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Acknowledgments

This report was prepared by a team led by Yewande Awe with the core team comprising Bjorn Larsen and Ernesto Sánchez-Triana. The task team also included Santiago Enriquez and Shafick Hoossein. This report updates the “2020 Cost of Air Pollution” report by using health data for the Global Burden of Disease study published at the end of 2020.

The team would like to acknowledge, with thanks, the valuable advice and inputs of the following colleagues: Stephen Dorey, Fernando Loayza, Helena Naber, Katelijn Van den Berg, and Martin Heger (World Bank); and Maureen Cropper (Professor of Economics, University of Maryland). Editorial support was provided by Stan Wanat.

This report is a product of the Environment, Natural Resources, and Blue Economy Global Practice of the World Bank. This work was conducted under the supervision of Juergen Voegele (Vice President, Sustainable Development Practice Group); Karin Kemper (Global Director, Environment, Natural Resources, and Blue Economy); Richard Damania (Chief Economist, Sustainable Development Practice Group); Iain Shuker (Practice Manager, Africa, Environment, Natural Resources, and Blue Economy); and Christian Albert Peter (Practice Manager, Global Engagement, Environment, Natural Resources, and Blue Economy).

The Pollution Management and Environmental Health Multi-donor Trust Fund of the World Bank provided financial support for the preparation of this report. That support is gratefully acknowledged.
In 2020, as cities around the world went into COVID-19-induced lockdowns, people took notice of the surprisingly blue skies above them. By painfully grinding economic and social activities to a halt, lockdowns resulted in rapid reductions of air pollutants. However, in most cities, air pollution returned to its pre-pandemic levels almost as soon as restrictions were eased. This was a stark reminder of the need to strengthen efforts to tackle air pollution and to integrate air-pollution reductions into countries’ recovery efforts.

According to the Global Burden of Disease 2019, PM$_{2.5}$ (fine particulate matter) air pollution—in both outdoor environments and inside households that use solid fuels for cooking and heating—caused 6.4 million deaths and 93 billion days lived with illness in 2019. While the toll of various risks, including household air pollution, has fallen over time, that of ambient air pollution has continued to rise over the last decade.

The significant health, social, and economic effects of air pollution compel us to support client countries in addressing air pollution as a core development challenge. To this end, the Bank is committed to continue strengthening the evidence base that can inform effective and efficient air-quality interventions. Recent groundbreaking research advanced by the Bank has made substantial contributions to this evidence base in areas that include (a) the importance of prioritizing efforts to reduce air-pollution emissions from coal-fired power plants and diesel-fueled vehicles because the particles in those emissions are more damaging to health than particles from most other air-pollution sources (Thurston, Awe, Ostro and Sánchez-Triana 2021); (b) demonstrating that particulate matter from dust should continue to be factored into global estimates of the burden of disease of air pollution given the substantial health impact of dust (Ostro, Awe, and Sánchez-Triana 2021); and (c) building a strong case for scaling up efforts to establish ground-level networks for monitoring air quality in low- and middle-income countries by demonstrating that satellite-based air-quality estimates are not a sufficiently accurate substitute for ground-level data (World Bank 2021).

This publication aims to further contribute to the evidence base on air-quality management by providing up-to-date estimates of the global economic costs of air pollution. The analysis builds on previous estimates by the Bank and its partners and is based on cutting-edge scientific findings of the health effects of air pollution.
pollution, as well as more comprehensive air-quality data from monitoring stations in a large number of cities across the world.

By providing monetary estimates of the health damage of air pollution, this publication aims to support policy makers and decision-makers in client countries to prioritize air pollution amid competing development challenges. Its findings build a strong economic case to invest scarce budgetary resources in the design and implementation of policies and interventions to improve air quality that will deliver benefits for societies at large, and particularly for vulnerable groups.

REFERENCES

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990-2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” Lancet 396: 1223–49.

Ostro, Bart, Yewande Awe, and Ernesto Sánchez-Triana. 2021. When the Dust Settles: A Review of the Health Implications of the Dust Component of Air Pollution. Washington, DC: World Bank.

Thurston, George, Yewande Awe, Bart Ostro, and Ernesto Sanchez-Triana. 2021. “Are All Air Pollution Particles Equal? How Constituents and Sources of Fine Air Pollution Particles (PM2.5) Affect Health.” A World Bank Study. World Bank, Washington, DC.

World Bank. 2021. Getting Down to Earth: Are Satellites Reliable for Measuring Air Pollutants that Cause Mortality in Low- and Middle-Income Countries? International Development in Focus. Washington, DC: World Bank.
About This Work

The analytical work in this report builds on a growing body of evidence that the World Bank is building to better understand the linkages between air pollution and health, strengthen quantification of the health damage from air pollution, and support improved air quality monitoring and data in low- and middle-income countries. Recent contributions from this body of work include (1) the monetary valuation of the global cost of mortality and morbidity caused by exposure to ambient PM$_{2.5}$ air pollution, (2) demonstration that the dust component of air pollution has substantial health effects and should thus continue to be factored into global estimates of the health burden of air pollution, and (3) demonstration of the importance of prioritizing efforts to reduce air pollution emissions from coal-fired power plants and diesel-fueled vehicles because their particles are more damaging to health than particles from most other air pollution sources.
Executive Summary

INTRODUCTION

Air pollution is a major cause of disease and death. “Ambient air pollution” refers to air pollution in the outdoor air; “household air pollution” refers to air pollution originating in the household environment. Air pollution is the world’s leading environmental risk to health and the cause of morbidity and mortality from diseases such as ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, pneumonia, type 2 diabetes, and neonatal disorders. Most deaths related to air pollution are caused by human exposure to fine inhalable particles or fine particulate matter, also known as PM$_{2.5}$.

Billions of people in developing countries live in places where the ambient and indoor concentrations of PM$_{2.5}$ are multiple times higher than the health-based guideline values for air quality established by the World Health Organization (WHO). An estimated 6.4 million people died prematurely worldwide in 2019 due to exposure to PM$_{2.5}$ air pollution. About 95 percent of those deaths occurred in low- and middle-income countries (LMICs) (GBD 2019 study). Seventy percent of the deaths occurred in East Asia and the Pacific, and South Asia. China and India accounted for 52 percent of global deaths from PM$_{2.5}$. There were six countries with more than 100,000 deaths from PM$_{2.5}$, and nine countries with 50,000–100,000 deaths.

Besides being a health problem, air pollution contributes to less-livable conditions and hinders economic competitiveness. Poor people are more likely to live in a polluted environment and suffer the adverse impacts of air pollution. In addition, people who are sick as a result of exposure to air pollution are more likely to take days off work and suffer reduced productivity, which in turn undermines their contributions to economic growth. Air pollution could also hinder cities’ ability to attract talented workers, thereby reducing competitiveness. Furthermore, air pollution imposes a heavy economic burden both on the economies of individual LMICs and on the global economy as a result of illness, premature death, lost earnings, and increased health-care expenditures—all of which constrain productivity and economic growth. Poor people who have the least means to address the health damage of air pollution often disproportionately carry the economic burden.
Air pollution is also associated with many detrimental, but less researched, health impacts and conditions (Sánchez-Triana et al. 2015), such as infant mortality (Heft-Neal et al. 2018), low birth weight (Ezziane 2013), pre-term delivery (Bowe et al. 2018), mental health conditions (Shin Park, and Choi 2018), and neurological impairment (Xu, Ha, and Basnet 2016; Zhang, Chen, and Zhang 2018) including dementia in later life (Carey et al. 2018). As the evidence base for these and other conditions becomes stronger, it is envisaged that exposure-response functions can be developed to obtain global estimates of the health burden of air pollution.

Some air pollutants, notably short-lived climate pollutants, such as black carbon, have climate-warming properties (Shindell et al. 2012). In addition, air pollution (particularly linked to sulfur dioxide) adversely affects the environment, resulting in acid rain and associated land and water pollution. Air pollution also has aesthetic impacts, such as reduced visibility. However, economic valuation of these impacts can be done only at local and regional levels. Further research is needed to determine how to effectively conduct economic valuation of these impacts at the global level.

Air pollution’s various adverse impacts on multiple facets of the society and economy, particularly of LMICs, squarely place air pollution as a core development challenge. This makes reducing air pollution in developing countries central to achieving poverty reduction and equitable prosperity objectives in those countries.

Global health crises further highlight the need for continued action in addressing a global and cross-cutting challenge such as air pollution. The current global COVID-19 pandemic, caused by the novel coronavirus, SARS-CoV-2, underscores the importance of reducing air pollution through preventive and abatement measures. People who contract COVID-19 and have underlying medical problems such as heart disease, lung disease, and cancer are at a higher risk of developing serious illnesses that could lead to death. It is noteworthy that air pollution is a cause of the aforementioned diseases. Ongoing research is finding relationships between air pollution and the incidence of illness and death due to COVID-19. Such research suggests that PM$_{2.5}$ air pollution plays an important role in increased COVID-19 incidence and death rates. One such study reported that PM$_{2.5}$ is a highly significant predictor of the number of confirmed cases of COVID-19 and related hospital admissions (Andrée 2020).

**MOTIVATION**

This report provides an estimate of the global, regional, and national costs of health damage—that is, premature mortality and morbidity—from exposure to PM$_{2.5}$ air pollution in 2019. While recognizing the various costs of air pollution to society, this report focuses on the cost of premature mortality and morbidity of health effects estimated by the GBD 2019 study. Estimating the health damage of air pollution in monetary terms provides a suitable metric for policy makers and decision makers in developing countries to prioritize the design and implementation of policies and interventions for controlling air pollution amid competing development challenges and budgetary and other resource constraints. An earlier study by the World Bank and IHME (2016) estimated the cost of premature mortality from ambient air pollution and household air pollution combined in 2013.²
The present report estimates the cost of health damages using the estimates of mortality and morbidity from PM$_{2.5}$ air pollution published in the Global Burden of Disease (GBD) 2019 study. The GBD assesses mortality and disability from numerous diseases, injuries, and risk factors, including air pollution. Air pollution has long been recognized as a significant environmental health risk. GBD estimates of the global, regional, and national health burden attributable to air pollution, based on nationwide exposures to ambient PM$_{2.5}$, as well as household use of solid fuels, were published for the first time in the GBD 2010 study, followed by GBD 2013, 2015, 2016, 2017, and 2019.

**METHODOLOGY**

This report uses the GBD 2019 estimates of premature mortality and morbidity attributable to PM$_{2.5}$ air pollution to value the economic cost in dollar terms. The GBD estimates the major health damages of population exposure to PM$_{2.5}$ from exposure-response relationships that have been established by global research on air pollution and health. These exposure-response relationships provide estimates of the number of cases of premature deaths and disease in a country that result from the population’s exposure to given concentrations of PM$_{2.5}$. Population-exposure levels to ambient PM$_{2.5}$ are estimated based on a combination of ground-level monitoring of ambient PM$_{2.5}$, satellite imagery, and chemical-transport models. Population-exposure levels to PM$_{2.5}$ household air pollution are estimated based on population use of solid fuels for cooking and other domestic purposes, combined with household PM$_{2.5}$ measurements, type of solid fuel and cookstove, urban-rural household location, and sociodemographic characteristics known to influence household air-pollution levels.

The cost of the health damages from PM$_{2.5}$ air pollution is quantified separately for premature deaths and morbidity. The cost of premature deaths is estimated from the value of statistical life (VSL). VSL is a measure of how much individuals are willing to pay for a reduction in the risk or likelihood of premature death. VSL is influenced by income level and other factors; it is unique for each country. The cost of morbidity is estimated based on years lived with disability (YLDs) estimated by the GBD. YLD is a measure of disease burden that reflects the duration and severity of diseases. YLDs from exposure to PM$_{2.5}$ are converted to days lived with disease, with the cost of a day of disease equated to a fraction of the average daily wage rate in each country.

This report recognizes that PM$_{2.5}$ comes from both natural (for example, dust) and anthropogenic (for example, vehicle exhausts, emissions from power generation, and household use of solid fuels) origins to varying extents. The epidemiologic literature indicates that short- and long-term exposures to dust have significant health impacts and provides a reasonable basis to assume that the health risk per microgram of natural dust is generally similar to that of other constituents of PM$_{2.5}$, with the exception of sulfates and elemental carbon (Ostro et al. 2021). Epidemiologic evidence supports inclusion of the effects of natural dust on mortality and morbidity in the quantification of health impacts of ambient air pollution. Furthermore, while global studies of health impacts of PM$_{2.5}$ have been based on particle mass, the epidemiologic evidence shows that adverse health damages of PM$_{2.5}$ vary according to PM$_{2.5}$ source and composition. Specifically, trace constituents from PM$_{2.5}$ and PM$_{2.5}$ mass from fossil-fuel combustion are among the greatest contributors to PM$_{2.5}$ toxicity (Thurston.
et al. 2021). Estimation of health impacts of natural dust, PM$_{2.5}$ constituents and PM$_{1}$ mass from different sources, at a global level, will require strengthening the measurement of PM$_{2.5}$ constituents and source-markers, and improved understanding of exposure-response relationships. In this report, the valuation of health damage from PM$_{2.5}$ is based on PM$_{2.5}$ mass and is not disaggregated by PM$_{2.5}$ source or constituent (Ostro et al. 2021).

**KEY FINDINGS**

- The global health cost of mortality and morbidity caused by exposure to PM$_{2.5}$ air pollution in 2019 was $8.1 trillion, equivalent to 6.1 percent of global gross domestic product (GDP). The cost ranged from an equivalent of 1.7 percent of GDP in North America, to 9.3 percent in East Asia and Pacific, and 10.3 percent in South Asia (figure ES.1). The cost was equivalent to

![Figure ES.1](image_url)

Source: Original calculations for this publication.

Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and Caribbean; MNA = Middle East and North Africa, NA = North America; SA = South Asia; SSA = Sub-Saharan Africa. Numbers may not add up due to rounding.
5.9 percent of GDP in low-income countries and rose to 8.9–9.0 percent in lower- and upper-middle-income countries (figure ES.2). The cost was equivalent to 10.6–12.9 percent of GDP in China and India.

- Globally, 64 percent of total deaths from PM$_{2.5}$ was due to ambient air pollution and 36 percent due to household air pollution from the use of solid fuels. However, the cost of household air pollution constituted the largest share in Sub-Saharan Africa and low-income countries, a substantial share in South Asia and lower-middle-income countries, and a moderate share in East Asia and Pacific, Latin America and Caribbean, and upper-middle-income countries.

- Of the estimated total global health cost of PM$_{2.5}$ air pollution, about 85 percent is due to premature mortality and 15 percent to morbidity.

- The estimated global cost of PM$_{2.5}$ air pollution in 2019 is 40 percent higher than the estimate for 2013 in World Bank and IHME (2016) in real terms. The higher cost estimate in this report is related to three sets of factors:

**FIGURE ES.2**
Annual cost of health damage from PM$_{2.5}$ exposure, as a share of GDP by income group, 2019

Source: Original calculations for this publication.
Note: LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. PM2.5 = fine particulate matter.
OECD = Organisation for Economic Co-operation and Development. Assignment of countries to categories based on World Bank income classification. Numbers may not add up due to rounding.
Improved methodology: This report uses updated exposure-response functions from the GBD 2019, which quantitatively relate exposure levels of PM$_{2.5}$ to the risk of a health damage (chronic obstructive pulmonary disease, stroke, ischemic heart disease, lower respiratory infection, lung cancer, and type 2 diabetes). The GBD 2019 also includes neonatal health effects of PM$_{2.5}$ exposure. Type 2 diabetes and neonatal health effects were not included in the GBD 2013.

Increased availability of data: Ground-level ambient PM measurements utilized by the GBD 2019 study came from the updated World Health Organization (WHO) Global Ambient Air Quality Database released in 2018, as well as additional data mainly from Bangladesh, Canada, China, the European Union, the United States, and PM measurement data from US embassies and consulates. Thus, measurement data from 10,408 ground monitors from 116 countries were utilized by the GBD 2019.

Inclusion of an estimate of the cost of morbidity, which was not provided in World Bank and IHME (2016).

Observations about the reasons for variations between GBD mortality estimates for different years were noted in Ostro et al. (2018), which examined estimates provided in GBD 2010, GBD 2013, and GBD 2015 of mortality related to air pollution. Methodological and technological improvements and demographic changes were found to account for the observed variations in the mortality estimates. Ostro et al. (2018) also noted the need to strengthen ground-level air-quality monitoring and epidemiological studies to improve estimates of PM$_{2.5}$ exposure and mortality in LMICs that are related to air pollution.

Although the global availability of exposure data in GBD 2019 increased due to increased ground-level monitoring data, there remains a great need to increase ground-level air-quality measurements in LMICs in order to reduce uncertainties regarding PM$_{2.5}$ exposure estimates in countries that have limited or no ground-level measurements, particularly of PM$_{2.5}$. Analysis of the WHO Global Ambient Air Quality Database 2018 version reveals that there was only one PM$_{2.5}$ ground-level monitor per 65 million people in low-income countries, and one monitor per 28 million people in Sub-Saharan Africa, in contrast to one monitor per 370,000 people in high-income countries.

Recommendations for policy action

The significant health and economic burdens of PM$_{2.5}$ air pollution call for urgent action from policy makers in LMICs to reduce air pollution and the resulting disease and deaths. Some key areas for action include the following:

- Improve ground-level air-quality monitoring. Properly operated and maintained ground-level monitoring networks for air quality provide data on the severity of air pollution, a fundamental input for effective air-quality management. Data for networks that monitor air quality are also useful for identifying the key sources that contribute to ambient air pollution. Such networks for air-quality monitoring must be subject to rigorous quality-assurance and quality-control regimes in order to ensure that the air-quality measurements generated are reliable for informing the design and implementation of interventions to reduce air pollution and protect public health. Thus, high-quality, routine air-quality monitoring, first and foremost, underpins programs for effective air-quality management that would also include (a) comprehensive
emission inventories; (b) application of models to understand the transport and fate of air pollutants; (c) assessment of costs and of health and other benefits; and (d) public outreach and stakeholder engagement. It is pertinent to note that beyond initial investments in networks for air-quality monitoring, governments need to ensure effective funding for sustained operation and maintenance of programs for air-quality monitoring in the long term.

