressive GHG emission reductions plus air quality control can avert up to 20.8 million premature deaths by 2050, with larger benefits among rural residents (11.2 million in rural vs. 9.5 million in urban areas). Even under current national mitigation commitments (scenario INDC), targeted air quality control can avert substantial premature deaths by 2050, comparable in magnitude to avoidable premature deaths from $PM_{2.5}$ under 2° C - MFR scenario (10.9 million under INDC-MFR compared to 13.3 million under 2° C - MFR, see Table SI.5).

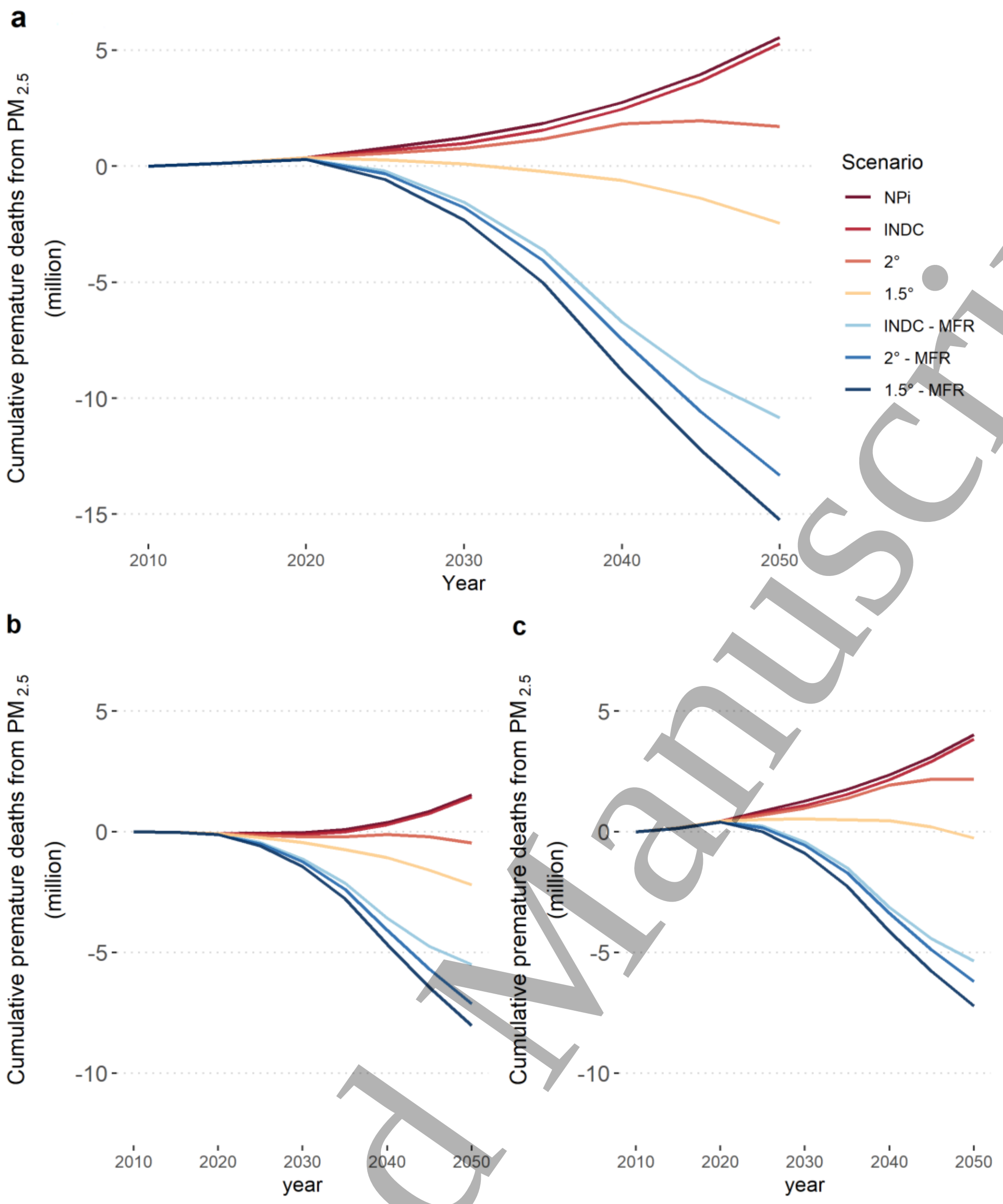

Fig. 5 Projected change in the cumulative number of premature deaths due to $PM_{2.5}$ exposure under modelled scenarios (2010-2050) for **(a)** India; **(b)** All urban areas; **(c)** All rural areas.

