

SPECIAL REPORT 21

January 2018



Burden of Disease Attributable to Major Air Pollution Sources in India

GBD MAPS Working Group

SUMMARY FOR POLICY MAKERS

Health Effects Institute

ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI typically receives balanced funding from the U.S. Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs; the William and Flora Hewlett Foundation and the Oak Foundation contributed the primary support for GBD MAPS. HEI has funded more than 330 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in more than 260 comprehensive reports published by HEI, as well as in more than 1,000 articles in the peer-reviewed literature.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public-private partnership that is central to the organization. For this report, a GBD MAPS International Steering Committee was appointed to provide high-level advice to and oversight of the GBD MAPS Working Group. In addition, the draft final report was reviewed by independent external peer reviewers from India and other countries, who were selected by HEI for their expertise. A draft final version of this report was also reviewed by experts on the GBD MAPS Steering Committee.

All project results are widely disseminated through HEI's website (www.healtheffects.org), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

SUMMARY FOR POLICY MAKERS

Burden of Disease Attributable to Major Air Pollution Sources in India

THE AIR POLLUTION CHALLENGE

India has some of the highest levels of outdoor air pollution in the world. The most comprehensive air pollution estimates available from both satellite and Indian ground-level measurements of fine particulate matter (PM_{2.5}*) indicate that 99.9% of the Indian population is estimated to live in areas where

the World Health Organization (WHO) Air Quality Guideline of 10 µg/m³ for PM_{2.5} was exceeded in 2015. Nearly 90% of people live in areas exceeding the WHO Interim Target-1 (35 µg/m³). Similarly, the population in most Indian states (21) and minor territories (6) was exposed to PM_{2.5} levels above the Indian annual standard of 40 µg/m³ in 2015. Summary Figure 1 shows that, although the air pollution levels experienced

What This Study Adds

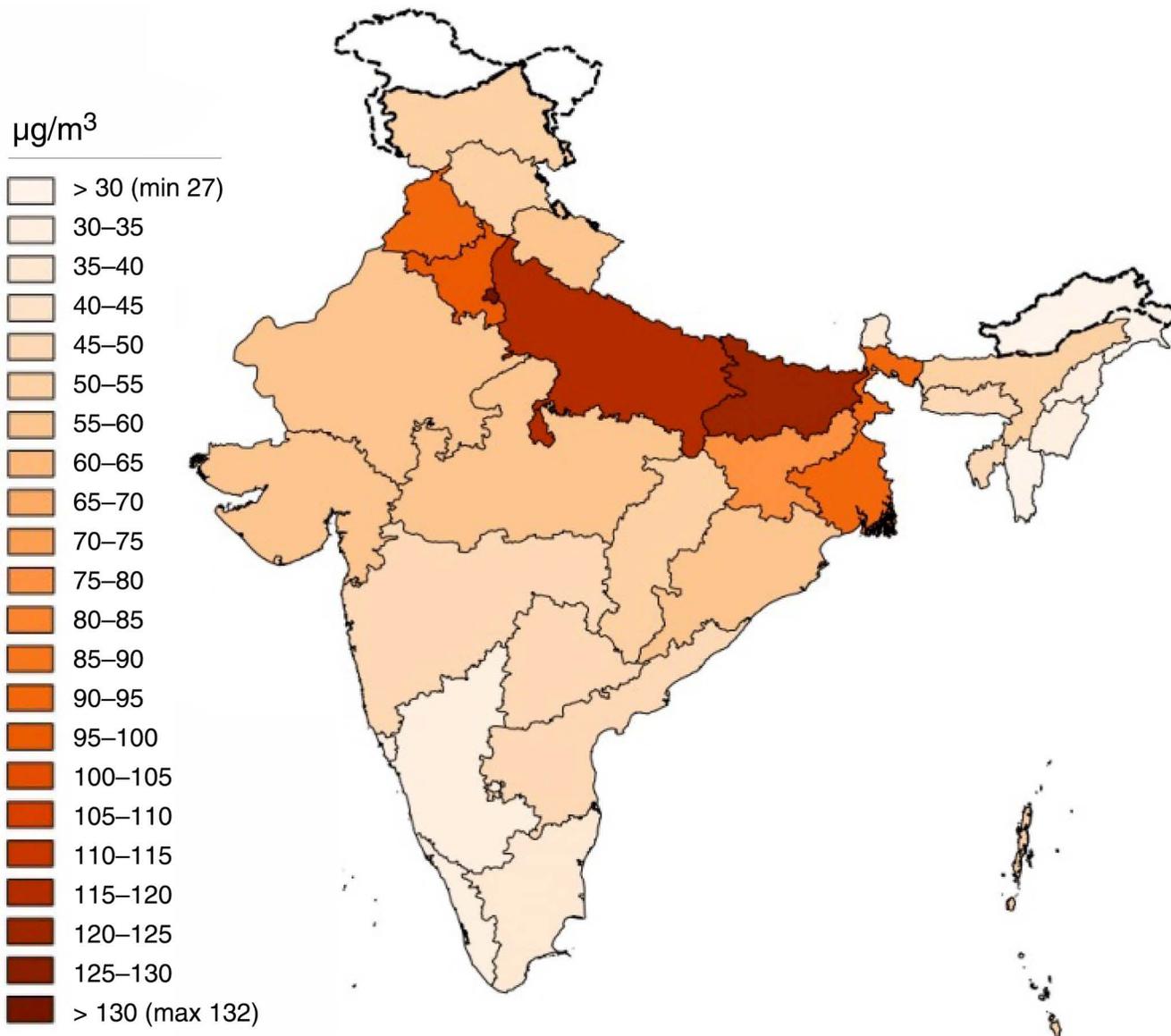
- **This report provides the first comprehensive assessment of the current and predicted burdens of disease attributable to major sources of air pollution in India.**
- **In 2015, particulate matter (PM) air pollution from several major sources was responsible for approximately 1.1 million deaths, or 10.6% of the total number of deaths in India.** Combustion sources are among the leading contributors:
 - **Residential biomass burning is the largest individual contributor to the burden of disease in India.** Residential biomass burning was responsible for 267,700 deaths, or nearly 25% of the deaths attributable to PM_{2.5}, making it the most important single anthropogenic source related to mortality in 2015. These burden estimates do not include the considerable additional burden from indoor exposure to biomass burning.
 - **Coal combustion and open burning also contribute substantially to disease burden.** Coal combustion, roughly evenly split between industrial sources and thermal power plants, was responsible for 169,300 deaths (15.5%) in 2015. The open burning of agricultural residue was responsible for 66,200 (6.1%) PM_{2.5}-attributable deaths.
 - **Transport, distributed diesel, and brick production are also important contributors to PM_{2.5}-attributable disease burden.** In 2015, transportation contributed 23,100 deaths, distributed diesel contributed 20,400 deaths, and brick production contributed 24,100 deaths.
- **If no action is taken, population exposures to PM_{2.5} are likely to increase by more than 40% by 2050.** Three different energy efficiency and air pollution control pathways (scenarios) were evaluated. In the reference scenario (REF), in which little additional action is taken, exposures increase from 74 µg/m³ in 2015 to 106 µg/m³ in 2050. Exposure levels are kept close to 2015 levels under an ambitious S2 scenario. Only under the most active reductions envisioned in the aspirational S3 scenario are exposures projected to be reduced in a major way — by nearly 35% from 2015 to 2050, reaching about 48 µg/m³.
- **If no action is taken, the future burden of disease from all sources will grow substantially by 2050.** The burden of disease is expected to grow in the future, as the population ages and grows and leaves more people susceptible to air pollution, despite the projected exposure decreases in the S2 and S3 scenarios. Compared with nearly 1.1 million deaths in 2015, deaths attributable to ambient PM_{2.5} are projected to rise to 3.6 million with no action.
- **Aggressive action could avoid nearly 1.2 million deaths; all major sectors will need to achieve reductions in air pollution to reduce disease burden.** The Indian government has begun taking actions to improve air quality. This analysis demonstrates that aggressive actions under the S3 scenario could avoid nearly 1.2 million deaths in 2050 compared with the REF scenario. That will be especially true for actions to reduce exposure from *residential biomass combustion, coal burning, and dusts related to human activities.*