- **Ensure public access to information on air quality.** To reinforce the impact of networks for air-quality monitoring, air-quality management efforts should include a robust system for public dissemination of air-quality data in formats that are widely understood and easily accessible to members of the public. Public dissemination of air-quality data allows members of the public to take adequate measures to reduce their exposure to air pollution and thus provides an important social safety net for the public—particularly for vulnerable groups such as young children, the elderly, and people with health conditions that can be exacerbated by poor air quality.

- **Harness innovation to drive air-quality improvements.** Technological developments can support more-targeted interventions for air-quality management while providing new avenues to engage local communities in their implementation. For instance, the Environmental Defense Fund and partners such as Google are piloting the use of low-cost sensing technologies and data analytics to provide air-quality data with a significantly higher frequency (every minute or few minutes) and resolution (for example, city block by city block). These hyperlocal monitoring networks can identify areas of poor air quality that a sparse network of traditional monitors often misses, help to better estimate actual exposure to air pollution, and even provide real-time data to help vulnerable populations make decisions that will protect their health.

- **Establish solid technical units with a clear mandate for air-quality management.** Technical units, staffed with specialists who can carry out a range of actions, including monitoring, enforcement, and planning, are indispensable to improve air quality. Such units should have clear responsibilities for designing air-quality interventions that can be endorsed by decision-makers and other stakeholders, as well as for conducting regular evaluations to assess the efficiency and effectiveness of supported interventions, identify opportunities for improvement, and incorporate new scientific evidence or emerging technologies that can drive air-quality improvements. Providing technical units with the mandate to work across sectors is paramount, given that air pollution originates from a wide range of sectors, including energy, transportation, industry, and agriculture, among others.

- **Adopt regional approaches to address air pollution across boundaries.** Air pollution typically cuts across boundaries of individual cities or countries. As a result, regional airshed approaches to addressing PM$_{2.5}$ air pollution may be called for, which require federal and international collaboration of governments across multiple administrative jurisdictions and geographical boundaries to ensure effective air-quality management.

- **Prioritize key sources of PM$_{2.5}$ air pollution, notably fossil-fuel combustion, such as sulfur-emitting coal-fired power plants and diesel-fueled traffic.** Efforts to control air pollution that prioritize fossil-fuel combustion sources are most likely to return greater health benefits than broad efforts that do not consider the source and composition of PM$_{2.5}$. Sulfate—a chemical constituent of PM$_{2.5}$ from coal burning—is one of the greatest contributors to
PM\textsubscript{2.5} toxicity and has one of the strongest associations with cardiovascular disease among the chemical constituents of PM\textsubscript{2.5} from fossil-fuel combustion. Reductions in PM\textsubscript{2.5} emissions from fossil-fuel combustion, such as sulfur-emitting coal-fired power plants and diesel vehicles, can be expected to produce the most-significant health benefits per unit of PM\textsubscript{2.5} reduced. Given that these sources are also key contributors to climate warming, air-pollution efforts that target these sources will also provide benefits to mitigating climate change. Notably, reducing PM\textsubscript{2.5} also means reducing black carbon, a component of PM\textsubscript{2.5} and short-lived climate pollutant.

- **Engage a wide range of instruments that are suited to effectively and efficiently reduce air pollution and ensure that their use is enforced.** In order to reduce air pollution, governments need to apply the instruments and approaches that are most effective for reducing air pollution. Command-and-control instruments (such as standards for ambient air quality and emission standards for vehicles and stationary sources, and vehicle inspection and maintenance programs) are well established and applied in many countries. Additional command-and-control instruments include regulations to improve fuel quality by, for example, decreasing the sulfur content of fuels. Economic instruments (such as air-pollution charges and repurposing of fossil-fuel subsidies) reduce air and climate pollutants while also augmenting the amount of government revenues that can be allocated to education, healthcare, renewable energy, and interventions to control air pollution. In addition, policies to promote conversion of vehicles from diesel to gas or to discourage the use of nitrogen-based fertilizers (which release ammonia—a precursor of secondary PM\textsubscript{2.5} formation) may also be used to reduce air pollution. It is important to note that effective application of the various instruments for air-quality management requires that governments put in place adequate enforcement mechanisms that also include incentives to reduce polluting behaviors.

- **Promote the use of clean cooking fuels to combat the health effects of household air pollution from solid fuels.** The populations in low- and middle-income countries using traditional cookstoves with solid fuels for cooking and other domestic purposes are exposed to PM\textsubscript{2.5} concentrations that are several times higher than ambient PM\textsubscript{2.5}. Improved cookstoves, often 40–60 percent more energy efficient than traditional stoves, have been found to reduce exposure by around 50 percent. This reduction, however, reduces health effects by as little as 11–12 percent, based on analysis of the exposure-response functions from the GBD 2019. Effectively combating the health effects requires clean cooking fuels and technologies, such as LPG or electricity. Some low- and middle-income countries have already achieved a high prevalence rate of the population using clean fuels and technologies, demonstrating this possibility even at moderate GDP per capita levels.

**NOTES**

1. The GBD 2019 study is listed in the references sections of this report as GBD 2019 Risk Factors Collaborators (2020).

2. Total air pollution damages in World Bank and IHME (2016) included ambient PM\textsubscript{2.5}, household PM\textsubscript{2.5}, and ambient ozone.
Global health cost and GDP are stated in purchasing power parity (PPP) adjusted US$. GDP in PPP-adjusted US$ allows for a comparison of the purchasing power of GDP of different countries. The global health cost is expressed as a percentage of GDP only to provide a convenient sense of relative scale.

REFERENCES

Andrée, P. J. 2020. “Incidence of COVID-19 and Connections with Air Pollution Exposure: Evidence from the Netherlands.” Policy Research Working Paper 9221, Washington, DC, World Bank.

Bowe, B., Y. Xie, T. Li, Y. Yan, H. Xian, and Z. Al-Aly. 2018. “The 2016 Global and National Burden of Diabetes Mellitus Attributable to PM$_{2.5}$ Air Pollution.” *Lancet Planetary Health* 2 (7): e301–e312.

Carey, I. M., H. R. Anderson, R. W. Atkinson, S. D. Beevers, D. G. Cook, D. P. Strachan, D. Dajnak, J. Gulliver, and F. J. Kelly. 2018. “Are Noise and Air Pollution Related to the Incidence of Dementia? A Cohort Study in London, England.” *BMJ Open* 8: e022404.

Ezziane, Z. 2013. “The Impact of Air Pollution on Low Birth Weight and Infant Mortality.” *Review of Environmental Health* 28 (2–3): 107–15.

GBD 2013 Risk Factors Collaborators. 2015. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013.” *Lancet* 386: 2287–323.

GBD 2015 Risk Factors Collaborators. 2016. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2015: A Systematic Analysis for the Global Burden of Disease Study 2015.” *Lancet* 388: 1659–724.

GBD 2016 Risk Factors Collaborators. 2017. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2016: A Systematic Analysis for the Global Burden of Disease Study 2016.” *Lancet* 390: 1345–422.

GBD 2017 Risk Factors Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” *Lancet* 392: 1923–94.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” *Lancet* 396: 1223–49.

Heft-Neal, S., J. Burney, E. Bendavid, and M. Burk. 2018. “Robust Relationship Between Air Quality and Infant Mortality in Africa.” *Nature* 559 (7713): 254–58.

Ostro, Bart, Yewande Awe, and Ernesto Sánchez-Triana. 2021. *When the Dust Settles: A Review of the Health Implications of the Dust Component of Air Pollution*. Washington, DC: World Bank.

Ostro, B., J. V. Spadaro, S. Gumy, P. Mudu, Y. Awe, F. Forastiere, and A. Peters. 2018. “Assessing the Recent Estimates of the Global Burden of Disease for Ambient Air Pollution: Methodological Changes and Implications for Low- and Middle-Income Countries.” *Environmental Research* 166: 713–25.

Sánchez-Triana, E., S. Enriquez, B. Larsen, P. Webster, and J. Afzal. 2015. *Sustainability and Poverty Alleviation: Confronting Environmental Threats in Sindh, Pakistan*. Directions in Development. Washington, DC: World Bank.

Shin J., J. Y. Park, and J. Choi. 2018. “Long-Term Exposure to Ambient Air Pollutants and Mental Health Status. A Nationwide Population-Based Cross-Sectional Study.” *PLOS One* 13 (4): e0195607.
Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler. 2012. “Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security.” *Science* 335: 183–89.

Thurston, George, Yewande Awe, Bart Ostro, and Ernesto Sanchez-Triana. 2021. *Are All Air Pollution Particles Equal? How Constituents and Sources of Fine Air Pollution Particles (PM$_{2.5}$) Affect Health.* World Bank, Washington, DC.

World Bank. 2021. *Getting Down to Earth: Are Satellites Reliable for Measuring Air Pollutants that Cause Mortality in Low- and Middle-Income Countries?* International Development in Focus. Washington, DC: World Bank.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action.* Washington, DC: World Bank.

Xu, X., S. U. Ha, and R. Basnet 2016. “A Review of Epidemiological Research on Adverse Neurological Effects of Exposure to Ambient Air Pollution.” *Frontiers in Public Health* 4: 157.

Zhang, X., X. Chen, and X. Zhang. 2018. “The Impact of Exposure to Air Pollution on Cognitive Performance.” *Proceedings of the National Academy of Sciences* 115 (37): 9193–97.
**Abbreviations**

| Abbreviation | Description |
|--------------|-------------|
| AAP          | ambient air pollution |
| COI          | cost of illness |
| COPD         | chronic obstructive pulmonary disease |
| EAP          | East Asia and Pacific |
| ECA          | Europe and Central Asia |
| GBD          | Global Burden of Disease |
| GDP          | gross domestic product |
| HAP          | household air pollution |
| HI           | high-income |
| IER          | Integrated Exposure-Response |
| IHD          | ischemic heart disease |
| IHME         | Institute for Health Metrics and Evaluation |
| LAC          | Latin America and the Caribbean |
| LI           | low-income |
| LMI          | lower-middle-income |
| LMICs        | low- and middle-income countries |
| LRI          | lower respiratory infection |
| MNA          | Middle East and North Africa |
| NA           | North America |
| OECD         | Organisation for Economic Co-operation and Development |
| PM           | particulate matter |
| PM$_{2.5}$   | fine particles (particles with a diameter of 2.5 micrometers or less) |
| PM$_{10}$    | inhalable particles (particles with a diameter of 10 micrometers or less) |
| PPP          | purchasing power parity |
| RR           | relative risks |
| SA           | South Asia |
| SSA          | Sub-Saharan Africa |
| UMI          | upper-middle-income |
| VSL          | value of statistical life |
| WHO          | World Health Organization |
| WTP          | willingness to pay |
| YLDs         | years lived with disability |
The detrimental effects of air pollution, notably PM$_{2.5}$ air pollution, to health are well known. “Ambient air pollution” refers to air pollution in the outdoor air; “household air pollution” refers to air pollution originating in the household environment. Air pollution is the world’s leading environmental risk to health and the cause of morbidity and mortality from diseases such as ischemic heart disease (IHD), stroke, lung cancer, chronic obstructive pulmonary disease (COPD), pneumonia, type 2 diabetes, and neonatal disorders. Most deaths related to ambient and household air pollution are caused by human exposure to fine inhalable particles or fine particulate matter (PM), also known as PM$_{2.5}$ (Thurston et al., 2021; Ostro et al., 2021). In 2019, about 6.4 million people died worldwide as a result of exposure to PM$_{2.5}$ air pollution, of which 4.1 million were due to PM$_{2.5}$ ambient air pollution and 2.3 million were due to PM$_{2.5}$ household air pollution from the use of solid fuels for cooking and other domestic purposes. Ninety-five percent of these deaths were in low- and middle-income countries (LMICs).

Understanding the welfare costs associated with air pollution has been a topic of continued attention. Several of these works have applied methodologies and estimates of exposure to air pollution used in the Global Burden of Disease (GBD) Project. They all point to the enormous global welfare cost of air pollution in the trillions of dollars, equivalent in magnitude to 2.5–6 percent of global gross domestic product (GDP), depending on valuation of health damages (table 1.1). Some estimates indicate an upward trend in the global welfare cost of ambient air pollution. For example, the Organisation for Economic Co-operation and Development (OECD) estimates that the cost of health damages of ambient air pollution could increase to $20.5–$27.6 trillion (9–12 percent of GDP) by 2060 (OECD 2016).

It is important to note the following two cost-related findings of these studies: (a) The global cost of ambient air pollution is substantially higher than the cost of household air pollution associated with the burning of solid fuels for cooking and other domestic purposes. (b) However, this report finds that the cost of household air pollution is still substantially higher than the cost of ambient air pollution in Sub-Saharan Africa and nearly as high as the cost of ambient air pollution in South Asia in 2019.
This report provides an updated estimate of the global, regional, and national cost of PM$_{2.5}$ air pollution in 2019 using the GBD 2019 estimates of mortality and morbidity from PM$_{2.5}$. The estimated global cost in 2019 was $8.1 trillion, equivalent to 6.1 percent of global GDP (PPP adjusted). In real terms, the estimated cost of PM$_{2.5}$ air pollution in 2019 is 40 percent higher than the estimate for 2013 in World Bank and IHME (2016). The reasons for the higher cost estimate are mainly changes in exposure-response functions, the substantially higher estimate of global ambient PM$_{2.5}$ exposure, and the inclusion of an estimate of the cost of morbidity, as discussed below. The higher estimate of global ambient PM$_{2.5}$ is due more to improved methodology and availability of data than actual worsening of global ambient PM$_{2.5}$ air quality from 2013 to 2019, although the exact contribution of each of these two factors is difficult to ascertain.

This report also provides an overview of global and regional PM$_{2.5}$ population exposure and the exposure-response functions developed by the GBD 2019 study.

### CONTEXT AND VALUE ADDED OF THIS REPORT

This report provides an estimate of the global, regional, and national costs of health damage—that is, of premature mortality and morbidity—from exposure to PM$_{2.5}$ air pollution in 2019. While recognizing the various costs of air pollution to society, this report focuses on estimating the cost of premature mortality and morbidity due to PM$_{2.5}$ ambient and household air pollution estimated by the GBD 2019 study. Estimating the health damage of air pollution in monetary terms provides a suitable metric for policy makers and decision-makers in developing countries to prioritize the design and implementation of policies and interventions for controlling PM$_{2.5}$ air pollution amid competing development challenges and budgetary and other resource constraints.

For the World Bank, as a development institution, the cost of PM$_{2.5}$ air pollution underscores the need for the Bank’s sustained support of governments’ efforts to reduce air pollution. Furthermore, the cost estimate provides a useful metric for informing decision-making and priority setting by governments in tackling the urgent problem of air pollution.

The value added of this report is as follows:

- The report is based on updated exposure-response functions as used by the GBD 2019 study. Exposure-response functions quantitatively relate the levels

| STUDY                          | DOMAIN  | YEAR                  | $ (PPP) | US$ | % OF GLOBAL GDP (PPP) | % OF GLOBAL GDP |
|-------------------------------|---------|-----------------------|---------|-----|-----------------------|-----------------|
| Larsen (2014)                 | AAP     | 2012 in 2012 prices   | -       | 1.7 | -                     | 2.5%            |
| World Bank and IHME (2016)    | AAP & HAP| 2013 in 2011 prices   | 5.1     | -   | 5.0%                  | -               |
| OECD (2016)                   | AAP     | 2015 in 2010 prices   | 3.4     | -   | 6.0%                  | -               |
| Landrigan et al. (2018)       | AAP & HAP| 2015 in 2015 prices   | -       | 3.8 | -                     | 5.1%*           |
| World Bank (2020)             | AAP     | 2016 in 2016 prices   | 5.7     | 3.3 | 4.8%                  | 4.4%            |

Note: $ (PPP) = international dollars or purchasing power parity adjusted US$. GDP in PPP-adjusted US$ allows a comparison of the purchasing power of GDP of different countries. AAP = air pollution originating in the household environment; HAP = air pollution in the outdoor air.

a. Gross national income.
of PM$_{2.5}$ exposure to the risk of a health damage (COPD, stroke, IHD, lower respiratory infection, lung cancer, and type 2 diabetes).

- The GBD 2019 also incorporates PM$_{2.5}$ exposure-response functions for health outcomes that were not included in the GBD 2013, notably type 2 diabetes and neonatal disorders. Deaths from these additional health outcomes were over 10 percent of total deaths from PM$_{2.5}$ in 2019.
- This report is based on global ambient PM$_{2.5}$ exposure estimates used in the GBD 2019. These exposure estimates are higher than the estimates used in the GBD 2013 and are based on a database of ground-level measurements of air quality that is used for calibrating satellite and chemical transport modeling estimates of PM$_{2.5}$. The database of ground-level measurements used by the GBD 2019 is substantially larger than the database used in the GBD 2013 study. Global population-weighted ambient PM$_{2.5}$ exposure was 43 μg/m$^3$ in 2019 according to the estimates used in the GBD 2019 study, and 32 μg/m$^3$ in 2013 according to the GBD 2013 study.
- As a result of the changes in exposure-response functions and PM$_{2.5}$ exposure estimates from the GBD 2013 study to the GBD 2019 study, this report is based on a global mortality estimate of 6.4 million deaths from PM$_{2.5}$ in 2019 compared to 5.3 million deaths from PM$_{2.5}$ in 2013 used by the World Bank and IHME (2016).
- This report also provides an order-of-magnitude estimate of the cost of morbidity of PM$_{2.5}$ exposure based on the disease burden of morbidity reported by the GBD 2019 study, which is found to vary substantially across countries and regions.