Note: Deaths are calculated relative to the demographic projection, assuming 2010 $PM_{2.5}$ levels remain constant for India.

Our results indicate that without any further policy action between 2010 and 2050 premature deaths due to $PM_{2.5}$ exposure will increase the most in rural areas, but with aggressive climate action and air quality control they can be reduced the most in urban areas (Fig. 5 b and c).

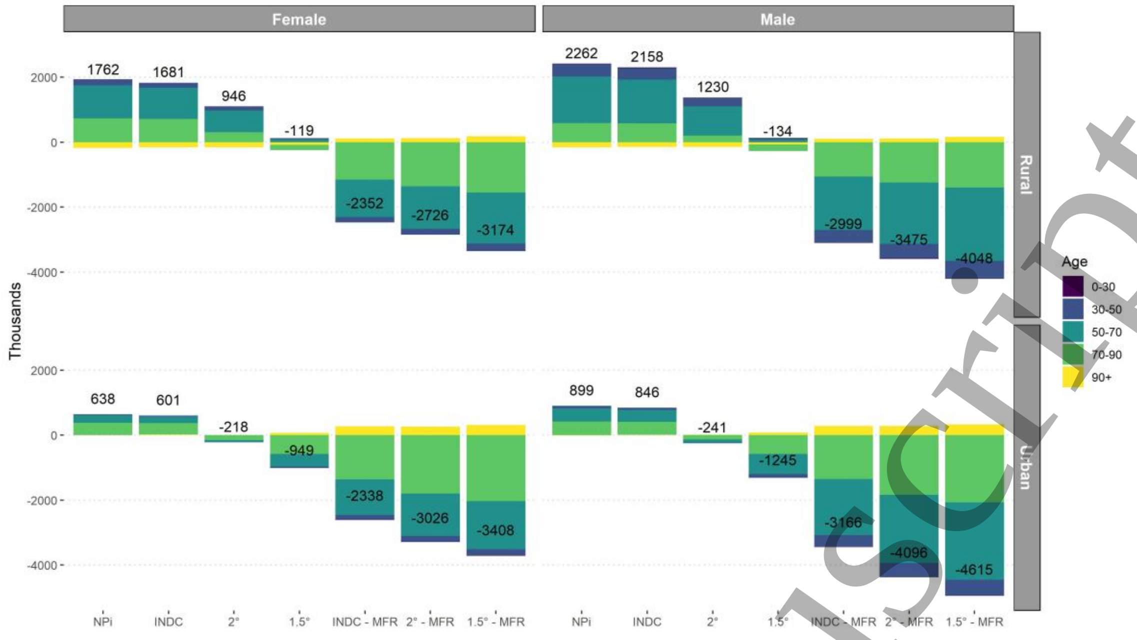

Fig. 6 Projected change in premature deaths (in thousands) due to $PM_{2.5}$ exposure from 2010 to 2050 for each scenario according to sex and urban/rural residence.

Note: Deaths are calculated relative to the demographic projection, assuming 2010 $PM_{2.5}$ levels remain constant

The reduction in premature deaths from lower $PM_{2.5}$ concentrations occur mainly among those aged 50-70 (47.4 % of the reduction in premature deaths over 2010-2050 under the 1.5° - MFR scenario) and 70-90 (43.5 % of the reduction premature deaths over 2010-2050 under the 1.5° - MFR scenario) as shown in Fig. 6. Under all scenarios coupling mitigation efforts with targeted air quality control, premature deaths across all age groups are projected to fall in the period 2010-2050 apart from the oldest (90+). In contrast, in the NPi, INDC and 2° scenarios, premature deaths from $PM_{2.5}$ are expected to increase for all age groups, but the eldest (90+).