This Summary for Policy Makers is excerpted from HEI Special Report 21, by the GBD MAPS Working Group. A list of contributors appears at the end of the Summary, along with the full citation for the report.

This document was made possible, in part, through support provided by the William and Flora Hewlett Foundation and the Oak Foundation. The contents of this document have not been reviewed by these or other institutions, including those

that support the Health Effects Institute; therefore, it may not reflect the views or policies of these parties, and no endorsement by them should be inferred.

*A list of abbreviations and other terms appears at the end of the Summary for Policy Makers.



Summary Figure 1. Population-weighted state-level mean $\text{PM}_{2.5}$ concentrations in 2015 across India. These state-level means are created by aggregating up from the 11-by-11-km-grid population and ambient $\text{PM}_{2.5}$ concentration data developed for GBD 2015 (see text for details).

by the Indian population can vary substantially depending on where people live, these levels are unusually high compared with WHO guidelines and Indian standards.

Trends in outdoor air pollution levels are not promising. Air pollution estimates indicate that, in the last 25 years, average exposure for India increased from about $60 \mu\text{g}/\text{m}^3$ in 1990 to $74 \mu\text{g}/\text{m}^3$ in 2015 — a level more than double the WHO Interim Target-1 and more than seven times higher than the WHO Air Quality Guideline (see related map at the State of Global Air website, www.stateofglobalair.org/air). The steepest increases have occurred in the last 10 years. The Indian government has begun to take action to improve air quality by addressing emissions from vehicles, thermal power plants, and household energy use, among other sources (see full report for details), but significant challenges remain.

THE EVIDENCE ON AIR POLLUTION AND HUMAN HEALTH IN INDIA

Exposure to air pollution has serious consequences for human health. A recent authoritative report of the Steering Committee on Air Pollution and Health-Related Issues of the Indian Ministry of Health and Family Welfare reviewed current evidence on the health effects of exposure to ambient and household air pollution and noted the “... long history and substantive volume of studies in India that have examined the health effects of ambient and household air pollution,” pointing out the “... comparability of available study results to the global pool of evidence ...” (MoHFW [Ministry of Health and Family Welfare] 2015). The report bases its assessment on the growing body of Indian studies on the adverse effects of air pollution whose results are consistent with

studies conducted elsewhere in Asia and with systematic scientific reviews of the worldwide literature by national governments and international agencies.

This report focuses on PM_{2.5} as the primary indicator of air pollution. A substantial body of evidence links PM_{2.5} to many adverse health effects, including diminished lung function, acute and chronic respiratory symptoms (such as asthma and cough and wheeze), and increased risk of mortality from non-communicable diseases such as chronic obstructive pulmonary (lung) disease, heart disease, stroke, and lung cancer, and from lower-respiratory infections in children and adults.

ESTIMATING THE HEALTH BURDEN ATTRIBUTABLE TO AIR POLLUTION: THE GBD PROJECT

Population exposure to air pollution places a substantial burden on public health and on society. The burden on public health is measured by the Global Burden of Diseases, Injuries, and Risk Factors project (GBD), which is the largest and most comprehensive effort to measure epidemiological levels and trends worldwide (www.healthdata.org/gbd). The 2015 update of the GBD involved more than 1,800 collaborators (including 229 Indian experts) from more than 120 countries and 3 territories. GBD 2015 estimated the burden of disease attributable to 79 risk factors — that is, behavioral, environmental (including ambient and household air pollution), and diet-related metabolic factors that can affect health — in 195 countries and territories over a 25-year period (1990–2015) (GBD 2015 Risk Factor Collaborators 2016). These estimates are updated annually, with the 2016 results released in September 2017 and the India-specific 2016 results for all diseases and risk factors published in November 2017 (Dandona et al. 2017; Indian Council of Medical Research, Public Health Foundation of India, and Institute for Health Metrics and Evaluation 2017).

The GBD project measures public health burden in terms of the numbers of deaths and years of healthy life lost (DALYs, or disability-adjusted life-years). The burden of disease attributable to air pollution is estimated from (1) integrated exposure–response relationships between air pollution exposure and the increased risk of mortality from specific diseases using the evidence from a large peer-reviewed international literature combined with (2) India-specific data on baseline population rates of each disease or cause of death and (3) India-specific exposures to air pollution.