The remaining sections of this report provide estimates of population exposure to PM$_{2.5}$, estimation of health damages from this exposure, the global costs of these health damages, and the policy implications underpinned by the report’s findings.

**NOTES**

1. PM$_{2.5}$ is particulate matter (PM) with a diameter equal to or less than 2.5 micrometers, a diameter that is about 30 times smaller than that of a single human hair.
2. Several studies have been completed since the 1990s to estimate the Global Burden of Disease (GBD), originally commissioned by the World Bank to inform the preparation of *World Development Report 1993*. Comprehensive evaluations on ambient air pollution were also supported by WHO and the World Bank in 2000 and 2004. In the GBD 2010, the scope of the GBD was updated with support from the Bill & Melinda Gates Foundation to include 235 causes of death and disability from diseases and injuries, and 67 risk factors (including ambient air pollution) in 187 countries and territories in 21 regions of the world. The Institute for Health Metrics and Evaluation (IHME) became the main provider for a broad range of GBD estimates that underpinned the preparation of GBD Reports for 2010, 2013, 2015, 2016, 2017, and 2019. Most recently, the GBD 2019 included estimates of deaths and disability from 369 diseases and injuries, and 87 risk factors in 204 countries and territories (GBD 2019 Risk Factors Collaborators 2020).
3. 2010 Purchasing Power Parity (PPP) adjusted US$.
4. The GBD 2019 study is listed in the references sections of this report as GBD 2019 Risk Factors Collaborators (2020).
5. International dollars or purchasing power parity adjusted US$. Expressed in US dollars, the global cost in 2019 was US$4.4 trillion, equivalent to 5.1 percent of global GDP.
6. The cost equivalent to percent of GDP is the same whether expressed in GDP or PPP-adjusted GDP for each individual country, but not when aggregated globally.
7. The cost of PM$_{2.5}$ in 2013 was $5.11 trillion (in 2011 $ [PPP]) according to World Bank and IHME (2016). The cost in 2019 was $8.1 trillion, or $7.06 trillion in 2011 $ (PPP). The estimated cost in 2019 is therefore 40 percent higher than in 2013 in real terms.

REFERENCES

GBD 2013 Risk Factors Collaborators. 2015. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013.” *Lancet* 386: 2287–323.

GBD 2015 Risk Factors Collaborators. 2016. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2015: A Systematic Analysis for the Global Burden of Disease Study 2015.” *Lancet* 388: 1659–724.

GBD 2016 Risk Factors Collaborators. 2017. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2016: A Systematic Analysis for the Global Burden of Disease Study 2016.” *Lancet* 390: 1345–422.

GBD 2017 Risk Factors Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” *Lancet* 392: 1923–94.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” *Lancet* 396: 1223–49.

GBD 2019 Viewpoint Collaborators. 2020. “Five Insights from the Global Burden of Disease Study 2019.” *Lancet* 396: 1135–59.

Landrigan, P. J., R. Fuller, N. J. R. Acosta, O. Adeyi, R. Arnold, N. N. Basu, A. B. Baldé, R. Bertollini, S. Bose-O’Reilly, J. I. Boufford, P. N. Breyssse, T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, A. Haines, D. Hanrahan, D. Hunter, M. Khare, A. Krupnick, B. Lanphear, B. Lohani, K. Martin, K. V. Mathiasen, M. A. McTeer, C. J. L. Murray, J. D. Ndahimananjara, F. Perera, J. Potočnik, A. S. Preker, J. Ramesh, J. Rockström, C. Salinas, L. D. Samson, K. Sandilya, P. D. Sly, K. R. Smith, A. Steiner, R. B. Stewart, W. A. Suk, O. C. P. van Schayck, G. N. Yadama, K. Yumkella, and M. Zhong. 2018. “The Lancet Commission on Pollution and Health.” *Lancet* 391 (10119): 462–512.

Larsen, B. 2014. “Benefits and Costs of the Air Pollution Targets for the Post-2015 Development Agenda.” Air Pollution Assessment Paper, Post-2015 Consensus Project. Copenhagen: Copenhagen Consensus Center. https://www.copenhagenconsensus.com/sites/default/files/air_pollution_assessment_-_larsen.pdf.

OECD (Organisation for Economic Co-operation and Development). 2016. *The Economic Consequences of Outdoor Air Pollution*. Paris: OECD.

Ostro, Bart; Yewande Awe; and Ernesto Sanchez-Triana. 2021. “When the Dust Settles: A Review of the Health Implications of the Dust Component of Air Pollution.” World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/36267.

Thurston, George, Yewande Awe, Bart Ostro, and Ernesto Sanchez-Triana. 2021. Are All Air Pollution Particles Equal? How Constituents and Sources of Fine Air Pollution Particles (PM$_{2.5}$) Affect Health. A World Bank Study: Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/36269.

World Bank. 2020. *The Global Health Cost of Ambient PM$_{2.5}$ Air Pollution*. Washington, DC: World Bank. http://hdl.handle.net/10986/35721.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action*. Washington, DC: World Bank.
AMBIENT PM$_{2.5}$ EXPOSURE

The GBD studies estimate nationwide population exposure to ambient PM$_{2.5}$ from a combination of satellite imagery, chemical-transport modeling, and ground-level PM$_{2.5}$ and PM$_{10}$ measurements.

The evolution in satellite imagery/chemical transport model estimation techniques, the number of ground-level monitoring locations, and the method of calibrating the satellite imagery/chemical transport model estimates with the ground-level measurements has been quite substantial from the GBD 2010 study to the GBD 2019 study (Brauer et al. 2012, 2016; GBD 2019 Risk Factors Collaborators 2020; Shaddick et al. 2018; van Donkelaar et al. 2015, 2016).

Ground-level measurements of PM$_{2.5}$ or PM$_{10}$ employed by the GBD 2010 study covered fewer than 700 locations (Brauer et al. 2012). This expanded to 4,073 data points from 3,387 unique locations in the GBD 2013 study (Brauer et al. 2016). The GBD 2015 and GBD 2016 studies utilized the WHO Global Ambient Air Quality Database 2016 containing PM measurements from 6,003 ground monitors in about 3,000 human settlements (GBD 2015 Risk Factors Collaborators 2016; GBD 2016 Risk Factors Collaborators 2017; WHO 2016). The GBD 2017 utilized the WHO updated database 2018 with PM$_{10}$ and PM$_{2.5}$ from about 9,690 stations in nearly 4,400 locations (defined geographic areas) in 108 countries (GBD 2017 Risk Factors Collaborators 2018). The GBD 2019 also utilized this updated database, along with additional measurement data mainly from Bangladesh, Canada, China, the European Union, the United States, and PM measurement data from US embassies and consulates. Thus, measurement data from 10,408 ground monitors from 116 countries were utilized by the GBD 2019 (GBD 2019 Risk Factors Collaborators 2020). Nevertheless, ground monitoring remains particularly scarce in low-income countries and Sub-Saharan Africa.

PM$_{2.5}$ HOUSEHOLD AIR POLLUTION EXPOSURE

The GBD 2019 study estimates population exposure to PM$_{2.5}$ household air pollution from a combination of data on the percentage of countries’ population using solid fuels for cooking and a household exposure prediction model.
The model is based on globally available measurement studies of PM$_{2.5}$ in the household environment, type of fuel used, and a sociodemographic index. The index is a composite of total fertility rate, education level, and income per capita, which all are considered important determinants of household air pollution exposure (GBD 2019 Risk Factors Collaborators 2020). This approach to exposure estimation represents a substantial improvement compared to simply using type of fuel—that is, percentage of the population using solid fuels—as a proxy for exposure, as was commonly done until less than a decade ago. Nevertheless, the number of measurement studies globally of personal exposure to PM$_{2.5}$ in the household environment is quite limited, and even more so for the male population and children (Shupler et al. 2018).

**PM$_{2.5}$ POPULATION EXPOSURE**

Global population annual exposure to ambient PM$_{2.5}$ was 43 μg/m$^3$ in 2019 according to estimates used by the GBD 2019 study. In contrast, the global population annual exposure in 2013 was 32 μg/m$^3$ according to estimates used by the GBD 2013 study. The difference is due more to changes in estimation methodology and increased availability of ground-level PM monitoring data reflected in the WHO database 2018 and other monitoring data used by the GBD 2019 study than to actual worsening of global ambient PM$_{2.5}$ air quality from 2013 to 2019, although the exact contribution of each of these two factors is difficult to ascertain. The changes in estimation methodology and availability of ground-level PM monitoring data are explained in the GBD 2019 study supplements (GBD 2019 Risk Factors Collaborators 2020).

The global ambient PM$_{2.5}$ population-exposure estimate for 2019 is over four times as high as WHO's Air Quality Guideline value of 10 μg/m$^3$ for annual average PM$_{2.5}$. Ambient PM$_{2.5}$ exposures in 2019 were highest in the South Asia (SA), Middle East and North Africa (MNA), and Sub-Saharan Africa (SSA) regions—that is, about 5–10 times as high as in North America (NA). PM$_{2.5}$ exposure is also high in East Asia and the Pacific (EAP), dominated by China at 48 μg/m$^3$ (figure 4.1, panel a).

Annual exposure to PM$_{2.5}$ is even higher among the population using solid fuels for cooking and other domestic purposes, with a global average of nearly 140 μg/m$^3$ for the population using traditional wood stoves (Shupler et al. 2018). The percentage of the population using solid fuels is highest in SSA (81 percent) and SA (61 percent) but also substantial in EAP (35 percent) and Latin America and the Caribbean (LAC) (13 percent) (figure 4.1, panel b).

**REFERENCES**

Brauer, M., M. Amann, R. T. Burnett, A. Cohen, F. Dentener, M. Ezzati, S. B. Henderson, M. Krzyzanowski, R. V. Martin, R. Van Dingenen, A. van Donkelaar, and G. D. Thurston. 2012. “Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution.” *Environ Sci Technol* 46 (2): 652–60.

Brauer, M., G. Freedman, J. Frostad, A. van Donkelaar, R. V. Martin, F. Dentener, R. van Dingenen, K. Estep, H. Amini, J. S. Apte, K. Balakrishnan, L. Barregard, D. Broday, V. Feigin, S. Ghosh, P. K. Hopke, L. D. Knibbs, Y. Kokubo, Y. Liu, S. Ma, L. Morawska, J. L. Sangrador, G. Shaddick, H. R. Anderson, T. Vos, M. H. Forouzanfar, R. T. Burnett, and A. Cohen. 2016. “Ambient Air
Pollution Exposure Estimation for the Global Burden of Disease 2013.” Environ Sci Technol 50 (1): 79–88.

GBD 2013 Risk Factors Collaborators. 2015. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013.” Lancet 386: 2287–323.

GBD 2015 Risk Factors Collaborators. 2016. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2015: A Systematic Analysis for the Global Burden of Disease Study 2015.” Lancet 388: 1659–724.

GBD 2016 Risk Factors Collaborators. 2017. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2016: A Systematic Analysis for the Global Burden of Disease Study 2016.” Lancet 390: 1345–422.

GBD 2017 Risk Factors Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” Lancet 392: 1923–94.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” Lancet 396: 1223–49.

GBD 2019 Viewpoint Collaborators. 2020. “Five Insights from the Global Burden of Disease Study 2019.” Lancet 396: 1135–59.

Shaddick, H. R. Anderson, T. Vos, M. H. Forouzanfar, R. T. Burnett, and A. Cohen. 2016. “Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013.” Environ Sci Technol 50 (1): 79–88.

Shaddick, G., M. L. Thomas, A. Green, M. Brauer, A. van Donkelaar, R. Burnett, H. Chang, A. Cohen, R. Van Dingenen, C. Dora, S. Gumy, Y. Liu, R. Martin, L. A. Waller, J. West, J. V. Zidek, and A. Prüss-Ustün. 2018. “Data Integration Model for Air Quality: A Hierarchical Approach to the Global Estimation of Exposures to Ambient Air Pollution.” Journal of the Royal Statistical Society, Series C, Applied Statistics 2018 67: 231–53.

Shupler, M., W. Godwin, J. Frostad, P. Gustafson, R. E. Arku, and M. Brauer. 2018. “Global Estimation of Exposure to Fine Particulate Matter (PM_{2.5}) from Household Air Pollution.” Environment International 120: 354–63.

Van Donkelaar, A., R. Martin, M. Brauer, and B. Boys. 2015. “Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter.” Environmental Health Perspectives 123: 135–43.

Van Donkelaar, A., R. V. Martin, M. Brauer, N. C. Hsu, R.A. Kahn, R. C. Levy, A. Lyapustin, A. M. Sayer, and D. M. Winker. 2016. “Global Estimates of Fine Particulate Matter Using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors.” Environmental Science and Technology 50: 3762–72.

WHO (World Health Organization). 2016. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. Geneva: WHO.
Exposure-response functions or concentration-response functions are a key input for quantifying the health burden of air pollution. One such function is the Integrated Exposure-Response (IER) function, so called because it integrates exposures to PM$_{2.5}$ from different sources. The GBD 2019 project estimates health damages of PM$_{2.5}$ exposure from IER functions for six major health outcomes, as well as using a somewhat different approach to estimating neonatal disorders. The GBD project first developed IER functions for the GBD 2010 study (see appendix B). These IER functions provide the relative risks of health damages of PM$_{2.5}$ at exposures ranging from less than 5 $\mu$g/m$^3$ to several hundred $\mu$g/m$^3$. Thus, the risk functions can be applied to a wide range of ambient PM$_{2.5}$ concentrations found around the world as well as to high household air-pollution levels of PM$_{2.5}$ from combustion of solid fuels.

The relative risks from the IER function used by the GBD 2019 study are published in the GBD 2019 study Supplement (GBD 2019 Risk Factors Collaborators 2020).

They are reproduced in figure 3.1 for PM$_{2.5}$ concentrations up to 200 $\mu$g/m$^3$. The relative risks rise very steeply to 35 $\mu$g/m$^3$. The relative risk of type 2 diabetes then flattens out with minimal additional risk at higher exposure levels. The relative risks of IHD, lung cancer, and stroke flatten out from 90 $\mu$g/m$^3$. The relative risks of lower respiratory infections (LRI) and chronic obstructively pulmonary disease (COPD) continue to rise with higher exposure levels.

The rise in relative risks (up to a PM$_{2.5}$ exposure level of about 90 $\mu$g/m$^3$ for five of the six health outcomes) means an increasing burden of health effects over the range of national population-weighted ambient PM$_{2.5}$ globally. The flattening of the relative risks for four of the six health outcomes also means that the health benefits of reducing PM$_{2.5}$ exposures (from, for instance, 200 $\mu$g/m$^3$ to 90 $\mu$g/m$^3$) are very modest and mostly related to COPD and LRI.
This has important implications for how to combat the health effects of PM$_{2.5}$ household air pollution from the use of traditional cookstoves with solid fuels in low- and middle-income countries (LMICs). Improved cookstoves, often 40–60 percent more energy efficient than traditional stoves, have been found to reduce exposure by around 50 percent. However, this exposure reduction (from, for instance, 200 to 100 μg/m$^3$ or 140 to 70 μg/m$^3$) reduces health effects by as little as 11–12 percent, based on analysis of the IER functions from the GBD 2019. Therefore, effectively combating the health effects requires clean cooking fuels and technologies, such as LPG or electricity. Some LMICs have already achieved a high prevalence rate of the population using clean fuels and technologies, demonstrating this possibility even at moderate GDP per capita levels.

The GBD 2019 exposure-response functions differ in important aspects from the exposure-response functions from the GBD 2016 and 2017 studies. The differences are presented in figure 3.2 for 45 μg/m$^3$ and 140 μg/m$^3$ of annual PM$_{2.5}$ exposure. These exposure levels correspond closely to the global average ambient PM$_{2.5}$ exposure in 2019 and the global average household air pollution PM$_{2.5}$ exposure level among populations using traditional wood stoves for cooking and other domestic purposes. The GBD 2019 exposure-response functions reveal much higher relative risk of stroke and IHD and lower relative risk of LRI for both PM$_{2.5}$ exposure levels than the GBD 2016 and GBD 2017 functions. The relative risk of COPD is similar for the three GBD editions at 45 μg/m$^3$ but substantially higher in the GBD 2019 than in GBD 2016 and GBD 2017. The relative risk of lung cancer is higher in the GBD 2019 at 45 μg/m$^3$ but lower at 140 μg/m$^3$ than in the GBD 2016 and GBD 2017.
GLOBAL HEALTH DAMAGES OF PM$_{2.5}$ EXPOSURE

As many as 6.45 million people died from PM$_{2.5}$ ambient and household air pollution in 2019 according to the GBD 2019 study. This makes PM$_{2.5}$ exposure the fifth-largest health risk factor of global deaths after high blood pressure, dietary risks, tobacco smoking, and diabetes, among dozens of risk factors assessed by the GBD 2019 study. However, PM$_{2.5}$ is the largest health risk factor in LI countries, the second-largest in LMI countries, and the fourth-largest in UMI countries.

Nearly two-thirds of global deaths from PM$_{2.5}$ exposure was from ambient air pollution (4.14 million) and nearly one-third from household air pollution (2.31 million). As many as 95 percent of deaths from PM$_{2.5}$ exposure occurred in low- and middle-income countries. A comparison of the risks considered in the GBD 2019 study shows that exposure to ambient air pollution increased at an annualized rate of change of 1.47 between 2010 and 2019, the second highest during this period, only after high body-mass index (GBD 2019 Viewpoint Collaborators 2020).

Globally, IHD and stroke account for 53 percent of deaths from PM$_{2.5}$; respiratory illnesses for 35 percent including COPD, LRI, and lung cancer;
neonatal disorders for 6 percent; diabetes for 5 percent; and other diseases for less than 1 percent according to the GBD 2019 study (figures 3.3a, 3.3b, 3.4).