3.3 Regional differences

State-level analyses revealed some regional variations in projected LEs (Fig. 7). LE gains from CO_2 and $PM_{2.5}$ emission controls were negatively correlated with baseline LE at birth and positively correlated with baseline $PM_{2.5}$ levels across states (Fig. 8). States with the highest potential gains in longevity through improvements in air quality were situated around the Indo-

Gangetic Plain and East India, in particular West Bengal, Jharkhand, Bihar, Odisha, Uttar Pradesh and Chhattisgharh (Fig. 7-8 and Fig.SI.7).

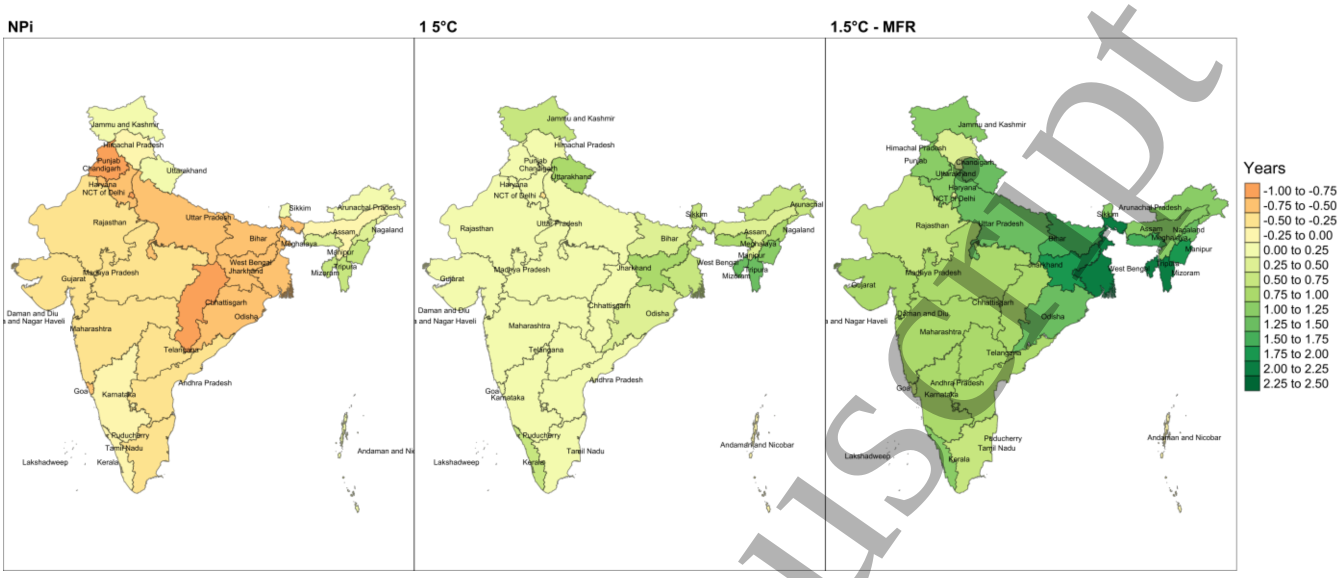

Fig. 7 Difference in LE at birth in 2050 between scenarios NPi, 1.5°C and 1.5°C – MFR relative to the demographic projection.

Note: Estimates calculated as population-weighted values for females, males and urban and rural residents

These states are at multiple disadvantages – they are highly polluted and are projected to experience the largest increases in $PM_{2.5}$ with climate change (NPi scenario); they are some of the most populated, have relatively low LE and have a large share of households using solid fuels for heating and cooking. Nevertheless, differences in overall state-level health inequalities across scenarios were small based on the coefficient of variation and absolute and relative LE gap between states (Table SI.7).