In India, the GBD 2015 study found exposure to outdoor PM_{2.5} to be the third leading risk factor contributing to mortality among the 79 behavioral, environmental, and metabolic factors that were analyzed; it was responsible for more than 1 million deaths in 2015, which represent nearly a quarter of the 4.2 million deaths attributable to outdoor air pollution worldwide. It also accounted for 29.6 million years of healthy life lost (i.e., DALYs). The number of deaths attributable to air pollution has been growing steadily in India over the past 25 years (Summary Figure 2). This trend is in part attributable to increases in ambient PM_{2.5} levels, but also to a growing and aging population with increasing numbers of people with ailments that are

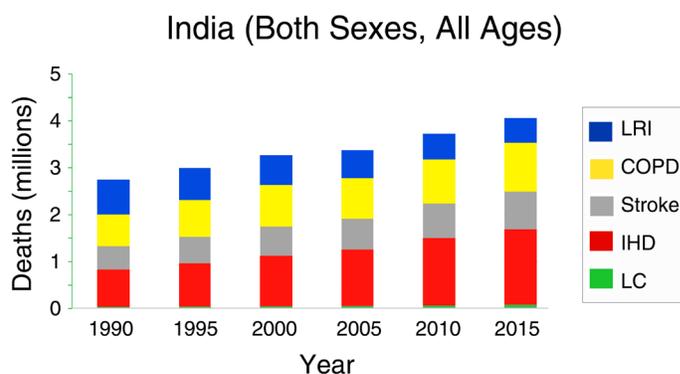
affected by exposure to air pollution, such as cardiovascular disease. When this loss of life is translated into economic terms, the costs are considerable — more than US\$225 billion in lost labor income and US\$5.11 trillion in welfare losses (considered a more comprehensive measure of economic losses, beyond just lost income) worldwide in 2013 according to an analysis by the World Bank and the Institute for Health Metrics and Evaluation (2016). For India alone, the estimate for lost labor output was US\$55 billion and for welfare losses US\$505 billion.

These estimates of burden do not include the additional effects that air pollution has on society via its impacts on climate and on the environment.

ESTIMATING BURDEN OF DISEASE ATTRIBUTABLE TO MAJOR AIR POLLUTION SOURCES: GBD MAPS

Understanding the major sources of air pollution and their relative contributions to PM_{2.5} exposure and, thereby, to disease is a critical next step toward implementing systematic and effective air quality management solutions and reducing exposures and health impacts. The Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project was designed to improve our understanding of these issues. Specifically, its objectives were

- To apply Indian emissions data to estimate ambient PM_{2.5} concentrations and the associated disease burden (defined in terms of numbers of deaths) for the baseline year 2015 that were attributable to major air pollution sources in India, including residential burning of biomass, the burning of coal for industry and power generation, open burning of agricultural residues, transportation, brick kilns, and dust related to industrial and human activities, among others.
- To estimate future (years 2030 and 2050) ambient PM_{2.5} concentrations and the disease burden attributable to major sources or sectors (hereafter referred to simply as “sources”) under three future scenarios. The three scenarios were



Summary Figure 2. Total deaths in India (1990–2015) from diseases for which exposure to PM_{2.5} is a risk factor. (LRI = lower-respiratory infection, COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, and LC = lung cancer). Data from the Institute for Health Metrics and Evaluation’s GBD Compare website (<http://vizhub.healthdata.org/gbd-compare/>) [accessed 2 February 2017].

designed to reflect population growth, development, energy policy, technology changes, and different strategies to address emissions from major sources.

GBD MAPS is a multiyear collaboration between the Health Effects Institute (HEI), the Institute for Health Metrics and Evaluation, the India Institute of Technology (IIT)–Bombay, Tsinghua University, the University of British Columbia, Sri Ramachandra Medical College and Research Institute, and other leading academic centers. (A list of GBD MAPS Working Group members can be found at the end of this document.) GBD MAPS builds on its parent project, the Global Burden of Disease (GBD). The current GBD MAPS study relies on the 2015 update of the GBD data.

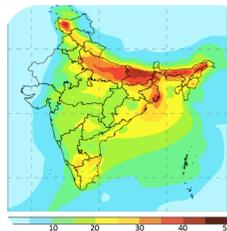
The GBD MAPS analysis involved four main stepwise components, which are illustrated schematically in Summary Figure 3.

In the first step, the GBD MAPS partners at IIT–Bombay developed detailed emissions inventories for 2015, the base year of the study. The inventories include primary emissions of sulfur dioxide, nitrogen oxides, PM_{2.5}, black carbon, organic carbon,

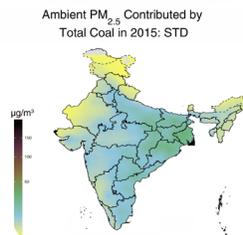
ammonia, and non-methane volatile organic hydrocarbons. The emissions were drawn from a multipollutant database for India, covering the period 1996–2015, that included emissions from the industrial, transport, power generation, residential, and agricultural sectors, as well as from the “informal industry” sectors, which included fuel consumption, process and fugitive emissions (unintended or irregular emissions that escape from processes other than through pipes or stacks), and solvent use. The emissions from each sector were estimated at the sub-state (district) level using official Indian statistics and specialized reports. The emissions were then projected forward by IIT–Bombay to 2030 and 2050 under three different energy and policy scenarios that represent a range of assumptions, based on data from the Government of India and others, about shifts in population growth, energy supply and use, technology, and emissions control over time in each of the major sectors (see Summary Table 1). These projections are used to help estimate changes in emissions of PM_{2.5}, its components (black carbon and organic carbon), and its gaseous precursors (sulfur dioxide, nitrogen oxides, ammonia, and non-methane volatile organic compounds).



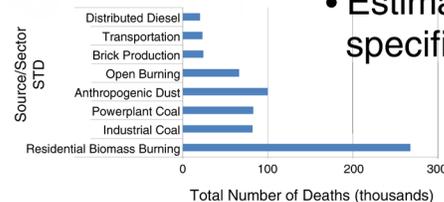
- Develop current and future emissions inventories



- Simulate the fraction of ambient PM_{2.5} due to each major source



- Estimate the GBD 2015 population exposure to each source



- Estimate source-specific burden

Summary Figure 3. Schematic representation of GBD MAPS methodology for estimating the burden of disease attributable to major sources of air pollution in India in 2015 and for future scenarios in 2030 and 2050.

Summary Table 1. Future Scenarios of Energy and Emissions Control Policies

REF, or Reference Scenario

Where the sectoral energy demand is met through sectoral technology-mix evolution at rates corresponding to changes observed during 2005–2015.