In perspective, global deaths from PM2.5 air pollution constituted as much as 11.4 percent of all global deaths in 2019. For the main health outcomes, PM2.5 exposure caused as much as 30–33 percent of global deaths from COPD and LRI; 20–26 percent of global deaths from IHD and stroke; and 19–20 percent of global deaths from lung cancer, neonatal disorders, and type 2 diabetes (figure 3.5).

Seventy percent of global deaths from PM2.5 air pollution in 2019 occurred in EAP and SA (figure 3.6). China accounted for 74 percent of the deaths in EAP, and India accounted for 76 percent in SA. Deaths from PM2.5 in these two countries constituted 52 percent of global deaths from PM2.5.

The three (and for one region, the two) countries with the most deaths from PM2.5 air pollution in each region in 2019 are presented in table 3.1. There are six countries with more than 100,000 deaths from PM2.5, and nine countries with 50,000–100,000 deaths, three of which are not in table 3.1.

Eighty-five percent of global deaths from PM2.5 air pollution occurred in middle-income countries, nearly evenly split between lower-middle-income and
upper-middle-income. Ten percent of deaths were in low-income countries and 5 percent in high-income countries (figure 3.7).

Not only are the majority of deaths from PM$_{2.5}$ air pollution in EAP and SA, but these regions also have the highest death rates from PM$_{2.5}$, reaching 103 and 111 deaths per 100,000 population, respectively. This is 7–8 times higher than in NA (figure 3.8).
By income group, the highest death rates from PM$_{2.5}$ exposure are in lower-middle-income countries, and lowest in the high-income OECD countries (figure 3.9).

The three (and in one region, the two) countries in each region with the highest death rates from PM$_{2.5}$ air pollution are presented in table 3.2. The countries with the highest death rates are in EAP, ECA, SA, and SSA, reaching 106–202 deaths per 100,000 population. There are 32 countries with death rates over 100 per 100,000 population. Thirty-one of the countries are in these four regions, and one is in LAC.

Globally, deaths from PM$_{2.5}$ air pollution constituted 11.4 percent of all deaths from all causes in 2019. The death rate reaches as high as 17 percent in SA, or ten
FIGURE 3.7  
Global number of deaths from PM\(_{2.5}\) exposure by income group, 2019

![Graph showing global number of deaths from PM\(_{2.5}\) exposure by income group, 2019.]

| Income Group | HAP | AAP |
|--------------|-----|-----|
| LI           | 492 | 133 |
| LMI          | 1,307 | 1,664 |
| UMI          | 506 | 2,011 |
| HI OECD      | 6 | 283 |
| HI non-OECD  | 3 | 49 |

Source: Based on data from IHME, GBD 2019 study.  
Note: AAP = ambient air pollution; HAP = household air pollution; LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Assignment of countries to categories based on World Bank income classification.

FIGURE 3.8  
Number of deaths from PM\(_{2.5}\) exposure per 100,000 population in 2019, by region

![Graph showing number of deaths from PM\(_{2.5}\) exposure per 100,000 population in 2019, by region.]

| Region       | Deaths by region |
|--------------|------------------|
| EAP          | 103              |
| SA           | 111              |
| SSA          | 83               |
| ECA          | 51               |
| MNA          | 63               |
| LAC          | 35               |
| NA           | 14               |

Source: Based on data from IHME, GBD 2019 study.  
Note: EAP = East Asia and Pacific; SA = South Asia; SSA = Sub-Saharan Africa; ECA = Europe and Central Asia; MNA = Middle East and North Africa; LAC = Latin America and Caribbean; NA = North America.

FIGURE 3.9  
Number of deaths from PM\(_{2.5}\) exposure per 100,000 population in 2019, by income group

![Graph showing number of deaths from PM\(_{2.5}\) exposure per 100,000 population in 2019, by income group.]

| Income Group | Deaths by income group |
|--------------|------------------------|
| LI           | 93                     |
| LMI          | 100                    |
| UMI          | 87                     |
| HI OECD      | 26                     |
| HI non-OECD  | 49                     |

Source: Based on data from IHME, GBD 2019 study.  
Note: LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Assignment of countries to categories based on World Bank income classification.
times higher than in NA. By income group, the death rate reaches 14–15 percent in low-income and lower middle-income countries, compared to 2.8 percent in high-income OECD countries (table 3.3, figure 3.10).

The three (and in one region, the two) countries in each region with the highest death rates—that is, number of deaths from PM$_{2.5}$ as a percentage of all deaths from all causes—are presented in table 3.4. The countries with the highest death rates are in EAP and SA, followed by ECA, MNA, and SSA. There are 17 countries in which deaths from PM$_{2.5}$ exceed 15 percent of total deaths. Thirteen of these countries are in EAP and SA.

### TABLE 3.2 Number of deaths from PM$_{2.5}$ exposure per 100,000 population, by country, 2019

| REGION  | COUNTRY                      | DEATH RATE | REGION  | COUNTRY                      | DEATH RATE |
|---------|-------------------------------|------------|---------|-------------------------------|------------|
| EAP     | Korea, Dem. People’s Rep.     | 202        | NA      | United States                 | 15         |
|         | Myanmar                       | 134        |         | Canada                        | 10         |
|         | China                         | 126        | SA      | Nepal                         | 130        |
| ECA     | Bulgaria                      | 157        |         | India                         | 114        |
|         | North Macedonia               | 153        |         | Bangladesh                     | 106        |
|         | Bosnia and Herzegovina        | 145        | SSA     | Central African Republic      | 149        |
| LAC     | Haiti                         | 113        |         | Somalia                        | 139        |
|         | Trinidad and Tobago           | 64         |         | Chad                           | 132        |
| MNA     | Egypt, Arab Rep.              | 91         |         |                               |            |
|         | Morocco                       | 80         |         |                               |            |
|         | Syria                         | 72         |         |                               |            |

Source: Based on data from IHME, GBD 2019 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

### TABLE 3.3 Deaths from PM$_{2.5}$ exposure as a share of all deaths by region, 2019

| REGION  | COUNTRY                      | DEATH RATE | REGION  | COUNTRY                      | DEATH RATE |
|---------|-------------------------------|------------|---------|-------------------------------|------------|
| EAP     | Korea, Dem. People’s Rep.     | 22%        | NA      | United States                 | 1.6%       |
|         | Papua New Guinea              | 18%        |         | Canada                        | 1.3%       |
|         | Myanmar                       | 17%        | SA      | Nepal                         | 20%        |
| ECA     | Tajikistan                    | 15%        |         | Bangladesh                     | 20%        |
|         | Uzbekistan                    | 15%        |         | India                         | 17%        |
|         | North Macedonia               | 14%        | SSA     | Somalia                        | 15%        |
| LAC     | Haiti                         | 14%        |         | Gambia, The                   | 15%        |
|         | Honduras                      | 11%        |         | Niger                          | 15%        |
|         | Guatemala                     | 10%        |         |                               |            |
| MNA     | Egypt, Arab Rep.              | 16%        |         |                               |            |
|         | Kuwait                        | 15%        |         |                               |            |
|         | Bahrain                       | 15%        |         |                               |            |

Source: Based on data from IHME, GBD 2019 study.
Note: EAP = East Asia and Pacific; SA= South Asia; SSA= Sub-Saharan Africa; ECA = Europe and Central Asia; MNA = Middle East and North Africa; LAC = Latin America and Caribbean; NA = North America.
The GBD 2019 study also estimates that PM$_{2.5}$ air pollution caused morbidity in the magnitude of 22.2 million years lived with disability (YLDs) in 2019, or about 3.3 YLDs per death from PM$_{2.5}$. About 13.3 million YLDs were from ambient PM$_{2.5}$ and 7.9 million from PM$_{2.5}$ household air pollution. As many as 82 percent of the YLDs were type 2 diabetes, COPD, and stroke (figures 3.11, 3.12).

The YLDs from PM$_{2.5}$ exposure are equivalent to 93 billion days lived with illness (table 3.4). The 93 billion days’ total is based on the following
FIGURE 3.11
Global YLDs from PM$_{2.5}$ air pollution by cause, 2019

Source: Based on data from IHME, GBD 2019 study.
Note: YLD = years lived with disability; AAP = ambient air pollution; HAP = household air pollution; COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, LRI = lower respiratory infections.

FIGURE 3.12
Share of global YLDs from PM$_{2.5}$ air pollution by cause, 2019

Source: Based on data from IHME, GBD 2019 study.
Note: YLD = years lived with disability; COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, LRI = lower respiratory infections.

formula: days lived with illness = (YLDs x 365) / disability weight of disease, with disability weight ranging from 0 to 1. This very large number is due to the fact that many individuals contracting many of the diseases associated with PM$_{2.5}$ exposure live with the diseases for many years. These include type 2 diabetes, COPD, stroke, cataracts, and IHD.
GLOBAL COST OF PM$_{2.5}$ EXPOSURE

The health damages of PM$_{2.5}$ air pollution can be monetized to provide an estimate of the welfare cost of PM$_{2.5}$. Valuation of mortality in this report follows the welfare approach or value of statistical life (VSL) in World Bank and IHME (2016) (see appendix C). Valuation of morbidity, measured as the cost of days of illness, is valued at a fraction of wage rates (see appendix D).

The global cost of health damages from PM$_{2.5}$ air pollution was $8.1 trillion in 2019, equivalent to 6.1 percent of global GDP (PPP adjusted).

The cost of ambient PM$_{2.5}$ was $6.43 trillion, equivalent to 4.8 percent of global GDP (PPP adjusted), and the cost of PM$_{2.5}$ household air pollution was $1.67 trillion, equivalent to 1.3 percent of global GDP (PPP adjusted).

The estimated cost of PM$_{2.5}$ air pollution in 2019 is 40 percent higher in real terms than the estimate for 2013 in World Bank and IHME (2016). The reasons for the higher cost estimate are mainly changes in exposure-response functions, substantially higher estimate of global ambient PM$_{2.5}$ exposure, and inclusion of an estimate of the cost of morbidity. The higher estimate of global ambient PM$_{2.5}$ exposure is more due to improved methodology and availability of ground-level PM monitoring data than actual worsening of global ambient PM$_{2.5}$ air quality from 2013 to 2019, although the exact contribution of each of these two factors is difficult to ascertain.

About 85 percent of the total global cost of health damages in 2019 is from premature mortality and 15 percent from morbidity. Cost of morbidity as a share of total cost of health damages by country varies from as low as 4 percent to as high as 33 percent across countries. The overall global cost of morbidity, relative to the cost of mortality, is very similar to the estimate by the OECD in its report on the global economic consequences of outdoor air pollution (OECD 2016) (see appendix D).

The cost of health damages from PM$_{2.5}$ air pollution was highest in SA and EAP, at equivalents of 10.3 and 9.3 percent of GDP (PPP adjusted), respectively. The cost of PM$_{2.5}$ household air pollution constituted a substantial share of total cost in SA and SSA; a moderate share in EAP and LAC; and a small share in MNA, ECA, and NA. Cost of mortality dominated total cost in all regions. The morbidity cost share ranged from 13 percent to 15 percent in EAP, ECA, LAC, MNA, and SSA; to 20 percent in SA; and to 22 percent in NA (figure 3.13).

By income group, the cost of PM$_{2.5}$ air pollution was equivalent to 8.9 percent of GDP (PPP adjusted) in low- and middle-income countries, and 3.0 percent in high-income countries. The cost peaked at 9.1 percent in UMI countries and 9.0 percent in LMI countries. The cost of PM$_{2.5}$ household air pollution was a dominant share in LI countries, a substantial share in LMI countries, and a moderate share in UMI countries. The cost of PM$_{2.5}$ air pollution was lowest in high-income OECD countries, equivalent to 2.8 percent of GDP (PPP adjusted) (figure 3.14).

The three (and for one region, the two) countries in each region with the highest welfare cost of PM$_{2.5}$ air pollution as a percentage of GDP are presented in table 3.5. The countries with the highest costs are in ECA, followed by EAP and SA. There are 17 countries in which the welfare cost of PM$_{2.5}$ exceeds the equivalent of 10 percent of GDP. Fifteen of these countries are in ECA and EAP, and two are in SA. The reason for the high cost in many ECA countries is largely associated with the high baseline death rates in many ECA countries. Costs by country are presented in appendix A.
The cost of PM$_{2.5}$ air pollution estimated in this report for the year 2019, along with cost estimates in previous reports for previous years, cannot readily be compared to infer whether global air quality has worsened or improved. This is mainly because each cost estimate is based on (a) exposure-response functions that are evolving over time as new evidence becomes available; (b) global ambient PM$_{2.5}$ population-exposure estimates that also evolve over time with methodological developments and increased availability of ground-level PM monitoring data; and (c) modifications in the valuation in health damages (that is, the inclusion of cost of morbidity in this report). Each cost estimate should rather be viewed as a reflection of available evidence and scientific understanding at the time of the estimate. The global burden, in YLDs and days lived with disease, of morbidity from PM$_{2.5}$ exposure is presented in table 3.6.

**FIGURE 3.13**
Annual cost of health damage from PM$_{2.5}$ exposure by region, percent equivalent of GDP (PPP), 2019

Source: Original calculations for this publication.
Note: Numbers may not add up due to rounding. AAP = ambient air pollution; HAP = household air pollution; EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.
FIGURE 3.14
Annual cost of health damage from PM$_{2.5}$ exposure by income group, percent equivalent of GDP (PPP), 2019

TABLE 3.5 Annual cost of health damages from PM$_{2.5}$ by country, percent equivalent of GDP, 2019

| REGION   | COUNTRY             | COST  | REGION   | COUNTRY            | COST  |
|----------|---------------------|-------|----------|--------------------|-------|
| EAP      | China               | 12.9% | NA       | United States      | 1.7%  |
|          | Papua New Guinea    | 12.0% |          | Canada             | 1.2%  |
|          | Myanmar             | 11.4% | SA       | India              | 10.6% |
| ECA      | Serbia              | 18.9% | SSA      | Burkina Faso       | 9.1%  |
|          | Bulgaria            | 16.3% | NA       | Nepal              | 10.2% |
|          | North Macedonia     | 15.9% |          | Pakistan           | 8.9%  |
| LAC      | Barbados            | 8.8%  |          | Mali               | 9.1%  |
|          | Haiti               | 8.1%  |          | Central African Republic | 8.7% |
|          | Trinidad and Tobago | 7.8%  |          |                    |       |
| MNA      | Egypt, Arab Rep.    | 8.6%  |          |                    |       |
|          | Morocco             | 7.3%  |          |                    |       |
|          | Tunisia             | 6.5%  |          |                    |       |

Source: Original calculations for this publication.
Note: AAP = ambient air pollution; HAP = household air pollution; LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Assignment of countries to categories based on World Bank income classification.

Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and Caribbean; MNA = Middle East and North Africa, NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.
NOTES

1. Relative risks are available at http://ghdx.healthdata.org/record/ihme-data/global-burden-disease-study-2019-gbd-2019-particulate-matter-risk-curves.
2. Relative risks for IHD and stroke are population age-weighted and vary across countries in relation to the age structure of IHD and stroke mortality.
3. The highest national population-weighted ambient PM$_{2.5}$ in 2019 was 83 $\mu$g/m$^3$ according to the GBD 2019 (HEI 2020).

REFERENCES

GBD 2016 Risk Factors Collaborators. 2017. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2016: A Systematic Analysis for the Global Burden of Disease Study 2016.” Lancet 390: 1345–422.

GBD 2017 Risk Factors Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” Lancet 392: 1923–94.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” Lancet 396: 1223–49.

GBD 2019 Viewpoint Collaborators. 2020. “Five Insights from the Global Burden of Disease Study 2019.” Lancet 396: 1135–59.

HEI (Health Effects Institute). 2020. State of Global Air 2020. Boston: HEI. www.stateofglobalair.org.

OECD (Organisation for Economic Co-operation and Development). 2016. The Economic Consequences of Outdoor Air Pollution. Paris: OECD.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. Washington, DC: World Bank.

### TABLE 3.6 Global burden of morbidity from PM$_{2.5}$ exposure, 2019

| DISEASE                  | YLDs     | DAYS LIVED WITH DISEASE (MILLION) |
|-------------------------|----------|-----------------------------------|
| Type 2 diabetes         | 6,653,020| 30,252                            |
| COPD                    | 5,830,818| 22,780                            |
| Stroke                  | 5,028,001| 10,497                            |
| Cataracts               | 2,143,472| 11,370                            |
| IHD                     | 1,248,232| 16,654                            |
| LRI                     | 198,029  | 1,214                             |
| Lung cancer             | 99,225   | 214                               |
| Neonatal disorders      | 19,482   | 35                                |
| Other                   | 8,415    |                                   |
| Total                   | 21,228,694| 93,016                           |

Source: Based on data from IHME, GBD 2019 study.

Note: YLD = years lived with disability; COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, LRI = lower respiratory infections.
This report provides an estimate of the global cost of PM$_{2.5}$ ambient and household air pollution in 2019 based on the GBD 2019 study. It thus represents an update of the estimated cost in 2013 reported in World Bank and IHME (2016) that was based on the GBD 2013 study.

This report distinguishes itself from the 2013 estimate in important aspects. It is based on

• Revised exposure-response functions from the GBD 2019 study that differ from the functions from the GBD 2013 study for several health outcomes;

• Revised global ambient PM$_{2.5}$ population-exposure estimates from the GBD 2019 study that are based on calibration from a substantially larger database of PM ground-level measurements than the data used for the GBD 2013 study; and

• Inclusion of an estimate of the cost of morbidity based on estimates of years living with disease from PM$_{2.5}$ air pollution reported by the GBD 2019 study.

Health damages and costs of PM$_{2.5}$ air pollution are staggering, especially in developing countries, globally reaching 6.4 million deaths and 93 billion days lived with illness in 2019, with a welfare cost of $8.1 trillion, equivalent to 6.1 percent of global GDP (PPP adjusted).