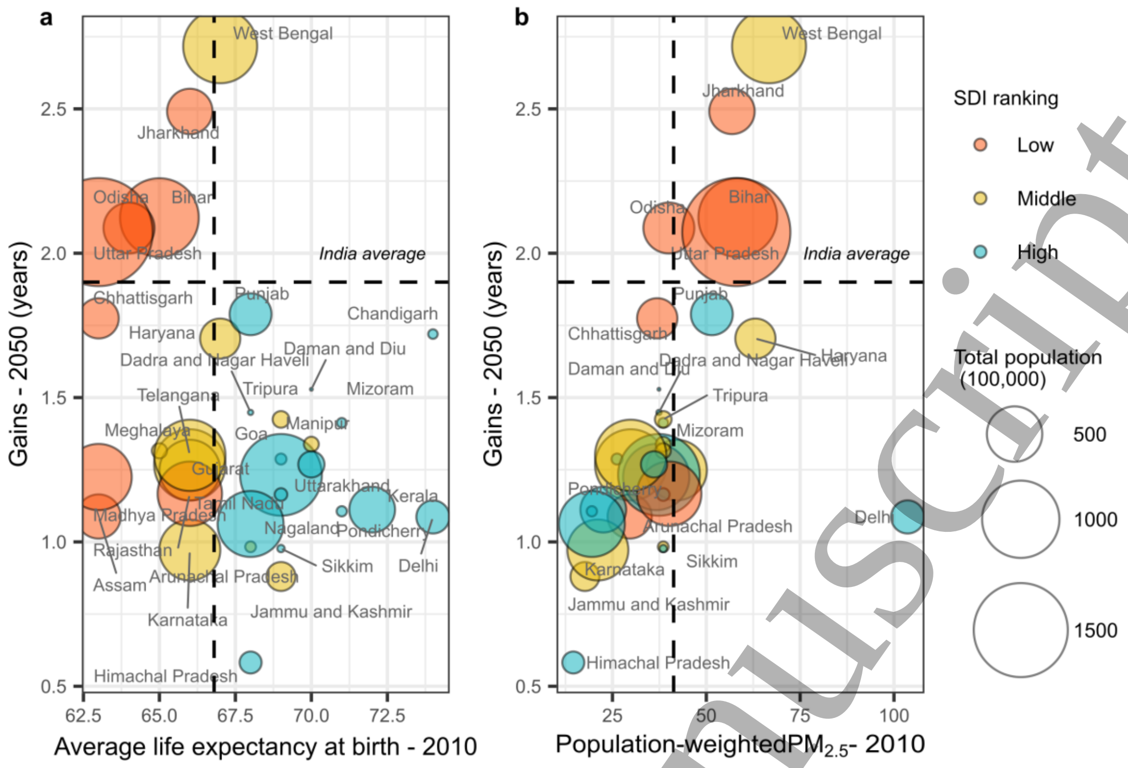

Fig. 8 Gains in LE at birth in 2050 (1.5° - MFR scenario compared to NPi scenario) against **(a)** LE at birth in 2010 and **(b)** population-weighted $PM_{2.5}$ by state in 2010.

Note: Size of the circles indicates baseline population size (in 100,000) and colour indicates state ranking based on the Socio-demographic Index (SDI) levels as calculated by GBD 2017 (Balakrishnan *et al* 2019), which is based on lag-distributed per-capita income, mean education in people aged 15 years or older, and total fertility rate in people younger than 25 years. LE at birth and gains in LE are calculated as a population-weighted average of female and male LE at birth.

To explore the relative importance of climate policy versus air pollution control at state-level, we compared gains in LE relative to NPi scenario between the INDC-MFR and 1.5°C-MFR scenarios, which only differ in the climate change mitigation ambition. Although air quality policies seem to dominate the LE gains for India overall, we find that the cleaner energy transition as envisioned in the 1.5°C-MFR scenario can double these potential gains in many urban regions, especially those in Northeast India, where the overall $PM_{2.5}$ burden is the largest (Table SI.8).

3.4 Implications for population size

In our dynamic method, $PM_{2.5}$ levels affect population survival in each specific age interval; i.e. deaths due to $PM_{2.5}$ in a population subgroup (sharing the same characteristics such as age, sex, education, residence) in one projection period will affect the shape and size of the population in subsequent periods. Therefore, the different emission scenarios modelled resulted in distinct total population sizes and structures. In the most aspirational scenario, the total population in 2050 is projected to be 16.2 million larger compared to the NPi scenario (Table SI.10). Differences in population survival will also slightly affect the structure of the population. For instance, the percentage of the population aged 65+, which was 5.5 % in 2010, is projected to reach 15.9 % in 2050 under the NPi scenario and 16.5 % under the 1.5° - MFR scenario.