S2, or Ambitious Scenario

Assumes that the technology mix will reflect (1) the energy-efficiency targets for thermal power and industry as desired in India’s INDC; (2) the emissions standards in transport as proposed in auto-fuel policy; and (3) the emissions controls expected from an influx of cleaner technologies in residential, brick production, and informal industry sectors.

S3, or Aspirational Scenario

Aimed at more profound energy efficiency targets, represented by published high-efficiency–low-carbon-growth pathways in industrial, electricity-generation, and transport sectors; high rates of shifting away from traditional biomass technologies (residential and informal industry); and including a complete end to agricultural field burning.

Note: INDC refers to India’s Intended Nationally Defined Contribution to greenhouse gases under the United Nations Framework Convention on Climate Change signed in Paris in 2015.

With the emissions from step one as inputs, the second step used the South Asia nested version of GEOS-Chem, a global chemical transport model, to estimate first the ambient PM_{2.5} concentrations from all sources or sectors and then the fraction of that total attributable to each of several major sources (see Summary Table 2). These sources were chosen given their inclusion in similar national- and global-level analyses and specific interest in potentially important sources within India. The simulations were conducted for the baseline year 2015, for 2030 (for total PM_{2.5} only), and for 2050 under the three scenarios described in Summary Table 1.

The third step, illustrated in Summary Figure 3, combined the fractional contributions of each source (step two) with higher-resolution estimates (defined by approximately 11-km by 11-km grids) of ambient PM_{2.5} concentrations developed for GBD 2015 to calculate the source contributions to population exposure (referred to as “population-weighted concentrations” of PM_{2.5}) in each grid cell. The GBD 2015 estimates combine (1) satellite-based PM_{2.5} estimates and GEOS-Chem data and (2) annual average PM measurements (2008–2014). This approach explicitly incorporated more than 400 Indian surface-level measurements (25 for PM_{2.5} and 411 for PM₁₀ [the larger particulate size fraction that can also be used to estimate PM_{2.5}, a size fraction within PM₁₀]) — all the measurements that were then available.

The final step in the analysis (see Summary Figure 3) estimates the source-specific burden of disease in India. This

Summary Table 2. Major Sources or Sectors Evaluated

Source or Sector Name / Subcategories of Sources or Activities Included

- **Residential Biomass**
Residential cooking, lighting, heating, and water heating
- **Open Burning**
Burning of agricultural residue
- **Total Coal**
Heavy and light industry, electricity generation
- **Industrial Coal**
Heavy and light industry
- **Power Plant Coal**
Electricity generation
- **Transportation**
Private passenger vehicles; public passenger vehicles; freight including light-duty and heavy-duty diesel vehicles; diesel railway locomotives. Shipping not included
- **Brick Production**
Traditional brick kilns (predominantly)
- **Distributed Diesel**
Agricultural pumps, agricultural tractors, and electric generator sets
- **Anthropogenic Dust**
Dust related to human activities — fugitive, combustion, and industrial production
- **Total Dust**
Windblown mineral dust and anthropogenic dust

step couples the source-specific exposures to PM_{2.5} with the GBD’s integrated exposure–response relationships for specific diseases (ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower-respiratory infections) and with India-specific disease and mortality rates. This Summary focuses on the burden from mortality, expressed in terms of the number of deaths attributable to air pollution. The complete results, including DALYs, can be found in the full report. The analyses were conducted for 2015 and for 2050 for each of the three future scenarios taking into account projections of future population, demographics (e.g., age structure and rates of illness), and economic activity. For 2030, the disease burden attributable to ambient PM_{2.5} in total was also estimated as an interim analysis. As with the exposure estimates, source-sector-specific contributions to disease burden were estimated for India as a whole and separately for urban and rural areas.

PREPARATION AND PEER REVIEW OF THE GBD MAPS REPORT

The draft final report prepared by the GBD MAPS Working Group was reviewed with regard to methodological approach, validity of estimates, and appropriateness of interpretation by

independent external peer reviewers from India and other countries, who were selected by HEI for their expertise in different technology sectors and their emissions, in air quality measurement, in atmospheric chemistry and modeling, and in health effects assessment. The list of reviewers can be found in the Contributors list at the end of this document. A draft final version of this report was also reviewed by experts on the GBD MAPS Steering Committee. The GBD MAPS Working Group prepared the final report in response to the comments received.

MAIN FINDINGS

THE SITUATION IN 2015

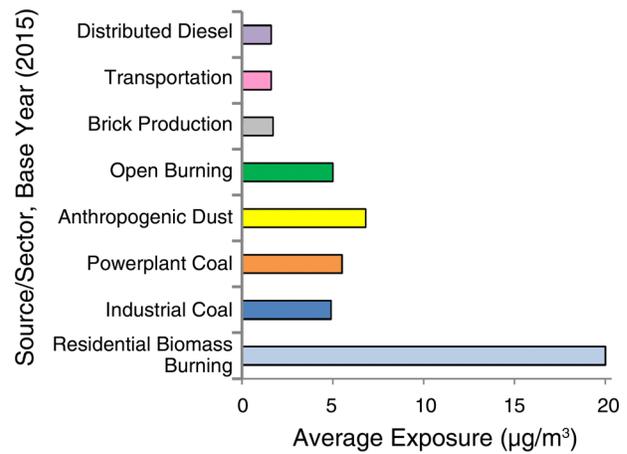
Sources Related to Human Activities Were Responsible for the Largest Proportion of the Population Exposure to PM_{2.5} in India.

In 2015, the leading contributors to ambient PM_{2.5} exposure (defined as “annual average population-weighted PM_{2.5} concentration”) were the sources associated with combustion of biomass and coal and other human activities that generate dust (Summary Figure 4). The India-wide average PM_{2.5} exposure in 2015 was 74.3 µg/m³. Residential biomass burning contributed nearly 24% of the total (see Table 2 in the main report); coal combustion was the next largest contributor (with 7.7% from industry and 7.6% from power generation); and anthropogenic dust (dust related to human activities, including fugitive dust from roads and fly-ash from coal burning and waste burning) contributed about 9%. Also, agricultural burning contributed more than 5%, and transportation, brick production, and distributed diesel each contributed about 2%. Windblown mineral dust contributes to ambient PM_{2.5} air pollution; however, the extent of the contribution varies greatly across India, with the most significant contribution in the northwest region.*