This estimated cost for 2019 is 40 percent higher in real terms than the estimate for 2013 in World Bank and IHME (2016). The reasons for the higher cost estimate are mainly changes in exposure-response functions, substantially higher estimate of global ambient PM$_{2.5}$ exposure due to improved methodology and ground-level PM monitoring data availability, and inclusion of an estimate of the cost of morbidity. The higher estimate of global ambient PM$_{2.5}$ exposure is more due to improved methodology and availability of ground-level PM monitoring data than actual worsening of global ambient PM$_{2.5}$ air quality from 2013 to 2019, although the exact contribution of each of these two factors is difficult to ascertain.

About 85 percent of the total global cost of health damages in 2019 is from premature mortality and 15 percent from morbidity. Cost of morbidity as a share of total cost varies from as low as 4 percent to as high as 33 percent across countries.
Seventy percent of the health damages occur in the SA and EAP regions. Costs reach as high as 10.6 to 12.9 percent of GDP in China and India, the two countries in which over half of global deaths from PM$_{2.5}$ air pollution occur.

The methodology and ground-level measurement data available for the global ambient PM$_{2.5}$ population-exposure estimates from the GBD 2019 study represent important improvements over the estimates from the GBD 2013 study, based on calibration from a larger PM ground-level measurement database. However, the database nevertheless contains PM measurements from only a little over half of the countries in the world and is almost entirely lacking from large parts of SSA.

PM$_{2.5}$ measurements are particularly scarce in low-income countries and SSA, with one monitor per 65 and 28 million people, respectively, in contrast to one monitor per 0.37 million people in high-income countries.

The estimates provided in this report indicate that PM$_{2.5}$ air pollution causes significant health and economic burdens. These burdens are particularly significant in low- and middle-income countries, and in regions such as South Asia and East Asia and Pacific. Even though the costs presented in this report are equivalent to a sizable share of national and regional GDPs, they should be considered as conservative estimates because they do not consider several health effects of air pollution that are still the subject of research, such as mental health conditions or neurological impairment. The estimates also do not include other economic and environmental impacts of air pollution, including aesthetic impacts, loss of agricultural productivity, or its contributions to climate change.

Since 2016, the World Health Organization (WHO) has been reviewing the growing body of scientific research assessing the health effects of air pollution. The reviews that have been published to date point at robust evidence of negative health effects of short- and long-term exposure to air pollutants, even at levels that were previously considered safe, including

• Long-term exposure to particulate matter pollution, particularly PM$_{2.5}$, is clearly associated with increased mortality from all causes, cardiovascular disease, respiratory disease, and lung cancer, even at exposure levels below the current WHO guideline annual exposure level of 10 $\mu$g/m$^3$ for PM$_{2.5}$ (Chen and Hoek 2020).

• There is strong evidence showing a robust, positive association between short-term exposure to PM$_{10}$, PM$_{2.5}$, NO$_2$, and O$_3$ and all-cause mortality, and between PM$_{10}$ and PM$_{2.5}$ and cardiovascular, respiratory, and cerebrovascular mortality (Orellano et al. 2020).

• Short-term exposure to sulfur dioxide (SO$_2$), ranging from increases in exposure from one hour to a 24-hour average, is robustly associated with increased mortality (Orellano, Reynoso, and Quaranta 2021)

**AREAS FOR ACTION**

As scientific research continues to evolve, there is a high probability that evidence will show that the health and economic burdens of air pollution are even higher than those presented in this report. Even with the evidence that is available today, it is clear that the impacts of PM$_{2.5}$ air pollution call for urgent action from policy makers in LMICs to reduce air pollution and the resulting disease and deaths. Some key areas for action include the following:
• **Improve ground-level air-quality monitoring.** Properly operated and maintained ground-level monitoring networks for air quality provide data on the severity of air pollution, a fundamental input for effective air-quality management. Data for networks that monitor air quality are also useful for identifying the key sources that contribute to ambient air pollution. Such networks for air-quality monitoring must be subject to rigorous quality-assurance and quality-control regimes in order to ensure that the air-quality measurements generated are reliable for informing the design and implementation of interventions to reduce air pollution and protect public health. Thus, high-quality, routine air-quality monitoring, first and foremost, underpins programs for effective air-quality management that would also include (a) comprehensive emission inventories, (b) application of models to understand the transport and fate of air pollutants, (c) assessment of costs and of health and other benefits, and (d) public outreach and stakeholder engagement. It is pertinent to note that beyond initial investments in networks for air-quality monitoring, governments need to ensure effective long-term funding for sustained operation and maintenance of programs for air-quality monitoring.

• **Ensure public access to information on air quality.** To reinforce the impact of networks for air-quality monitoring, air-quality management efforts should include a robust system for dissemination of air-quality data to members of the public in formats that are widely understood and easily accessible. Public dissemination of air-quality data allows members of the public to take adequate measures to reduce their exposure to air pollution and thus provides an important social safety net for the public—particularly for vulnerable groups such as young children, the elderly, and people with health conditions that can be exacerbated by poor air quality. Public dissemination of air-quality information is also key to empower constituencies, strengthen environmental accountability, and empower stakeholders to participate in the development of interventions to improve air quality.

• **Harness innovation to drive air-quality improvements.** Technological developments can support more-targeted interventions for air-quality management while providing new avenues to engage local communities in their implementation. For instance, the Environmental Defense Fund and partners such as Google are piloting the use of low-cost sensing technologies and data analytics to provide air-quality data with a significantly higher frequency (every minute or few minutes) and resolution (for example, city block by city block). These hyperlocal monitoring networks can identify areas of poor air quality that a sparse network of traditional monitors often misses, help to better estimate actual exposure to air pollution, and even provide real-time data to help vulnerable populations make decisions that will protect their health.

• **Establish solid technical units with a clear mandate for air-quality management.** Technical units, staffed with specialists who can carry out a range of actions, including monitoring, enforcement, and planning, are indispensable to improve air quality. Such units should have clear responsibilities for designing air-quality interventions that can be endorsed by decision-makers and other stakeholders, as well as for conducting regular evaluations to assess the efficiency and effectiveness of supported interventions, identify opportunities for improvement, and incorporate new scientific evidence or emerging technologies that can drive air-quality improvements. Providing technical units with the mandate to work across sectors is paramount given that air
pollution originates from a wide range of sectors, including energy, transportation, industry, and agriculture, among others.

- **Adopt regional approaches to address air pollution across boundaries.** Air pollution typically cuts across boundaries of individual cities or countries. As a result, regional airshed approaches to addressing PM$_{2.5}$ air pollution may be called for, which require federal and international collaboration of governments across multiple administrative jurisdictions and geographical boundaries to ensure effective air-quality management.

- **Prioritize key sources of PM$_{2.5}$ air pollution, notably fossil-fuel combustion, such as sulfur-emitting coal-fired power plants and diesel-fueled traffic.** Efforts to control air pollution that prioritize fossil-fuel combustion sources are most likely to return greater health benefits than broad efforts that do not consider the source and composition of PM$_{2.5}$. Sulfate—a chemical constituent of PM$_{2.5}$ from coal burning—is one of the greatest contributors to PM$_{2.5}$ toxicity and has one of the strongest associations with cardiovascular disease among the chemical constituents of PM$_{2.5}$ from fossil-fuel combustion. Reductions in PM$_{2.5}$ emissions from fossil-fuel combustion, such as sulfur-emitting coal-fired power plants and diesel vehicles, can be expected to produce the most-significant health benefits per unit of PM$_{2.5}$ reduced. Given that these sources are also key contributors to climate warming, air-pollution efforts that target these sources will also provide benefits to mitigating climate change. Notably, reducing PM$_{2.5}$ also means reducing black carbon, a component of PM$_{2.5}$ and short-lived climate pollutant.

- **Engage a wide range of instruments that are suited to reduce air pollution effectively and efficiently and ensure that they are enforced.** In order to reduce air pollution, governments need to apply the instruments and approaches that are most effective for reducing air pollution. Command-and-control instruments (such as standards for ambient-air quality and emission standards for vehicles and stationary sources, and vehicle inspection and maintenance programs) are well established and applied in many countries. Additional command-and-control instruments include regulations to improve fuel quality by, for example, decreasing the sulfur content of fuels. Economic instruments (such as air-pollution charges and repurposing of fossil-fuel subsidies) reduce air and climate pollutants while also augmenting the amount of government revenues that can be allocated to education, health care, renewable energy, and interventions to control air pollution. In addition, policies to promote conversion of vehicles from diesel to gas or to discourage the use of nitrogen-based fertilizers (which release ammonia—a precursor of secondary PM$_{2.5}$ formation) may also be used to reduce air pollution. It is important to note that effective application of the various instruments for air-quality management requires that governments put in place adequate enforcement mechanisms that also include incentives to reduce polluting behaviors.

- **Promote the use of clean cooking fuels to combat the health effects of household air pollution from solid fuels.** The populations in low- and middle-income countries using traditional cookstoves with solid fuels for cooking and other domestic purposes are exposed to PM$_{2.5}$ concentrations that are several times higher than ambient PM$_{2.5}$. Improved cookstoves, often 40 to 60 percent more energy efficient than traditional stoves, have been found to reduce exposure by around 50 percent. This reduction, however, reduces health effects by as little as 11 to 12 percent, based on analysis of the
exposure-response functions from the GBD 2019. Effectively combating the health effects requires clean cooking fuels and technologies, such as LPG or electricity. Some low- and middle-income countries have already achieved a high prevalence rate of the population using clean fuels and technologies, demonstrating this possibility even at moderate GDP per capita levels.

REFERENCES

Chen, J., and G. Hoek. 2020, “Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis.” Environment International 143. https://doi.org/10.1016/j.envint.2020.105974.

GBD 2013 Risk Factors Collaborators. 2015. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013.” Lancet 386: 2287–323.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” Lancet 396: 1223–49.

Orellano, P., J. Reynoso, and N. Quaranta. 2021. “Short-Term Exposure to Sulphur Dioxide (SO₂) and All-Cause and Respiratory Mortality: A Systematic Review and Meta-Analysis.” Environment International 150. https://doi.org/10.1016/j.envint.2021.106434.

Orellano, P., J. Reynoso, N. Quaranta, A. Bardach, and A. Ciapponi. 2020. “Short-Term Exposure to Particulate Matter (PM₁₀ and PM₂·₅), Nitrogen Dioxide (NO₂), and Ozone (O₃) and All-Cause and Cause-Specific Mortality: Systematic Review and Meta-Analysis.” Environment International 142. https://doi.org/10.1016/j.envint.2020.105876.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. Washington, DC: World Bank.
APPENDIX A

Annual Health Damages and Costs of PM$_{2.5}$ Exposure, 2019

TABLE A.1 Annual health damages from PM$_{2.5}$ exposure, 2019

| ECONOMY            | AMBIENT PM$_{2.5}$ | SOLID-FUEL USE (POPULATION) | DEATHS FROM PM$_{2.5}$ | YLDS FROM PM$_{2.5}$ |
|--------------------|--------------------|-----------------------------|------------------------|---------------------|
|                    | ($\mu G/m^3$)      | (AAP)           | (HAP)                  | (AAP)   | (HAP)       |
| Afghanistan        | 52.4               | 62              | 8,679                  | 28,168  | 15,748      | 61,111 |
| Albania            | 18.6               | 29              | 1,532                  | 724     | 3,609       | 1,987  |
| Algeria            | 32.8               | 0               | 21,613                 | 66      | 89,757      | 412    |
| American Samoa     | 6.3                | 18              | 8                      | 6       | 48          | 45     |
| Andorra            | 9.1                | 0               | 11                     | 0       | 57          | 0      |
| Angola             | 28.4               | 36              | 5,563                  | 8,726   | 13,379      | 22,060 |
| Antigua and Barbuda| 17.6               | 1               | 30                     | 0       | 161         | 3      |
| Argentina          | 13.5               | 3               | 12,590                 | 708     | 38,711      | 2,912  |
| Armenia            | 33.7               | 3               | 3,091                  | 78      | 7,849       | 321    |
| Aruba              | —                  | —               | —                      | —       | —           | —      |
| Australia          | 6.7                | 0               | 1,781                  | 13      | 9,308       | 125    |
| Austria            | 12.2               | 0               | 2,389                  | 9       | 10,389      | 60     |
| Azerbaijan         | 25.5               | 7               | 7,860                  | 666     | 17,590      | 2,049  |
| Bahamas, The       | 15.6               | 2               | 99                     | 2       | 532         | 15     |
| Bahrain            | 59.2               | 1               | 624                    | 2       | 5,447       | 22     |
| Bangladesh         | 63.4               | 76              | 73,976                 | 94,789  | 203,529     | 388,497|
| Barbados           | 21.3               | 0               | 175                    | 0       | 779         | 1      |
| Belarus            | 16.4               | 1               | 8,403                  | 96      | 13,940      | 232    |
| Belgium            | 12.7               | 0               | 3,491                  | 6       | 15,824      | 40     |
| Belize             | 21.2               | 13              | 93                     | 30      | 370         | 138    |
| Benin              | 46.9               | 92              | 2,304                  | 9,891   | 3,794       | 18,322 |
| Bermuda            | 7.1                | 5               | 8                      | 1       | 39          | 6      |
| Bhutan             | 40.3               | 37              | 270                    | 352     | 837         | 1,186  |
| Bolivia            | 26.8               | 21              | 3,885                  | 2,276   | 8,808       | 7,019  |
| Bosnia and Herzegovina | 29.5       | 38              | 3,622                  | 1,148   | 12,151      | 4,272  |

(continued)
TABLE A.1, continued

| ECONOMY             | AMBIENT PM$_{2.5}$ (µg/M³) | SOLID-FUEL USE (POPULATION) | DEATHS FROM PM$_{2.5}$ | YLDS FROM PM$_{2.5}$ |
|---------------------|-----------------------------|-----------------------------|------------------------|-----------------------|
|                     | AAP | HAP | AAP | HAP | AAP | HAP |
| Botswana            | 24.7 | 39  | 942 | 636 | 2,355 | 1,925 |
| Brazil              | 11.7 | 9  | 43,575 | 14,016 | 167,643 | 65,241 |
| British Virgin Islands | — | — | — | — | — | — |
| Brunei Darussalam   | 7.7  | 1  | 39  | 1  | 285  | 6   |
| Bulgaria            | 19.4 | 20 | 9,072 | 1,812 | 20,028 | 4,493 |
| Burkina Faso        | 53.7 | 94 | 3,384 | 24,303 | 4,186  | 35,106 |
| Burundi             | 33.3 | 99 | 977  | 10,004 | 1,674  | 17,415 |
| Cabo Verde          | 51.1 | 19 | 319  | 99  | 892   | 366  |
| Cambodia            | 22.1 | 79 | 3,499 | 14,034 | 8,731  | 46,805 |
| Cameroon            | 64.5 | 73 | 10,250 | 12,068 | 20,235 | 26,946 |
| Canada              | 7.1  | 0  | 3,765 | 8  | 16,567 | 63   |
| Cayman Islands      | — | — | — | — | — | — |
| Central African Republic | 46.4 | 100 | 931 | 6,961 | 1,284  | 9,730 |
| Chad                | 59.3 | 96 | 2,614 | 19,066 | 2,966  | 23,939 |
| Channel Islands     | — | — | — | — | — | — |
| Chile               | 22.8 | 6 | 5,808 | 330 | 29,554 | 2,570 |
| China               | 47.7 | 36 | 1,423,633 | 363,029 | 4,588,122 | 1,496,251 |
| Colombia            | 22.0 | 9 | 13,033 | 2,454 | 71,733 | 17,650 |
| Comoros             | 17.2 | 79 | 93  | 552 | 197  | 1,344 |
| Congo, Dem. Rep.    | 35.9 | 93 | 11,060 | 58,038 | 23,430 | 122,993 |
| Congo, Rep.         | 39.3 | 60 | 1,803 | 1,638 | 4,886  | 4,803 |
| Costa Rica          | 17.4 | 6 | 938  | 104 | 6,710  | 1,042 |
| Côte d'Ivoire       | 55.6 | 82 | 6,732 | 16,262 | 12,355 | 33,903 |
| Croatia             | 18.5 | 6 | 3,072 | 169 | 11,479 | 775  |
| Cuba                | 17.7 | 2 | 5,845 | 200 | 24,912 | 1,140 |
| Curacao             | — | — | — | — | — | — |
| Cyprus              | 15.6 | 0 | 413  | 1  | 1,909  | 5   |
| Czech Republic      | 16.8 | 2 | 6,255 | 80 | 33,999 | 537  |
| Denmark             | 9.8  | 0 | 1,298 | 2  | 4,701  | 13   |
| Djibouti            | 43.2 | 16 | 453  | 201 | 1,132  | 572  |
| Dominica            | 18.6 | 9 | 33   | 4  | 155   | 23   |
| Dominican Republic  | 17.7 | 8 | 3,798 | 939 | 8,591  | 2,535 |
| Ecuador             | 20.0 | 6 | 4,236 | 476 | 17,433 | 2,792 |
| Egypt, Arab Rep.    | 67.9 | 0 | 90,559 | 73 | 240,586 | 315  |
| El Salvador         | 22.3 | 12 | 1,901 | 618 | 7,836  | 3,146 |
| Equatorial Guinea   | 45.3 | 25 | 397  | 84 | 1,243  | 395  |
| Eritrea             | 44.1 | 68 | 1,380 | 3,936 | 2,575  | 8,194 |
| Estonia             | 5.9  | 10 | 160  | 40 | 523   | 217  |
| Eswatini            | 23.3 | 56 | 344  | 482 | 794   | 1,338 |
| Ethiopia            | 33.8 | 96 | 8,957 | 67,827 | 16,037 | 160,370 |