4 Discussion

Our study estimates gains in LE and avoidable premature deaths from reduced fine particle concentrations in India under different climate change mitigation scenarios using an integrated framework that incorporates demographic dynamics. Most prior research on future health benefits of air quality improvement has relied on more static methods that assume future population structure and mortality rates are independent from changes in exposure. In contrast, we assessed the feedback effects of air pollution on LE and population size and structure, a largely neglected aspect in the co-benefits literature. We find compelling evidence for the health co-benefits related to air quality improvement under the aspirational 2° and 1.5° climate change mitigation targets laid out in the Paris Agreement. In particular, a child born in India under these low emission pathways in 2050 could expect to live on average 0.4 or 0.7 years longer, respectively, than if she were born in a world following a business-as-usual trajectory. Furthermore, meeting the Paris Agreement targets has the potential to avert between 3.9 million and 8.0 million premature deaths due to $PM_{2.5}$ exposure in the country over the period 2010-2050 compared to the NPi scenario. These immediate and localised health co-benefits of cleaner air provide a strong incentive for climate action from the third largest CO_2 emitting nation.

Our results indicate that with maximum and coordinated efforts of both climate change mitigation and end-of-pipe air quality control, LE increases between 2010-2050 could be 1.6 years higher compared to the NPi scenario, which is far beyond current estimates of the LE impacts of tobacco or all cancer in South Asia (Apte *et al* 2018). Avoided premature deaths between 2010-2050 can amount to 20.8 million. This is of particular relevance, considering that policy responses to air pollution and climate change are often formulated independently by different policy departments. While further studies are needed to compare the financial viabilities of such measures and identify a portfolio of most cost-effective controls, implementation of any policies in this direction is likely to bring substantial gains for public health. A previous study demonstrated that the economic costs of maximum feasible reduction policies in India would still be extremely low compared to the economic benefits of cleaner air associated with higher productivity through reduction in mortality and work absenteeism (Sanderson *et al* 2013) and this has been confirmed for climate change mitigation efforts (Markandya *et al* 2018). Although our results suggest that targeted air pollution control might be more effective in reducing premature mortality from $PM_{2.5}$, stronger coordination with climate change mitigation is indispensable considering the multiple additional health, socio-economic and environmental benefits of limiting climate change. Furthermore, we show that purely technical end-of-pipe emission control measures without a large-scale transformation in the energy system would have much more limited scope for reducing the health burden of $PM_{2.5}$ throughout the most highly affected areas in Delhi and in Northeastern India. In addition, it has been recently demonstrated that these one-way solutions would be associated with higher implementation costs (Purohit *et al* 2019).

In line with recent scenario-based studies (GBD MAPS Working Group, 2018, Karambelas *et al* 2018), we find that without climate change mitigation efforts premature deaths from $PM_{2.5}$ will increase the most in rural areas. Despite their lower ambient air pollution levels, rural areas have higher $PM_{2.5}$ related health burden due to their larger population and lower baseline LE compared to urban areas. Previous studies estimate the total mortality burden of air pollution in rural areas to be three to five times larger than in urban areas (GBD MAPS Working Group, 2018, Karambelas et al., 2018). Holding demographic change constant, we find that climate change mitigation can contribute slightly more to LE increases and avoided premature deaths for urban residents over the period 2010-2050, likely due to larger improvements in $PM_{2.5}$. We note that our results likely underestimate impacts at highly polluted urban areas due to the logarithmic form of the exposure-response function at concentrations above 84 μg/m^3, implying impacts at lower exposures increase more rapidly compared to higher exposures, and the fact that we average concentrations across urban grid cells. Quantifying the health impacts at grid level would have involved an additional set of assumptions regarding spatial distribution of future population growth and mortality. Modelling not only improvements in outdoor but also indoor air quality associated with decreasing use of solid fuels for household energy would likely demonstrate even greater health co-benefits in rural areas, especially in some less-developed states, where the proportion of people using solid fuels for heating and cooking is as high as 75 % (Balakrishnan *et al* 2019). For instance, one study estimated that household air pollution in India shortens the average lifespan by 0.7 years (Balakrishnan *et al* 2019). We do not find substantial differences in health co-benefits according to sex; however, this could change when accounting for changes in indoor air pollution levels, which mostly affect children and women in India (Balakrishnan *et al* 2019).