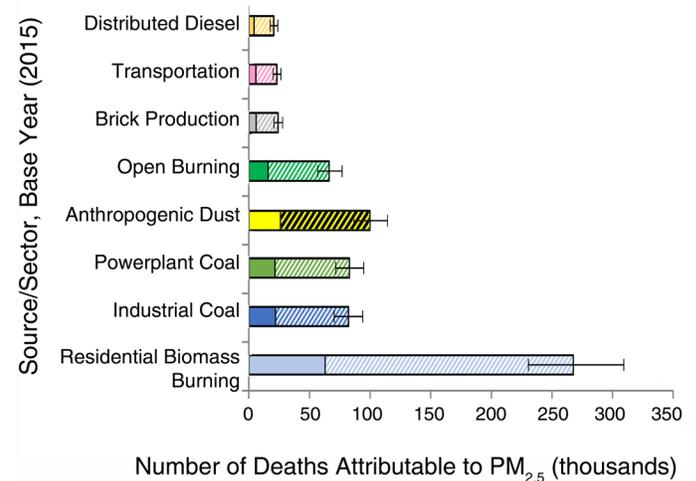
Sources of Air Pollution Linked to Human Activity Are Also the Largest Overall Contributors to the 2015 Burden of Disease in India, and the Rural Population Faces the Highest Burdens.

Consistent with their contribution to exposure, sources associated with human activity contributed to nearly 70% of all PM_{2.5}-attributable mortality in 2015. Summary Figure 5 shows that the PM_{2.5}-attributable mortality estimates for India as a whole in 2015 were dominated by the mortality estimates for the rural population (as defined by the 2011 Indian Census and indicated by the hatched portion of the bars); that is, about 75% of the deaths in India occur among the rural population. This result reflects the fact that a large proportion of the Indian population lives in rural areas (about two-thirds in 2015) and that there are differences in mortality rates and age structures in these populations. Unlike the situation in many other countries, where urban exposures dominate, this study found that the PM_{2.5} exposure levels in rural and urban areas in India were similar (i.e., both more than 70 µg/m³).

* Note that, although it was not included in the set of sources related to human activities, windblown dust also arguably results in part from human activities that contribute to desertification, for example, either directly through agricultural or forestry practices or indirectly through impacts on climate.



Summary Figure 4. Contribution by selected sources to average population exposure to PM_{2.5} in India for 2015 (see Table 3 in the main report).



Summary Figure 5. Contributions (including 95% uncertainty intervals) by selected sources to mortality burden in India in the baseline year, 2015. Hatched bars indicate rural population, and solid bars indicate urban populations.

Residential biomass burning is the largest individual contributor to the burden of disease in India. Among all sources related to human activities, residential biomass burning was responsible for 267,700 deaths or nearly 25% of the deaths attributable to PM_{2.5}, making it the most important single anthropogenic source related to mortality in 2015. These burden estimates do not include the additional substantial burden from indoor exposure to biomass burning.

Coal combustion and open burning are also substantial contributors to disease burden. Coal combustion, roughly evenly split between industrial sources and thermal power plants, was responsible for 169,300 deaths (15.5%) in 2015. The open burning of agricultural residue was responsible for 66,200 PM_{2.5}-attributable deaths (6.1%).

Transport, distributed diesel, and brick production are also important contributors to disease burden. Compared with other sources in this nationwide analysis, transportation, brick kilns, and distributed diesel have relatively small percentage

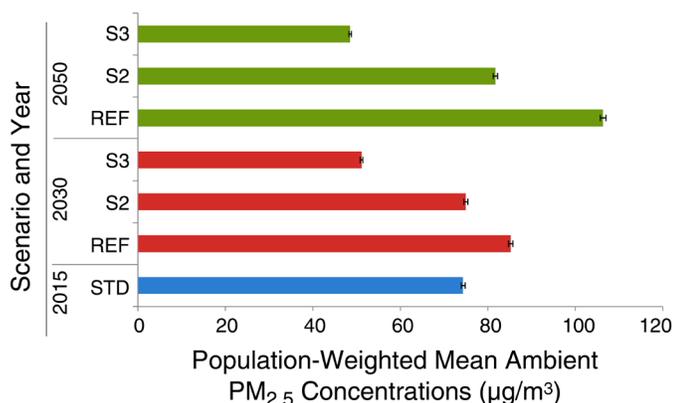
impacts on health burden in 2015. Nonetheless, the numbers of deaths in 2015 attributable to these sources in this study are substantial: 23,100 for transportation; 20,400 for distributed diesel; and 24,100 for brick production.

On a national basis, transportation’s contribution to mortality burden was around 2% in both rural and urban areas. These national-level contributions to exposure and burden attributable to transportation are relatively low compared with some produced for city-specific analyses, in part because the geographic scale of the grid used for the analysis is relatively larger and less likely to capture detailed variation in traffic-related exposure within urban areas and near roads. Transportation and distributed diesel sources typically operate in closer proximity to populations than do large stationary sources such as power plants and industrial facilities; for that reason the approach taken in this analysis may underestimate actual exposures and the related disease burden attributable to these sources. Indeed, Indian analyses conducted at finer scales — albeit with their own uncertainties — have found transportation to be a more significant contributor to exposure in India’s cities.

LOOKING AHEAD

If No Action Is Taken, Population Exposures to PM_{2.5} Are Likely to Increase Substantially in India by 2050.

As indicated in the introduction, the annual average levels of exposure to PM_{2.5} in India are already high relative to guidelines for air quality set by the WHO and Indian national air quality standards. The analysis of alternative future energy and control scenarios shows that choices made on the actions taken to reduce emissions have important implications for reducing both exposure to (see Summary Figure 6) and disease burden from ambient PM_{2.5}. Not surprisingly, the scenario with the least aggressive measures (REF) leads to the largest expected increases in the mean population-weighted exposures to PM_{2.5} in both 2030 and in 2050 relative to current levels. Even the S2 scenario, an ambitious scenario that will require major commitments to emissions reductions in the face of continued economic growth, is projected just to hold PM_{2.5} to current levels by 2030, and to a more modest increase (10%) by 2050. Only



Summary Figure 6. Projected average exposures to PM_{2.5} from all study sources in India for 2015 and for the three scenarios in the years 2030 and 2050.

under the most active reductions envisioned in the aspirational S3 scenario are exposures projected to be reduced substantially by 2030 and 2050 compared with current levels. The 2050 population-weighted mean exposure for the S3 scenario, even excluding any impact from windblown mineral dust, is estimated to be nearly three times higher than the WHO Air Quality Guideline.