(continued)
| ECONOMY                | AMBIENT PM$_{2.5}$ (µg/M$^3$) | SOLID-FUEL USE (POPULATION) | DEATHS FROM PM$_{2.5}$ AAP | HAP | YLDS FROM PM$_{2.5}$ AAP | HAP |
|-----------------------|--------------------------------|----------------------------|-----------------------------|-----|--------------------------|-----|
| Faroe Islands         | —                              | —                          | —                           |     | —                        |     |
| Fiji                  | 11.0                           | 28                         | 330                         | 302 | 1,117                    | 1,307|
| Finland               | 5.6                            | 0                          | 385                         | 2   | 1,881                    | 22  |
| France                | 11.4                           | 0                          | 13,245                      | 37  | 43,214                   | 218 |
| French Polynesia      | —                              | —                          | —                           |     | —                        |     |
| Gabon                 | 36.7                           | 8                          | 821                         | 69  | 2,554                    | 253 |
| Gambia, The           | 58.1                           | 95                         | 487                         | 1,493| 945                      | 3,638|
| Georgia               | 17.9                           | 34                         | 3,112                       | 1,594| 7,222                    | 5,132|
| Germany               | 11.8                           | 0                          | 27,041                      | 30  | 135,725                  | 238 |
| Ghana                 | 54.0                           | 70                         | 12,544                      | 11,065| 29,588                   | 32,419|
| Gibraltar             | —                              | —                          | —                           |     | —                        |     |
| Greece                | 14.3                           | 1                          | 5,715                       | 41  | 18,472                   | 182 |
| Greenland             | 6.5                            | 2                          | 6                           | 0   | 20                       | 1   |
| Grenada               | 21.5                           | 3                          | 51                          | 2   | 226                      | 12  |
| Guam                  | 8.2                            | 8                          | 31                          | 5   | 144                      | 41  |
| Guatemala             | 27.6                           | 47                         | 3,734                       | 5,296| 12,255                   | 20,434|
| Guinea                | 52.5                           | 98                         | 2,455                       | 13,752| 3,397                    | 22,145|
| Guinea-Bissau         | 54.1                           | 98                         | 355                         | 1,639| 603                      | 3,072|
| Guyana                | 20.1                           | 5                          | 411                         | 55  | 1,311                    | 195 |
| Haiti                 | 19.0                           | 90                         | 1,822                       | 12,151| 3,489                    | 24,779|
| Honduras              | 22.9                           | 49                         | 1,783                       | 3,875| 5,130                    | 12,149|
| Hong Kong SAR, China  | —                              | —                          | —                           |     | —                        |     |
| Hungary               | 16.5                           | 19                         | 6,940                       | 1,347| 24,748                   | 6,089|
| Iceland               | 5.7                            | 0                          | 16                          | 0   | 84                       | 1   |
| India                 | 83.2                           | 61                         | 979,682                     | 606,890| 2,965,720                | 2,524,841|
| Indonesia             | 19.4                           | 34                         | 106,710                     | 76,867| 342,829                  | 448,090|
| Iran, Islamic Rep.    | 38.0                           | 0                          | 41,742                      | 97  | 188,106                  | 590 |
| Iraq                  | 48.5                           | 0                          | 25,378                      | 64  | 82,065                   | 325 |
| Ireland               | 7.9                            | 0                          | 535                         | 2   | 2,420                    | 15  |
| Isle of Man           | —                              | —                          | —                           |     | —                        |     |
| Israel                | 19.8                           | 0                          | 2,280                       | 4   | 11,164                   | 27  |
| Italy                 | 16.1                           | 0                          | 24,666                      | 121 | 110,372                  | 1,027|
| Jamaica               | 15.3                           | 10                         | 938                         | 199 | 4,021                    | 986 |
| Japan                 | 13.5                           | 0                          | 39,692                      | 95  | 210,849                  | 828 |
| Jordan                | 30.6                           | 0                          | 3,074                       | 2   | 18,079                   | 11  |
| Kazakhstan            | 20.3                           | 11                         | 10,133                      | 1,424| 29,228                   | 5,752|
| Kenya                 | 21.6                           | 87                         | 5,490                       | 22,109| 14,691                   | 67,103|
| Kiribati              | 9.5                            | 58                         | 18                          | 133 | 41                       | 330 |
| Korea, Dem. People's Rep. | 44.3               | 86                         | 21,590                      | 31,515| 55,398                   | 87,506|

(continued)
| ECONOMY            | AMBIENT PM$_{2.5}$ | SOLID-FUEL USE | DEATHS FROM PM$_{2.5}$ | YLDS FROM PM$_{2.5}$ |
|-------------------|--------------------|----------------|------------------------|----------------------|
|                   | (µg/M³)            | (POPULATION)   | AAP                    | HAP                  |
| Korea, Rep.       | 27.4               | 0              | 21,837                 | 15                   |
| Kosovo            | —                  | —              | —                      | —                    |
| Kuwait            | 61.0               | 0              | 1,526                  | 1                    |
| Kyrgyz Republic  | 24.1               | 24             | 2,586                  | 1,432                |
| Lao PDR           | 20.5               | 93             | 1,376                  | 6,332                |
| Latvia            | 12.0               | 8              | 1,119                  | 104                  |
| Lebanon           | 29.0               | 0              | 3,303                  | 10                   |
| Lesotho           | 27.5               | 55             | 839                    | 1,633                |
| Libya             | 50.6               | 95             | 656                    | 2,714                |
| Liechtenstein     | —                  | —              | —                      | —                    |
| Lithuania         | 10.4               | 4              | 1,264                  | 61                   |
| Luxembourg        | 10.1               | 0              | 91                     | 0                    |
| Macao SAR, China  | —                  | —              | —                      | —                    |
| Madagascar        | 17.9               | 98             | 2,246                  | 21,459               |
| Malawi            | 22.3               | 97             | 1,312                  | 12,379               |
| Malaysia          | 16.6               | 1              | 10,551                 | 111                  |
| Maldives          | 10.9               | 9              | 49                     | 23                   |
| Mali              | 60.6               | 99             | 3,246                  | 22,580               |
| Malta             | 13.0               | 0              | 147                    | 0                    |
| Marshall Islands  | 9.0                | 26             | 12                     | 24                   |
| Mauritania        | 66.8               | 52             | 1,411                  | 1,208                |
| Mauritius         | 14.9               | 1              | 606                    | 14                   |
| Mexico            | 20.1               | 13             | 36,582                 | 9,854                |
| Micronesia, Fed. Sts. | 10.4          | 28             | 32                     | 48                   |
| Moldova           | 13.7               | 6              | 2,102                  | 282                  |
| Monaco            | 11.7               | 15             | 0                      | 51                   |
| Mongolia          | 38.1               | 44             | 2,245                  | 1,009                |
| Montenegro        | 21.3               | 39             | 564                    | 168                  |
| Morocco           | 35.1               | 3              | 27,063                 | 1,679                |
| Mozambique        | 20.8               | 96             | 1,879                  | 25,017               |
| Myanmar           | 29.4               | 80             | 24,169                 | 49,223               |
| Namibia           | 24.2               | 50             | 789                    | 775                  |
| Nauru             | —                  | —              | —                      | —                    |
| Nepal             | 83.1               | 67             | 17,948                 | 21,603               |
| Netherlands       | 12.0               | 0              | 4,569                  | 6                    |
| New Caledonia     | —                  | —              | —                      | —                    |
| New Zealand       | 6.0                | 0              | 303                    | 3                    |
| Nicaragua         | 20.4               | 44             | 1,002                  | 1,735                |

(continued)
TABLE A.1, continued

| ECONOMY                  | AMBIENT PM$_{2.5}$ (μg/m$^3$) | SOLID-FUEL USE (POPULATION) | DEATHS FROM PM$_{2.5}$ AAP | DEATHS FROM PM$_{2.5}$ HAP | YLDS FROM PM$_{2.5}$ AAP | YLDS FROM PM$_{2.5}$ HAP |
|-------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------|---------------------------|
| Niger                   | 80.1                          | 99                          | 2,971                       | 26,507                      | 3,292                     | 32,931                    |
| Nigeria                 | 70.4                          | 77                          | 68,533                      | 128,259                     | 106,948                   | 203,795                   |
| North Macedonia         | 30.3                          | 27                          | 2,751                       | 535                         | 7,476                     | 1,626                     |
| Northern Mariana Islands| —                             | 20                          | 10                          | 5                           | 49                        | 34                        |
| Norway                  | 6.6                           | 0                           | 393                         | 1                           | 2,350                     | 13                        |
| Oman                    | 44.6                          | 1                           | 1,553                       | 6                           | 6,742                     | 69                        |
| Pakistan                | 62.6                          | 53                          | 114,008                     | 116,090                     | 256,359                   | 356,704                   |
| Palau                   | —                             | —                           | 5                           | 0                           | 18                        | 0                         |
| Panama                  | 13.2                          | 10                          | 650                         | 154                         | 4,178                     | 1,535                     |
| Papua New Guinea        | 16.2                          | 85                          | 1,181                       | 11,169                      | 2,919                     | 31,702                    |
| Paraguay                | 12.5                          | 33                          | 1,045                       | 1,193                       | 3,426                     | 5,103                     |
| Peru                    | 30.8                          | 19                          | 8,905                       | 2,439                       | 30,643                    | 16,308                    |
| Philippines             | 18.8                          | 48                          | 32,019                      | 42,675                      | 97,367                    | 161,885                   |
| Poland                  | 22.6                          | 14                          | 27,762                      | 2,808                       | 106,179                   | 13,451                    |
| Portugal                | 8.3                           | 1                           | 2,086                       | 34                          | 9,794                     | 210                       |
| Puerto Rico (US)        | 6.9                           | 0                           | 427                         | 1                           | 3,188                     | 8                         |
| Qatar                   | 76                            | —                           | 539                         | 0                           | 7,822                     | 1                         |
| Romania                 | 15.7                          | 13                          | 14,577                      | 2,434                       | 36,650                    | 7,437                     |
| Russian Federation      | 11.6                          | 2                           | 73,859                      | 2,448                       | 146,425                   | 6,865                     |
| Rwanda                  | 36.2                          | 99                          | 1,758                       | 7,468                       | 3,840                     | 16,920                    |
| Samoa                   | 11.0                          | 61                          | 41                          | 139                         | 122                       | 489                       |
| São Tomé and Príncipe   | 31.1                          | 55                          | 52                          | 87                          | 159                       | 313                       |
| Saudi Arabia            | 61.5                          | 1                           | 17,795                      | 37                          | 87,210                    | 485                       |
| Senegal                 | 60.2                          | 78                          | 3,369                       | 9,075                       | 8,124                     | 24,176                    |
| Serbia                  | 25.4                          | 24                          | 10,609                      | 1,969                       | 30,589                    | 6,472                     |
| Seychelles              | 15.6                          | 1                           | 35                          | 0                           | 220                       | 3                        |
| Sierra Leone            | 51.1                          | 97                          | 1,542                       | 7,813                       | 2,327                     | 12,562                    |
| Singapore               | 18.8                          | 0                           | 1,331                       | 2                           | 9,629                     | 24                       |
| Sint Maarten (Dutch part)| —                             | —                           | —                           | —                           | —                         | —                         |
| Slovak Republic         | 18.4                          | 1                           | 3,472                       | 34                          | 11,557                    | 148                       |
| Slovenia                | 17.0                          | 10                          | 823                         | 62                          | 4,151                     | 430                       |
| Solomon Islands         | 12.9                          | 90                          | 109                         | 1,211                       | 144                       | 1,815                     |
| Somalia                 | 30.4                          | 98                          | 770                         | 27,553                      | 906                       | 35,021                    |
| South Africa            | 28.7                          | 13                          | 24,780                      | 4,590                       | 92,417                    | 21,061                    |
| South Sudan             | 37.6                          | 99                          | 1,390                       | 7,678                       | 2,261                     | 15,647                    |
| Spain                   | 9.7                           | 1                           | 8,880                       | 178                         | 49,400                    | 1,748                     |
| Sri Lanka               | 20.0                          | 61                          | 7,261                       | 6,643                       | 43,062                    | 52,603                    |
### TABLE A.1, continued

| ECONOMY                          | AMBIENT PM$_{2.5}$ (µg/M³) | SOLID-FUEL USE (POPULATION) | DEATHS FROM PM$_{2.5}$ | YLDS FROM PM$_{2.5}$ |
|---------------------------------|-----------------------------|-----------------------------|------------------------|-----------------------|
|                                 | AAP                         | HAP                         | AAP                    | HAP                   |
| St. Kitts and Nevis             | —                           | —                           | 11                     | 54                    |
| St. Lucia                       | 21.2                        | 3                           | 80                     | 5                     |
| St. Martin (French part)        | —                           | —                           | —                      | —                     |
| St. Vincent and the Grenadines  | 21.1                        | 3                           | 62                     | 268                   |
| Sudan                           | 54.7                        | 41                          | 16,634                 | 42,558                |
| Suriname                        | 21.2                        | 9                           | 649                    | 3,157                 |
| Sweden                          | 5.6                         | 0                           | 1,374                  | 7,196                 |
| Switzerland                     | 9.9                         | 0                           | 1,619                  | 4,219                 |
| Syrian Arab Republic            | 31.0                        | 0                           | 10,474                 | 30,779                |
| Tajikistan                      | 38.3                        | 29                          | 4,758                  | 8,634                 |
| Tanzania                        | 24.7                        | 98                          | 6,246                  | 10,717                |
| Thailand                        | 27.4                        | 21                          | 32,211                 | 171,033               |
| Timor-Leste                     | 15.7                        | 81                          | 210                    | 525                   |
| Togo                            | 46.2                        | 91                          | 1,619                  | 3,221                 |
| Tonga                           | 10.6                        | 36                          | 20                     | 74                    |
| Trinidad and Tobago             | 22.0                        | 0                           | 890                    | 4,219                 |
| Tunisia                         | 30.4                        | 0                           | 7,337                  | 31,432                |
| Turkey                          | 26.0                        | 1                           | 41,524                 | 178,545               |
| Turkmenistan                    | 26.2                        | 0                           | 3,577                  | 7,447                 |
| Turks and Caicos Islands        | —                           | —                           | —                      | —                     |
| Tuvalu                          | —                           | —                           | 2                      | 6                     |
| Uganda                          | 35.2                        | 98                          | 4,586                  | 9,018                 |
| Ukraine                         | 14.5                        | 4                           | 42,916                 | 62,746                |
| United Arab Emirates            | 43.7                        | —                           | 3,252                  | 25,073                |
| United Kingdom                  | 10.1                        | 0                           | 14,449                 | 74,545                |
| United States                   | 7.7                         | 0                           | 47,787                 | 291,895               |
| Uruguay                         | 9.5                         | 2                           | 733                    | 2,083                 |
| Uzbekistan                      | 34.8                        | 10                          | 26,749                 | 46,908                |
| Vanuatu                         | 12.9                        | 88                          | 54                     | 118                   |
| Venezuela, RB                   | 21.7                        | 0                           | 12,384                 | 47,739                |
| Vietnam                         | 20.4                        | 41                          | 37,457                 | 120,815               |
| Virgin Islands (US)             | 9.0                         | 2                           | 31                     | 126                   |
| West Bank and Gaza              | 31.3                        | 1                           | 1,792                  | 6,663                 |
| Yemen, Rep.                     | 44.5                        | 24                          | 11,282                 | 22,975                |
| Zambia                          | 25.9                        | 80                          | 2,949                  | 5,308                 |
| Zimbabwe                        | 20.8                        | 69                          | 2,607                  | 5,276                 |

Sources: Ambient PM$_{2.5}$ and solid-fuel use are from Health Effects Institute (HEI), State of Global Air 2020 (Boston: HEI, 2020). www.stateofglobalair.org Annual deaths and YLDs from PM$_{2.5}$ are from GBD 2019 Risk Factors Collaborators, “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019,” Lancet 396 (2020): 1223–49.