In agreement with previous studies (Purohit et al., 2019, Balakrishnan et al., 2019, Chowdhury et al., 2018, Limaye et al., 2019) we find that regions with lower socio-economic development, especially those along the Indo-Gangetic Plain, would reap the largest benefits with relation to LE gains and avoided premature mortality from reaching stringent targets on emissions. Although these regions have a lower incidence of NCDs, they have large health burdens because of their larger population size, lower LE and higher $PM_{2.5}$ concentrations (Purohit *et al* 2019). These heterogeneous regional effects have important implications for geographical equity in health and economic and social development.

Our results should be interpreted in light of the following main limitations. Firstly, the GEMM function considers only health impacts in adults, but in many regions in India mortality from LRIs in children is high, and childhood mortality has been shown to contribute to about 10 % of the loss in LE in India (Apte *et al* 2018). Hence, our estimates should be considered as a lower bound of potential LE gains from improving air quality. Secondly, we did not consider possible climate-change-induced meteorological impacts on $PM_{2.5}$ concentrations as well as the feedback effects of stricter air quality control on the climate (although these are likely to be smaller and more local compared to changes in GHG emissions). Although uncertainties in estimating these are still very large, especially at the regional and local level, a previous study (Chowdhury *et al* 2018) estimated that climate change might diminish the rise in surface $PM_{2.5}$ over India by 7-17 % through its effects on local meteorology. Lastly, quantitative uncertainty analysis of our results was beyond the scope of this study due to the complexity of the linked models and lack of uncertainty bounds for important parameters, e.g. in the population projection, integrated assessment model and air pollution model. Uncertainty in our model will likely stem from assumptions and parameters related to (1) baseline populations, emissions and disease burden data; (2) the integrated assessment model, (2) the GAINS model, (3) the demographic projection model, (4) the disease burden projection, (6) the GEMM model and its extrapolation in the future, beyond observed $PM_{2.5}$ ranges, and to settings with very different population and air pollution characteristics, (7) the calculation of health impacts at aggregate level (state and urban/rural residence) and (8) the assumption of constant air pollution in the demographic projection. Due to the large uncertainties inherent in our model, the study results should not be considered as predictions or forecasts, but rather as plausible future outcomes that are most appropriate for relative comparisons between scenarios and for providing insights regarding the range of potential health implications of global and national policy decisions.

Our integrated and dynamic approach allowed us to: 1) report the impacts of air pollution on mortality independent of demographic change; and 2) explore feedback effects of climate change mitigation and $PM_{2.5}$ emissions control on future population size and structure. In contrast to previous studies, which report an increasing burden of $PM_{2.5}$-related mortality even with reduction in emissions (GBD MAPS Working Group, 2018, International Energy Agency, 2016, Conibear et al., 2018b), we find that emission controls can reduce the number of premature deaths from $PM_{2.5}$ in India. These contrasting results can be explained by differences in the definition of premature deaths as well as overall methodological approach. . Our results also suggest that while most aspirational policies will contribute to improving LE, this will also have the effect of increasing population size and the proportion of the population at older ages. Larger populations can in turn produce additional feedback mechanisms on the climate system through higher energy use and CO_2 emissions, which should be examined in future studies. Two policy questions that arise in this respect are 1) whether changes in population size and structure delivered by reduction in premature mortality from climate change mitigation and air quality control can make meeting CO_2 reduction targets more challenging and 2) if the productivity gains from lower mortality and morbidity will outweigh the higher social and healthcare costs of sustaining a larger elderly population. While public policy strives to improve population health and prolong LE, it is important, especially in a dynamic country such as India, that this progress is accompanied by measures for reducing the carbon footprint of individuals and decoupling increases in GHG emissions and air pollutants from economic growth.

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