Summary Figure 7 illustrates the contributions of different sources to PM_{2.5} under the three future scenarios. It shows that, in 2050, both the magnitude and relative importance of different sources would vary substantially by scenario, reflecting the impacts of the various energy, policy, and other actions assumed under the three scenarios. Although not shown here, the contributions of different sources to PM_{2.5} can also vary substantially across India given differences in the location and prominence of those sources regionally. Details can be found in the full report.

If No Action Is Taken, the Future Burden of Disease from All Sources Will Grow Substantially by 2050; Aggressive Action Could Avoid Nearly 1.2 Million Deaths.

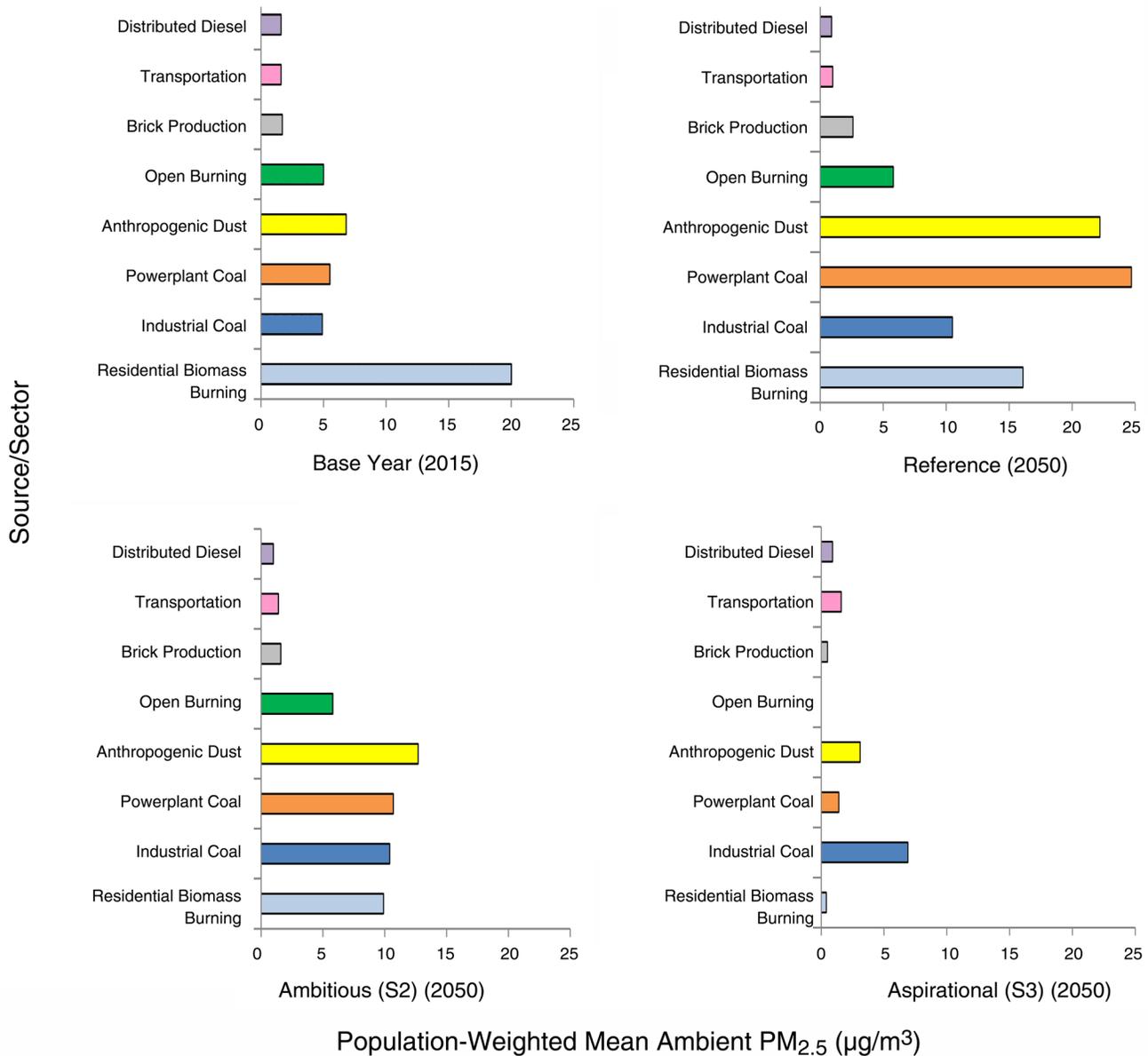
The burden of disease, in terms of the numbers of deaths attributable to total PM_{2.5}, is substantial and expected to grow in the future, as the population ages and grows and leaves more people susceptible to air pollution, despite the projected exposure decreases in the both the S2 and S3 scenarios (Summary Figure 8). Compared with 1.09 million deaths in 2015, ambient PM_{2.5} was projected to be responsible for 1.7 million, 1.6 million, and 1.3 million deaths in 2030, rising to 3.6 million, 3.2 million, and 2.5 million deaths in 2050 for REF, S2, and S3, respectively. Over time, some of the increases in mortality from 2015 can be explained by increases in the numbers and susceptibility of people exposed to air pollution. However, comparison among scenarios suggests that the number of deaths attributable to PM_{2.5} was consistently lower in the more aggressive S2 and S3 scenarios than in the REF scenario. Nearly 100,000 to 400,000 deaths could be avoided in 2030 and as many as 340,000 to nearly 1.2 million deaths avoided in 2050 if the more aggressive measures described in scenarios S2 and S3 are implemented.

Aggressive Action Will Need to Be Taken in All Major Sectors.

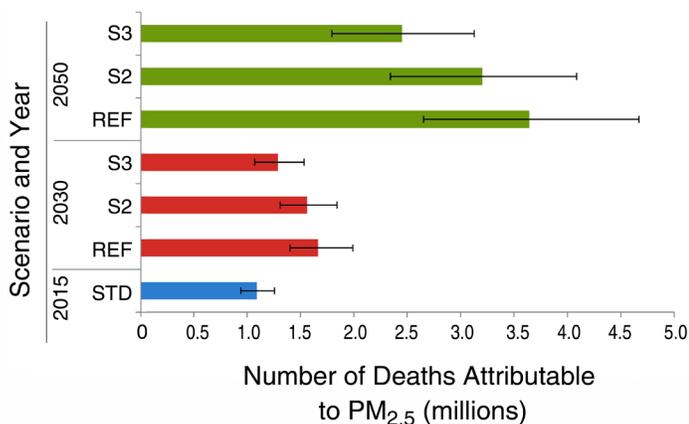
Summary Figure 9 breaks down total contributions to disease burden by source for urban and rural areas in 2015 and in 2050 for all three scenarios.