Note: HAP = household air pollution; AAP = ambient air pollution; YLD = years lived with disability; — = not available.
| ECONOMY                  | DEATHS FROM PM$_{2.5}$ (AAP+HAP) | YLDS FROM PM$_{2.5}$ (AAP+HAP) | PM$_{2.5}$ DEATHS PER 100,000 POPULATION | PM$_{2.5}$ YLDS PER 100,000 POPULATION |
|-------------------------|----------------------------------|---------------------------------|------------------------------------------|----------------------------------------|
| Afghanistan             | 36,847                           | 76,859                          | 96                                       | 201                                    |
| Albania                 | 2,257                            | 5,596                           | 83                                       | 206                                    |
| Algeria                 | 21,680                           | 90,169                          | 52                                       | 215                                    |
| American Samoa          | 14                               | 93                              | 24                                       | 168                                    |
| Andorra                 | 11                               | 57                              | 13                                       | 69                                     |
| Angola                  | 14,288                           | 35,440                          | 47                                       | 118                                    |
| Antigua and Barbuda     | 30                               | 164                             | 34                                       | 186                                    |
| Argentina               | 13,298                           | 41,623                          | 29                                       | 92                                     |
| Armenia                 | 3,169                            | 8,170                           | 105                                      | 271                                    |
| Aruba                   | —                                | —                               | —                                        | —                                      |
| Australia               | 1,795                            | 9,433                           | 7                                        | 38                                     |
| Austria                 | 2,398                            | 10,449                          | 27                                       | 117                                    |
| Azerbaijan              | 8,526                            | 19,639                          | 83                                       | 191                                    |
| Bahamas, The            | 101                              | 547                             | 27                                       | 145                                    |
| Bahrain                 | 625                              | 5,469                           | 43                                       | 379                                    |
| Bangladesh              | 168,765                          | 592,027                         | 106                                      | 372                                    |
| Barbados                | 175                              | 780                             | 59                                       | 262                                    |
| Belarus                 | 8,499                            | 14,172                          | 89                                       | 149                                    |
| Belgium                 | 3,497                            | 15,864                          | 31                                       | 139                                    |
| Belize                  | 123                              | 508                             | 30                                       | 124                                    |
| Benin                   | 12,195                           | 22,116                          | 96                                       | 175                                    |
| Bermuda                 | 9                                | 46                              | 14                                       | 71                                     |
| Bhutan                  | 621                              | 2,023                           | 82                                       | 268                                    |
| Bolivia                 | 6,161                            | 15,827                          | 51                                       | 132                                    |
| Bosnia and Herzegovina  | 4,770                            | 16,423                          | 145                                      | 498                                    |
| Botswana                | 1,578                            | 4,280                           | 67                                       | 183                                    |
| Brazil                  | 57,591                           | 232,883                         | 27                                       | 107                                    |
| British Virgin Islands  | —                                | —                               | —                                        | —                                      |
| Brunei Darussalam       | 39                               | 291                             | 9                                        | 67                                     |
| Bulgaria                | 10,884                           | 24,521                          | 157                                      | 354                                    |
| Burkina Faso            | 27,687                           | 39,291                          | 122                                      | 173                                    |
| Burundi                 | 10,980                           | 19,090                          | 92                                       | 160                                    |
| Cabo Verde              | 417                              | 1,258                           | 74                                       | 223                                    |
| Cambodia                | 17,533                           | 55,536                          | 106                                      | 334                                    |
| Cameroon                | 22,318                           | 47,181                          | 77                                       | 162                                    |
| Canada                  | 3,774                            | 16,630                          | 10                                       | 46                                     |
| Cayman Islands          | —                                | —                               | —                                        | —                                      |
| Central African Republic| 7,892                            | 11,014                          | 149                                      | 208                                    |
| Chad                    | 21,680                           | 26,904                          | 132                                      | 164                                    |

(continued)
| ECONOMY                  | DEATHS FROM PM$_{2.5}$ AAP+HAP | YLDS FROM PM$_{2.5}$ AAP+HAP | PM$_{10}$ DEATHS PER 100,000 POPULATION | PM$_{2.5}$ YLDS PER 100,000 POPULATION |
|-------------------------|--------------------------------|-------------------------------|----------------------------------------|----------------------------------------|
| Channel Islands         | —                              | —                             | —                                      | —                                      |
| Chile                   | 6,139                          | 32,124                        | 34                                     | 177                                    |
| China                   | 1,786,662                      | 6,084,373                     | 126                                    | 428                                    |
| Colombia                | 15,487                         | 89,383                        | 32                                     | 187                                    |
| Comoros                 | 645                            | 1,541                         | 90                                     | 216                                    |
| Congo, Dem. Rep.        | 69,098                         | 146,423                       | 79                                     | 167                                    |
| Congo, Rep.             | 3,441                          | 9,688                         | 65                                     | 184                                    |
| Costa Rica              | 1,041                          | 7,753                         | 22                                     | 164                                    |
| Côte d’Ivoire           | 22,994                         | 46,259                        | 88                                     | 177                                    |
| Croatia                 | 3,241                          | 12,254                        | 76                                     | 288                                    |
| Cuba                    | 6,045                          | 26,052                        | 53                                     | 229                                    |
| Curacao                 | —                              | —                             | —                                      | —                                      |
| Cyprus                  | 414                            | 1,914                         | 32                                     | 146                                    |
| Czech Republic          | 6,335                          | 34,535                        | 60                                     | 324                                    |
| Denmark                 | 1,300                          | 4,714                         | 22                                     | 81                                     |
| Djibouti                | 654                            | 1,704                         | 54                                     | 142                                    |
| Dominica                | 37                             | 178                           | 54                                     | 260                                    |
| Dominican Republic      | 4,737                          | 11,126                        | 44                                     | 102                                    |
| Ecuador                 | 4,712                          | 20,225                        | 27                                     | 115                                    |
| Egypt, Arab Rep.        | 90,632                         | 240,901                       | 91                                     | 243                                    |
| El Salvador             | 2,520                          | 10,981                        | 40                                     | 176                                    |
| Equatorial Guinea       | 481                            | 1,638                         | 34                                     | 115                                    |
| Eritrea                 | 5,316                          | 10,769                        | 79                                     | 160                                    |
| Estonia                 | 200                            | 740                           | 15                                     | 56                                     |
| Eswatini                | 825                            | 2,132                         | 72                                     | 187                                    |
| Ethiopia                | 76,783                         | 176,406                       | 71                                     | 164                                    |
| Faroe Islands           | —                              | —                             | —                                      | —                                      |
| Fiji                    | 633                            | 2,423                         | 69                                     | 266                                    |
| Finland                 | 387                            | 1,902                         | 7                                      | 34                                     |
| France                  | 13,282                         | 43,431                        | 20                                     | 66                                     |
| French Polynesia        | —                              | 0                             | 0                                      | —                                      |
| Gabon                   | 890                            | 2,807                         | 51                                     | 160                                    |
| Gambia, The             | 1,980                          | 4,584                         | 88                                     | 204                                    |
| Georgia                 | 4,706                          | 12,355                        | 128                                    | 337                                    |
| Germany                 | 27,070                         | 135,963                       | 32                                     | 160                                    |
| Ghana                   | 23,608                         | 62,008                        | 75                                     | 197                                    |
| Gibraltar               | —                              | —                             | —                                      | —                                      |
| Greece                  | 5,757                          | 18,655                        | 56                                     | 180                                    |
| Greenland               | 6                              | 22                            | 11                                     | 39                                     |

(continued)
| ECONOMY                | DEATHS FROM PM$_{2.5}$ AAP+HAP | YLDS FROM PM$_{2.5}$ AAP+HAP | PM$_{2.5}$ DEATHS PER 100,000 POPULATION | PM$_{2.5}$ YLDS PER 100,000 POPULATION |
|-----------------------|-------------------------------|-------------------------------|-----------------------------------------|----------------------------------------|
| Grenada               | 54                            | 238                           | 52                                      | 230                                    |
| Guam                  | 36                            | 185                           | 21                                      | 109                                    |
| Guatemala             | 9,030                         | 32,689                        | 51                                      | 184                                    |
| Guinea                | 16,207                        | 25,541                        | 128                                     | 202                                    |
| Guinea-Bissau         | 1,994                         | 3,675                         | 105                                     | 193                                    |
| Guyana                | 466                           | 1,506                         | 60                                      | 195                                    |
| Haiti                 | 13,973                        | 28,267                        | 113                                     | 228                                    |
| Honduras              | 5,658                         | 17,279                        | 58                                      | 176                                    |
| Hong Kong SAR, China  | —                             | —                             | —                                       | —                                      |
| Hungary               | 8,287                         | 30,837                        | 86                                      | 319                                    |
| Iceland               | 16                            | 85                            | 5                                       | 25                                     |
| India                 | 1,586,571                     | 5,490,561                     | 114                                     | 395                                    |
| Indonesia             | 183,577                       | 790,919                       | 71                                      | 305                                    |
| Iran, Islamic Rep.    | 41,839                        | 188,696                       | 50                                      | 224                                    |
| Iraq                  | 25,442                        | 82,390                        | 60                                      | 196                                    |
| Ireland               | 537                           | 2,435                         | 11                                      | 50                                     |
| Isle of Man           | —                             | —                             | —                                       | —                                      |
| Israel                | 2,284                         | 11,191                        | 25                                      | 120                                    |
| Italy                 | 24,787                        | 111,400                       | 41                                      | 185                                    |
| Jamaica               | 1,137                         | 5,007                         | 40                                      | 178                                    |
| Japan                 | 39,787                        | 211,677                       | 31                                      | 166                                    |
| Jordan                | 3,075                         | 18,090                        | 26                                      | 155                                    |
| Kazakhstan            | 11,557                        | 34,980                        | 63                                      | 190                                    |
| Kenya                 | 27,600                        | 81,794                        | 55                                      | 163                                    |
| Kiribati              | 151                           | 371                           | 127                                     | 313                                    |
| Korea, Dem. People’s Rep. | 53,105              | 142,904                       | 202                                     | 545                                    |
| Korea, Rep.           | 21,852                        | 134,538                       | 41                                      | 252                                    |
| Kosovo                | —                             | —                             | —                                       | —                                      |
| Kuwait                | 1,527                         | 11,606                        | 34                                      | 262                                    |
| Kyrgyz Republic       | 4,018                         | 9,020                         | 61                                      | 138                                    |
| Lao PDR               | 7,708                         | 21,589                        | 108                                     | 302                                    |
| Latvia                | 1,223                         | 2,933                         | 64                                      | 153                                    |
| Lebanon               | 3,312                         | 14,018                        | 64                                      | 271                                    |
| Lesotho               | 2,472                         | 5,079                         | 118                                     | 243                                    |
| Liberia               | 3,370                         | 9,051                         | 70                                      | 189                                    |
| Libya                 | 3,375                         | 18,173                        | 50                                      | 270                                    |
| Liechtenstein         | —                             | —                             | —                                       | —                                      |
| Lithuania             | 1,325                         | 2,984                         | 47                                      | 107                                    |
| Luxembourg            | 91                            | 626                           | 15                                      | 101                                    |

(continued)
| ECONOMY                  | DEATHS FROM PM$_{2.5}$ AAP+HAP | YLDS FROM PM$_{2.5}$ AAP+HAP | PM$_{2.5}$ DEATHS PER 100,000 POPULATION | PM$_{2.5}$ YLDS PER 100,000 POPULATION |
|-------------------------|-------------------------------|-------------------------------|------------------------------------------|---------------------------------------|
| Macao SAR, China        | —                             | —                             | —                                        | —                                     |
| Madagascar              | 23,706                        | 51,214                        | 89                                       | 192                                   |
| Malawi                  | 13,691                        | 30,138                        | 74                                       | 163                                   |
| Malaysia                | 10,662                        | 46,600                        | 34                                       | 149                                   |
| Maldives                | 72                             | 450                           | 14                                       | 90                                    |
| Mali                    | 25,827                        | 46,723                        | 118                                      | 213                                   |
| Malta                   | 148                            | 684                           | 34                                       | 156                                   |
| Marshall Islands        | 36                             | 143                           | 63                                       | 251                                   |
| Mauritania              | 2,619                          | 6,682                         | 65                                       | 166                                   |
| Mauritius               | 621                            | 3,458                         | 49                                       | 271                                   |
| Mexico                  | 46,436                        | 267,384                       | 37                                       | 214                                   |
| Micronesia, Fed. Sts.   | 80                             | 217                           | 79                                       | 212                                   |
| Moldova                 | 2,385                          | 5,861                         | 65                                       | 159                                   |
| Monaco                  | 15                             | 51                            | 40                                       | 135                                   |
| Mongolia                | 3,254                          | 5,314                         | 96                                       | 157                                   |
| Montenegro              | 732                            | 2,032                         | 118                                      | 328                                   |
| Morocco                 | 28,743                        | 88,204                        | 80                                       | 245                                   |
| Mozambique              | 26,895                        | 51,388                        | 91                                       | 174                                   |
| Myanmar                 | 73,393                        | 240,552                       | 134                                      | 440                                   |
| Namibia                 | 1,564                          | 4,114                         | 65                                       | 171                                   |
| Nauru                   | —                              | —                             | —                                        | —                                     |
| Nepal                   | 39,552                        | 108,992                       | 130                                      | 358                                   |
| Netherlands             | 4,575                          | 20,579                        | 27                                       | 120                                   |
| New Caledonia           | —                              | —                             | —                                        | —                                     |
| New Zealand             | 305                            | 1,258                         | 7                                        | 28                                    |
| Nicaragua               | 2,738                          | 11,540                        | 42                                       | 177                                   |
| Niger                   | 29,477                        | 36,222                        | 127                                      | 155                                   |
| Nigeria                 | 196,793                       | 310,743                       | 92                                       | 145                                   |
| North Macedonia         | 3,286                          | 9,103                         | 153                                      | 423                                   |
| Northern Mariana Islands| 16                             | 83                            | 36                                       | 195                                   |
| Norway                  | 394                            | 2,363                         | 7                                        | 44                                    |
| Oman                    | 1,559                          | 6,811                         | 34                                       | 149                                   |
| Pakistan                | 230,098                       | 613,063                       | 103                                      | 274                                   |
| Palau                   | 5                              | 18                            | 25                                       | 100                                   |
| Panama                  | 804                            | 5,713                         | 19                                       | 137                                   |
| Papua New Guinea        | 12,350                         | 34,621                        | 125                                      | 351                                   |
| Paraguay                | 2,239                          | 8,528                         | 32                                       | 123                                   |
| Peru                    | 11,345                         | 46,951                        | 33                                       | 138                                   |
| Philippines             | 74,693                         | 259,252                       | 67                                       | 231                                   |

(continued)
### Table A.2, continued

| Economy          | Deaths from PM$_{2.5}$ | Ylds from PM$_{2.5}$ | PM$_{2.5}$ Deaths Per 100,000 Population | PM$_{2.5}$ Ylds Per 100,000 Population |
|------------------|-------------------------|----------------------|----------------------------------------|----------------------------------------|
| Poland           | 30,570                  | 119,630              | 80                                     | 311                                    |
| Portugal         | 2,120                   | 10,005               | 20                                     | 94                                     |
| Puerto Rico (US) | 427                     | 3,196                | 12                                     | 91                                     |
| Qatar            | 539                     | 7,823                | 19                                     | 273                                    |
| Romania          | 17,010                  | 44,087               | 88                                     | 229                                    |
| Russian Federation| 76,307                  | 153,290              | 52                                     | 104                                    |
| Rwanda           | 9,226                   | 20,760               | 73                                     | 164                                    |
| Samoa            | 180                     | 611                  | 85                                     | 289                                    |
| San Marino       | 6                       | 29                   | 17                                     | 88                                     |
| São Tomé and Príncipe | 139                   | 472                  | 68                                     | 230                                    |
| Saudi Arabia     | 17,832                  | 87,695               | 50                                     | 245                                    |
| Senegal          | 12,444                  | 32,300               | 82                                     | 213                                    |
| Serbia           | 12,578                  | 37,061               | 144                                    | 424                                    |
| Seychelles       | 35                      | 224                  | 35                                     | 219                                    |
| Sierra Leone     | 9,355                   | 14,890               | 113                                    | 180                                    |
| Singapore        | 1,333                   | 9,653                | 24                                     | 170                                    |
| Sint Maarten (Dutch part) | —                  | —                    | —                                      | —                                      |
| Slovak Republic  | 3,506                   | 11,705               | 64                                     | 215                                    |
| Slovenia         | 885                     | 4,581                | 43                                     | 221                                    |
| Solomon Islands  | 1,320                   | 1,958                | 201                                    | 299                                    |
| Somalia          | 28,323                  | 35,927               | 139                                    | 177                                    |
| South Africa     | 29,370                  | 113,478              | 53                                     | 204                                    |
| South Sudan      | 9,068                   | 17,909               | 98                                     | 193                                    |
| Spain            | 9,058                   | 51,149               | 20                                     | 111                                    |
| Sri Lanka        | 13,904                  | 95,665               | 64                                     | 438                                    |
| St. Kitts and Nevis | 12                   | 59                   | 20                                     | 99                                     |
| St. Lucia        | 85                      | 518                  | 49                                     | 297                                    |
| St. Martin (French part) | —                  | —                    | —                                      | —                                      |
| St. Vincent and the Grenadines | 67                  | 290                  | 59                                     | 256                                    |
| Sudan            | 27,944                  | 77,330               | 68                                     | 189                                    |
| Suriname         | 307                     | 1,451                | 53                                     | 252                                    |
| Sweden           | 651                     | 3,183                | 6                                      | 31                                     |
| Switzerland      | 1,375                   | 7,210                | 16                                     | 82                                     |
| Syrian Arab Republic | 10,491             | 30,854               | 72                                     | 213                                    |
| Tajikistan       | 7,365                   | 14,321               | 78                                     | 151                                    |
| Tanzania         | 45,412                  | 88,438               | 80                                     | 156                                    |
| Thailand         | 39,660                  | 235,993              | 57                                     | 337                                    |
| Timor-Leste      | 1,238                   | 3,521                | 93                                     | 264                                    |
| Togo             | 6,679                   | 15,103               | 84                                     | 191                                    |

(continued)
TABLE A.2, continued

| ECONOMY                | DEATHS FROM PM$_{2.5}$ | YLDS FROM PM$_{2.5}$ | PM$_{2.5}$ DEATHS PER 100,000 POPULATION | PM$_{2.5}$ YLDS PER 100,000 POPULATION |
|------------------------|------------------------|----------------------|-----------------------------------------|-----------------------------------------|
|                        | AAP+HAP                | AAP+HAP              |                                         |                                         |
| Tonga                  | 51                     | 203                  | 50                                      | 199                                     |
| Trinidad and Tobago    | 891                    | 4,227                | 64                                      | 305                                     |
| Tunisia                | 7,358                  | 31,572               | 64                                      | 273                                     |
| Turkey                 | 41,760                 | 180,156              | 51                                      | 221                                     |
| Turkmenistan           | 3,582                  | 7,467                | 70                                      | 147                                     |
| Turks and Caicos Islands | —                     | —                    | —                                       | —                                       |
| Tuvalu                 | 4                      | 12                   | 32                                      | 104                                     |
| Uganda                 | 27,587                 | 56,593               | 67                                      | 138                                     |
| Ukraine                | 45,643                 | 68,403               | 104                                     | 155                                     |
| United Arab Emirates   | 3,252                  | 25,075               | 35                                      | 271                                     |
| United Kingdom         | 14,461                 | 74,630               | 22                                      | 111                                     |
| United States          | 47,937                 | 293,133              | 15                                      | 89                                      |
| Uruguay                | 786                    | 2,263                | 23                                      | 66                                      |
| Uzbekistan             | 29,913                 | 54,008               | 89                                      | 160                                     |
| Vanuatu                | 416                    | 1,006                | 141                                     | 341                                     |
| Venezuela, RB          | 12,471                 | 48,162               | 44                                      | 172                                     |
| Vietnam                | 70,703                 | 260,016              | 73                                      | 270                                     |
| Virgin Islands (US)    | 32                     | 131                  | 31                                      | 126                                     |
| West Bank and Gaza     | 1,820                  | 6,811                | 37                                      | 137                                     |
| Yemen, Rep.            | 20,991                 | 45,942               | 67                                      | 146                                     |
| Zambia                 | 11,771                 | 23,567               | 65                                      | 129                                     |
| Zimbabwe               | 12,626                 | 28,618               | 84                                      | 191                                     |

Source: GBD 2019 Risk Factors Collaborators, “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019,” Lancet 396 (2020): 1223–49.