Residential biomass burning. Left unaddressed, as it is under the REF scenario, the burden of disease from the burning of residential biomass to outdoor air pollution could grow to more than 500,000 annual deaths in 2050. There is, however, substantial opportunity to reduce these exposures and effects, especially through a major shift to use of cleaner fuels (e.g., liquefied petroleum gas).

Combustion of coal by industries and power plants. In all future scenarios, coal combustion is projected to replace residential biomass burning as the leading contributor to burden in India. Under the REF scenario, its contribution to disease burden is projected to increase considerably — to nearly 1.3 million annual deaths in 2050. In the REF scenario, this increase is attributable primarily to coal-fired power plants; however, in all three scenarios



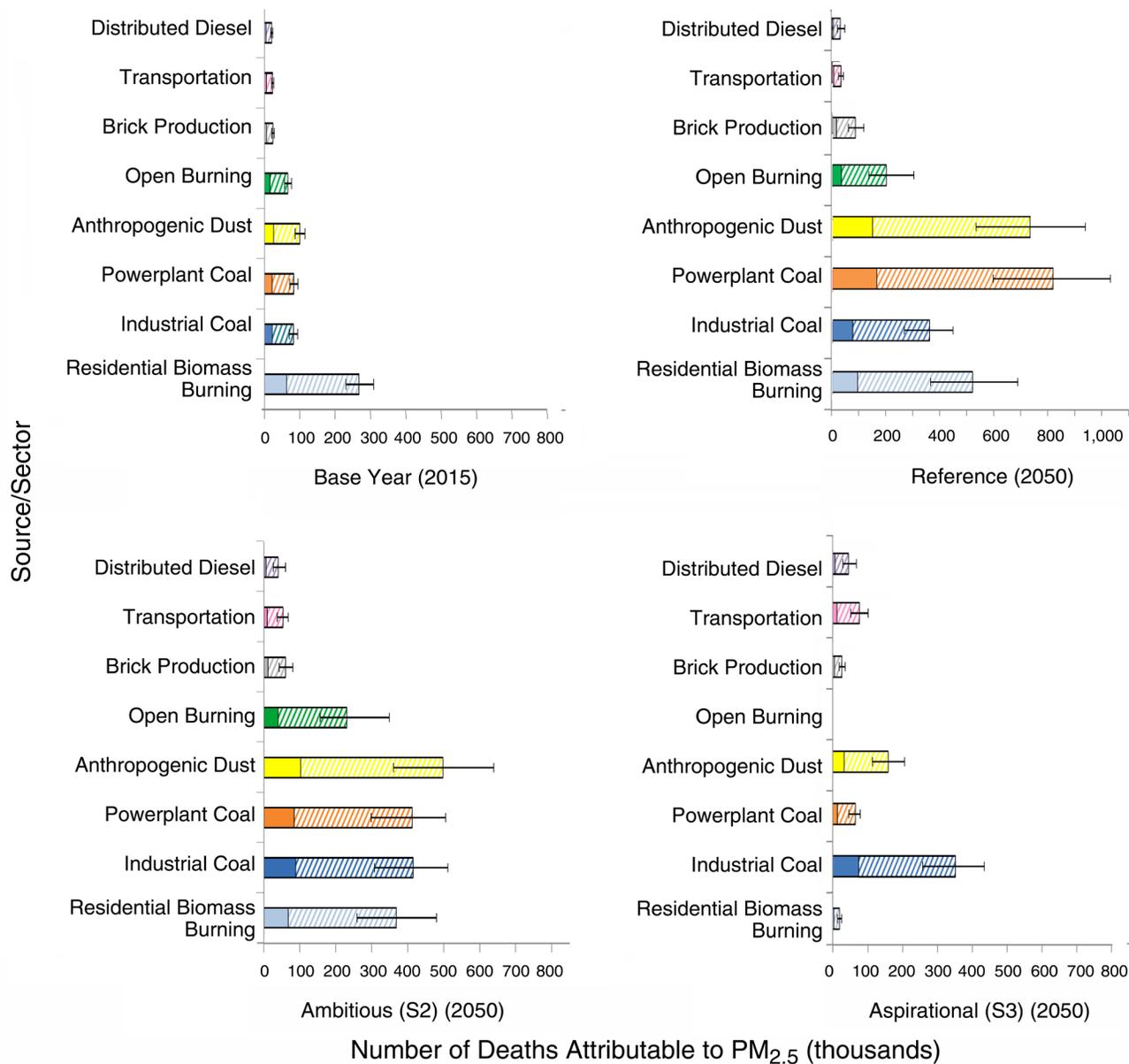
Summary Figure 7. Source contributions to PM_{2.5} exposures in India in 2015 and for each of the three scenarios in 2050.



Summary Figure 8. Total number of deaths (including 95% uncertainty intervals) attributable to total PM_{2.5} from all sources in 2015 and for each of the three scenarios in 2030 and 2050.

the contributions to burden from industrial burning of coal are also projected to increase. In the most aspirational scenario, S3, contributions from industrial burning of coal will exceed those from power plants. Aggressive emissions control measures, such as those incorporated into scenarios S2 and S3 for coal-burning thermal-power plants and industries, could help avoid between 400,000 and 850,000 coal-attributable deaths in 2050.

Transportation, distributed diesel, and brick kilns. Although small in this analysis in comparison to other sources, the impacts of transportation and distributed diesel sources are projected to increase substantially under all future scenarios. The increases are attributable both to factors affecting emissions and to the growth and aging of the population, as discussed for other sectors. The relative contribution of transportation to disease burden was projected to increase in the S3 scenario in 2050 compared with 2015 (3% versus 2.1%, respectively), although the number of deaths remained the same. For transportation,



Summary Figure 9. Source contributions to disease burden (deaths) in urban (solid) and rural (hatched) areas of India in 2015 and in 2050 for each of the three scenarios. The 95% uncertainty intervals on the combined urban and rural deaths are also presented. (Note that the x-axis scales vary.)

the future scenarios reflect a complex interplay. This analysis assumes decreased per-vehicle emissions as a result of the implementation of the more stringent Bharat Stage VI/6 emissions standards. The improvements in emissions per individual vehicle, however, will be offset in part by increases in the numbers of vehicles and in vehicle use. The analysis also assumes changes in transportation modes, especially in S2 and S3, which involve, for example, shifts to bus fleets powered by compressed natural gas and electricity in urban areas. The analysis assumes a continued reliance on diesel in rural areas.

Brick production is projected to have increased impacts on disease burden under the REF and S2 scenarios. Under the aspirational scenario, S3, the impacts on mortality remained at levels similar to those estimated for 2015, reflecting a balance between the impacts of reductions in emissions and the impact of demographic trends on mortality.

Anthropogenic dust. The potential future impacts of anthropogenic dust are large. Anthropogenic dust includes fugitive dust and dusts from combustion and industrial production. Of the total 1.09 million deaths attributable to PM_{2.5} in 2015 in India, approximately 99,900 deaths are attributable to dust from anthropogenic activities. In each of the future scenarios, the increases in population-weighted dust concentrations and the related burden on health are entirely attributable to changes in the anthropogenic component. For example, under the REF scenario, the anthropogenic component of dust more than tripled from 6.8 µg/m³ in 2015 to 22.2 µg/m³ in 2050. Specifically, road dust emissions are projected to nearly double between 2015 and 2030 and to stabilize (but not decrease) from 2030 to 2050 as emissions reductions from improvements to road quality are offset by increased vehicle use. Left unchecked, as in the REF scenario, dust emissions from anthropogenic activities are projected to be responsible for 743,000 attributable deaths. These projections

from our analysis suggest that more attention should be directed toward reductions in anthropogenic dust emissions in particular.

LIMITATIONS

Although this study has many strengths as the first detailed national-level analysis of source-sector-related exposure and burden of disease in India, it has — like any analysis — some limitations. The analysis necessarily required a number of decisions and assumptions, which were based on the best data available to the Working Group at the time. Some of the decisions may underestimate the true burden attributable to air pollution. For example, this report focused only on PM_{2.5} exposures; however, the GBD project also evaluates the contribution of ozone exposure to the burden of disease from air pollution. Although ozone's contribution has been much smaller than that of PM_{2.5}, recent research suggests that exposures to ozone are likely to increase in India in the future. Other decisions may introduce uncertainties whose potential magnitude and biases are not yet known; these include the use of the integrated exposure-response curves to predict disease-specific burden and the assumption that all airborne particles smaller than 2.5 µm in aerodynamic diameter are equally toxic, among others. Similarly, our projections of pollution under future scenarios in 2030 and 2050 are based on a range of assumptions about planned initiatives, expected growth and development, and feasible policies and technology changes. The extent to which these will be realized or perhaps replaced by as-yet-unknown disruptive technologies and trends is unknown. As such, the reference scenario and the more aspirational S3 scenario are best viewed as bounding the likely path of changes in emissions in India. Finally, with the exception of windblown mineral dust, this report does not address the impact of specific emissions sources outside India on exposure and disease burden within India, nor does it estimate the impact of emissions that originate within India on the health of populations outside the country, as some recent analyses have done.

CONCLUSIONS

The analyses conducted in this study have shown that multiple air pollution sources contribute to a significant health burden attributable to ambient PM_{2.5} air pollution in India today. They also pose major challenges for air quality management and for the reduction of air-pollution-related health burden in the future. As is the case for all countries that are growing and aging in ways that make them more susceptible to the effects of air pollution, future mortality attributable to air pollution in India is expected to grow even with reduction in air pollution levels. In India, given expected growth in economic activity and population, our estimates predict that future exposures to ambient PM_{2.5} will increase by 2050 under the REF scenario and even under the ambitious S2 scenario. Reductions in exposure are projected in 2030 and 2050 only under S3, the most aspirational air pollution control scenario. When combined with the changes in population demographics, these exposures are predicted to

increase the number of deaths attributable to air pollution in India in the future. However, our estimates also indicate that there are significant opportunities in both urban and rural India to avoid hundreds of thousands to more than a million deaths by 2050 if the emission control measures described in scenarios S2 and S3 are implemented. The Indian government has begun to initiate actions to improve air quality; ultimately, aggressive implementation of air quality management, such as that simulated for our aspirational S3 scenario, will be required to lead India to a reduction of disease burden and protection of public health from air pollution in the future.

ACKNOWLEDGMENTS

HEI and the GBD MAPS Working Group are particularly grateful to Katherine Walker for managing and contributing to the completion of this report, to Kushal Tibrewal of IIT Mumbai for his careful technical assistance with the emissions estimation in the report, to Allison Patton for managing the review, to Kathryn Liziewski for assistance throughout the preparation of the report, to Mary Brennan for science editing of the report, to Hilary Selby Polk for production management, to Fred Howe for proofreading, to Ruth Shaw for composition, and to Pallavi Pant of the University of Massachusetts for reviewing the Hindi translation of the Summary for Policy Makers.

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ABBREVIATIONS AND OTHER TERMS

DALY	disability-adjusted life-year
GBD	Global Burden of Disease (project)
GBD MAPS	Global Burden of Disease from Major Air Pollution Sources (initiative)
GEOS-Chem	Goddard Earth Observing System Global Chemical Transport Model
HEI	Health Effects Institute
MoHFW	Ministry of Health and Family Welfare (Government of India)
PM ₁₀	particulate matter $\leq 10 \mu\text{m}$ in aerodynamic diameter
PM _{2.5}	particulate matter $\leq 2.5 \mu\text{m}$ in aerodynamic diameter
REF	reference scenario
WHO	World Health Organization

Publishing history: This document was posted at www.healtheffects.org in January 2018.

Citation for this Summary for Policy Makers:

GBD MAPS Working Group. 2018. Summary for Policy Makers. Burden of Disease Attributable to Major Air Pollution Sources in India. Special Report 21. Boston, MA: Health Effects Institute.

Citation for whole document:

GBD MAPS Working Group. 2018. Burden of Disease Attributable to Major Air Pollution Sources in India. Special Report 21. Boston, MA: Health Effects Institute.

© 2018 Health Effects Institute, Boston, Mass. Library of Congress Catalog Number for the HEI Report Series: WA 754 R432.

The entire report is available at www.healtheffects.org/publication or from HEI.

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