Note: HAP = household air pollution; AAP = ambient air pollution; YLDs = years lived with disability; — = not available.

TABLE A.3 Annual cost of health damages from PM$_{2.5}$ exposure, 2019

| ECONOMY              | US$, MILLIONS | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|----------------------|---------------|-------------------|---------------------|--------------------------|
|                      | AAP           | HAP               | TOTAL               | AAP                      | HAP                      | TOTAL                     |                             |
| Afghanistan          | 312           | 1,047             | 1,359               | 1,425                    | 4,781                    | 6,206                     | 7.1                          | 19                         |
| Albania              | 784           | 377               | 1,160               | 2,122                    | 1,020                    | 3,142                     | 7.6                          | 11                         |
| Algeria              | 9,385         | 32                | 9,417               | 28,095                   | 97                       | 28,192                    | 5.5                          | 25                         |
| American Samoa       | —             | —                 | —                   | —                        | —                        | —                         | —                            | —                          |
| Andorra              | —             | —                 | —                   | —                        | —                        | —                         | —                            | —                          |
| Angola               | 1,407         | 2,222             | 3,630               | 3,280                    | 5,179                    | 8,458                     | 3.8                          | 13                         |
| Antigua and Barbuda  | 72            | 1                 | 73                  | 92                       | 2                        | 94                        | 4.2                          | 15                         |
| Argentina            | 13,176        | 766               | 13,942              | 30,217                   | 1,757                    | 31,974                    | 3.1                          | 10                         |
| Armenia              | 1,412         | 39                | 1,450               | 4,342                    | 119                      | 4,462                     | 10.6                         | 14                         |

(continued)
Table A.3, continued

| ECONOMY       | US$, MILLIONS | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|---------------|--------------|-------------------|---------------------|--------------------------|
|               | AAP          | HAP               | TOTAL               | AAP                      | HAP            | TOTAL               |                          |                          |
| Aruba         | —            | —                 | —                   | —                        | —              | —                   | —                        | —                        |
| Australia     | 11,418       | 97                | 11,516              | 11,088                   | 95             | 11,183              | 0.8                      | 18                       |
| Austria       | 13,481       | 54                | 13,535              | 15,850                   | 64             | 15,913              | 3.0                      | 16                       |
| Azerbaijan    | 3,394        | 292               | 3,686               | 10,621                   | 914            | 11,535              | 7.7                      | 4                        |
| Bahamas, The  | 383          | 8                 | 391                 | 433                      | 10             | 442                 | 3.0                      | 12                       |
| Bahrain       | 1,671        | 5                 | 1,676               | 3,334                    | 10             | 3,344               | 4.3                      | 13                       |
| Bangladesh    | 11,173       | 15,365            | 26,538              | 29,808                   | 40,989         | 70,798              | 8.8                      | 18                       |
| Barbados      | 459          | 1                 | 460                 | 412                      | 0              | 413                 | 8.8                      | 16                       |
| Belarus       | 5,480        | 64                | 5,544               | 16,401                   | 193            | 16,593              | 8.8                      | 7                        |
| Belgium       | 19,198       | 35                | 19,233              | 22,706                   | 41             | 22,748              | 3.6                      | 20                       |
| Belize        | 41           | 13                | 54                  | 62                       | 20             | 82                  | 2.9                      | 19                       |
| Benin         | 206          | 898               | 1,105               | 579                      | 2,522          | 3,101               | 7.7                      | 13                       |
| Bermuda       | —            | —                 | —                   | —                        | —              | —                   | —                        | —                        |
| Bhutan        | 94           | 125               | 219                 | 333                      | 441            | 774                 | 8.5                      | 20                       |
| Bolivia       | 1,184        | 716               | 1,901               | 3,030                    | 1,832          | 4,862               | 4.6                      | 10                       |
| Bosnia and Herzegovina | 2,377 | 769 | 3,147 | 6,181 | 2,001 | 8,182 | 15.7 | 20 |
| Botswana      | 716          | 490               | 1,206               | 1,665                    | 1,138          | 2,803               | 6.6                      | 6                        |
| Brazil        | 38,830       | 12,888            | 51,719              | 67,970                   | 22,560         | 90,530              | 2.8                      | 16                       |
| British Virgin Islands | — | — | — | — | — | — | — | — |
| Brunei Darussalam | 137 | 3 | 140 | 285 | 5 | 291 | 1.0 | 19 |
| Bulgaria      | 9,229        | 1,863             | 11,092              | 23,278                   | 4,699          | 27,978              | 16.3                     | 9                        |
| Burkina Faso  | 173          | 1,264             | 1,437               | 509                      | 3,720          | 4,229               | 9.1                      | 11                       |
| Burundi       | 14           | 148               | 163                 | 43                       | 445            | 488                 | 5.4                      | 16                       |
| Cabo Verde    | 100          | 33                | 133                 | 208                      | 67             | 276                 | 6.7                      | 15                       |
| Cambodia      | 440          | 1,829             | 2,268               | 1,223                    | 5,086          | 6,310               | 8.4                      | 13                       |
| Cameroon      | 1,135        | 1,356             | 2,491               | 2,883                    | 3,444          | 6,327               | 6.4                      | 12                       |
| Canada        | 20,022       | 48                | 20,070              | 22,253                   | 54             | 22,306              | 1.2                      | 16                       |
| Cayman Islands | — | — | — | — | — | — | — | — |
| Central African Republic | 23 | 170 | 193 | 48 | 357 | 405 | 8.7 | 4 |
| Chad          | 115          | 850               | 965                 | 267                      | 1,970          | 2,237               | 8.5                      | 11                       |
| Channel Islands | — | — | — | — | — | — | — | — |
| Chile         | 11,102       | 674               | 11,776              | 18,747                   | 1,138          | 19,885              | 4.2                      | 13                       |
| China         | 1,465,524    | 386,116           | 1,851,640           | 2,397,105                | 631,557        | 3,028,662           | 12.9                     | 12                       |
| Colombia      | 9,271        | 1,859             | 11,130              | 22,547                   | 4,521          | 27,069              | 3.4                      | 22                       |
| Comoros       | 10           | 62                | 73                  | 24                       | 144            | 167                 | 6.1                      | 21                       |
| Congo, Dem. Rep. | 382    | 2,006            | 2,388               | 801                      | 4,206          | 5,008               | 5.0                      | 19                       |
| Congo, Rep.   | 279          | 257               | 536                 | 477                      | 439            | 916                 | 5.0                      | 17                       |
| Costa Rica    | 1,435        | 176               | 1,611               | 2,395                    | 294            | 2,689               | 2.6                      | 27                       |

(continued)
TABLE A.3, continued

| ECONOMY              | US$, MILLIONS |  $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|----------------------|---------------|--------------------|---------------------|--------------------------|
|                      | AAP | HAP | TOTAL | AAP | HAP | TOTAL |                     |                          |
| Côte d’Ivoire        | 1,235 | 3,031 | 4,266 | 2,947 | 7,234 | 10,180 | 7.3 | 13 |
| Croatia              | 5,883 | 335 | 6,218 | 11,872 | 677 | 12,549 | 10.3 | 16 |
| Cuba                 | — | — | — | — | — | — | — | — |
| Curacao              | — | — | — | — | — | — | — | — |
| Cyprus               | 1,340 | 3 | 1,342 | 1,984 | 4 | 1,988 | 4.0 | 13 |
| Czech Republic       | 17,422 | 233 | 17,654 | 32,108 | 429 | 32,536 | 7.2 | 17 |
| Denmark              | 8,566 | 15 | 8,581 | 8,567 | 15 | 8,582 | 2.5 | 15 |
| Djibouti             | 131 | 59 | 191 | 221 | 100 | 321 | 5.7 | 17 |
| Dominica             | 28 | 4 | 32 | 43 | 6 | 48 | 5.3 | 19 |
| Dominican Republic   | 3,225 | 815 | 4,040 | 7,469 | 1,888 | 9,357 | 4.5 | 12 |
| Ecuador              | 2,520 | 301 | 2,821 | 4,828 | 576 | 5,404 | 2.6 | 15 |
| Egypt, Arab Rep.     | 25,958 | 23 | 25,981 | 105,299 | 92 | 105,391 | 8.6 | 13 |
| El Salvador          | 767 | 260 | 1,028 | 1,674 | 569 | 2,243 | 3.8 | 20 |
| Equatorial Guinea    | 331 | 74 | 405 | 788 | 176 | 964 | 3.7 | 12 |
| Eritrea              | — | — | — | — | — | — | — | — |
| Estonia              | 437 | 118 | 556 | 717 | 194 | 911 | 1.8 | 13 |
| Eswatini             | 124 | 180 | 304 | 292 | 424 | 716 | 6.9 | 19 |
| Ethiopia             | 512 | 4,008 | 4,519 | 1,379 | 10,804 | 12,183 | 4.7 | 13 |
| Faroe Islands        | — | — | — | — | — | — | — | — |
| Fiji                 | 206 | 197 | 403 | 479 | 457 | 935 | 7.3 | 16 |
| Finland              | 2,229 | 16 | 2,244 | 2,349 | 17 | 2,366 | 0.8 | 19 |
| France               | 61,275 | 189 | 61,464 | 74,805 | 231 | 75,036 | 2.3 | 15 |
| French Polynesia     | — | — | — | — | — | — | — | — |
| Gabon                | 607 | 52 | 659 | 1,225 | 105 | 1,330 | 4.0 | 10 |
| Gambia, The          | 26 | 82 | 108 | 79 | 252 | 331 | 6.1 | 18 |
| Georgia              | 1,416 | 750 | 2,166 | 4,644 | 2,459 | 7,103 | 12.2 | 10 |
| Germany              | 146,383 | 178 | 146,561 | 177,374 | 216 | 177,590 | 3.8 | 19 |
| Ghana                | 2,254 | 2,050 | 4,304 | 5,769 | 5,248 | 11,017 | 6.4 | 14 |
| Gibraltar            | — | — | — | — | — | — | — | — |
| Greece               | 13,393 | 100 | 13,493 | 21,475 | 161 | 21,636 | 6.4 | 11 |
| Greenland            | — | — | — | — | — | — | — | — |
| Grenada              | 60 | 3 | 63 | 98 | 5 | 103 | 5.1 | 16 |
| Guam                 | — | — | — | — | — | — | — | — |
| Guatemala            | 1,555 | 2,257 | 3,811 | 3,027 | 4,394 | 7,421 | 5.0 | 15 |
| Guinea               | 174 | 990 | 1,165 | 438 | 2,485 | 2,923 | 8.6 | 9 |
| Guinea-Bissau        | 16 | 76 | 93 | 48 | 226 | 275 | 6.9 | 13 |
| Guyana               | 213 | 29 | 242 | 394 | 53 | 447 | 5.7 | 16 |
| Haiti                | 89 | 597 | 686 | 212 | 1,425 | 1,637 | 8.1 | 13 |
| Honduras             | 393 | 866 | 1,259 | 910 | 2,007 | 2,917 | 5.0 | 17 |

(continued)
| ECONOMY                         | US$, MILLIONS | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|--------------------------------|---------------|-------------------|---------------------|-------------------------|
|                                | AAP           | HAP               | TOTAL               | AAP                     | HAP                  | TOTAL               |                              |
| Hong Kong SAR, China           | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Hungary                        | 13,892        | 2,793             | 16,685              | 28,650                  | 5,760                | 34,410              | 10.4                          | 14                          |
| Iceland                        | 123           | 1                 | 124                 | 111                     | 1                    | 111                 | 0.5                           | 21                          |
| India                          | 184,291       | 121,397           | 305,689             | 616,091                 | 405,835              | 1,021,926           | 10.6                          | 19                          |
| Indonesia                       | 41,396        | 32,602            | 73,998              | 123,137                 | 96,979               | 220,116             | 6.6                           | 15                          |
| Iran, Islamic Rep.             | 23,610        | 57                | 23,667              | 62,132                  | 151                 | 62,283              | 5.0                           | 13                          |
| Iraq                           | 14,331        | 39                | 14,369              | 27,270                  | 74                   | 27,344              | 6.1                           | 14                          |
| Ireland                        | 4,353         | 18                | 4,370               | 4,883                   | 20                   | 4,903               | 1.1                           | 16                          |
| Isle of Man                    | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Israel                         | 12,096        | 22                | 12,117              | 11,694                  | 21                   | 11,716              | 3.1                           | 17                          |
| Italy                          | 98,553        | 556               | 99,109              | 131,238                 | 741                  | 131,978             | 5.0                           | 17                          |
| Jamaica                        | 517           | 113               | 630                 | 941                     | 206                  | 1,147               | 3.8                           | 19                          |
| Japan                          | 194,886       | 520               | 195,406             | 209,359                 | 558                  | 209,917             | 3.8                           | 18                          |
| Jordan                         | 1,596         | 1                 | 1,597               | 3,803                   | 2                    | 3,805               | 3.7                           | 33                          |
| Kazakhstan                     | 10,497        | 1,525             | 12,022              | 29,604                  | 4,302                | 33,905              | 6.7                           | 9                           |
| Kenya                          | 769           | 3,148             | 3,917               | 1,910                   | 7,814                | 9,724               | 4.1                           | 13                          |
| Kiribati                        | 2             | 15                | 17                  | 3                       | 22                   | 25                  | 8.9                           | 13                          |
| Korea, Dem. People’s Rep.      | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Korea, Rep.                    | 84,385        | 64                | 84,449              | 114,318                 | 87                   | 114,405             | 5.1                           | 17                          |
| Kosovo                         | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Kuwait                         | 5,306         | 2                 | 5,309               | 8,599                   | 4                    | 8,603               | 3.9                           | 11                          |
| Kyrgyz Republic                | 275           | 157               | 432                 | 1,147                   | 656                  | 1,804               | 5.1                           | 14                          |
| Lao PDR                        | 297           | 1,374             | 1,671               | 954                     | 4,419                | 5,373               | 9.2                           | 11                          |
| Latvia                         | 2,311         | 226               | 2,536               | 4,172                   | 407                  | 4,579               | 7.4                           | 8                           |
| Lebanon                        | 2,735         | 9                 | 2,744               | 5,385                   | 18                   | 5,403               | 5.1                           | 18                          |
| Lesotho                        | 69            | 138               | 207                 | 172                     | 343                  | 515                 | 8.4                           | 14                          |
| Liberia                        | 26            | 111               | 138                 | 63                      | 266                  | 329                 | 4.5                           | 17                          |
| Libya                          | 2,827         | 8                 | 2,835               | 5,815                   | 16                   | 5,831               | 5.4                           | 20                          |
| Liechtenstein                  | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Lithuania                      | 2,702         | 138               | 2,840               | 5,307                   | 271                  | 5,578               | 5.2                           | 7                           |
| Luxembourg                     | 1,140         | 3                 | 1,143               | 1,206                   | 3                    | 1,209               | 1.6                           | 25                          |
| Macao SAR, China               | —             | —                 | —                   | —                       | —                    | —                   | —                             |
| Madagascar                    | 75            | 717               | 792                 | 245                     | 2,355                | 2,600               | 5.6                           | 12                          |
| Malawi                         | 32            | 311               | 343                 | 87                      | 833                  | 920                 | 4.5                           | 16                          |
| Malaysia                       | 13,977        | 168               | 14,145              | 36,153                  | 434                  | 36,587              | 3.9                           | 15                          |
| Maldives                        | 59            | 28                | 87                  | 107                     | 52                   | 159                 | 1.5                           | 19                          |
| Mali                           | 196           | 1,396             | 1,592               | 534                     | 3,798                | 4,333               | 9.1                           | 13                          |
| Malta                          | 512           | 1                 | 513                 | 794                     | 2                    | 797                 | 3.5                           | 16                          |

(continued)
| ECONOMY       | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|--------------|------------------|---------------------|--------------------------|
|              | AAP HAP TOTAL    |                     |                          |
| Marshall Islands | 199 178 377     | 642 575 1,216       | 5.0 18                   |
| Mauritania    | 764 19 783      | 1,632 41 1,674     | 5.5 16                   |
| Mexico        | 39,513 10,875 50,388 | 81,769 22,504 104,273 | 4.0 16                   |
| Micronesia, Fed. Sts. | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Moldova       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Monaco        | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Mongolia      | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Montenegro    | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Morocco       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Mozambique    | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Myanmar       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Namibia       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Nauru         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Nepal         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Netherlands   | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| New Caledonia | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| New Zealand   | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Nicaragua     | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Niger         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Nigeria       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| North Macedonia | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Northern Mariana Islands | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Norway        | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Oman          | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Pakistan      | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Palau         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Panama        | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Papua New Guinea | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Paraguay      | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Peru          | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Philippines   | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Poland        | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Portugal      | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Puerto Rico (US) | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Qatar         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Romania       | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Russian Federation | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Rwanda        | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| Samoa         | 940 136 1,076 | 2,837 410 3,246 | 9.0 16                   |
| ECONOMY                  | US$, MILLIONS | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|-------------------------|---------------|-------------------|---------------------|--------------------------|
|                         | AAP | HAP | TOTAL | AAP | HAP | TOTAL |                         |
| San Marino              | —   | —   | —     | —   | —   | —     | —                       |
| São Tomé and Príncipe   | 9   | 17  | 26    | 20  | 34  | 54    | 6.1  | 29                      |
| Saudi Arabia            | 45,216 | 111 | 45,327 | 95,568 | 235 | 95,803 | 5.7  | 11                      |
| Senegal                 | 381  | 1,046 | 1,427 | 932  | 2,555 | 3,487 | 6.1  | 18                      |
| Serbia                  | 8,172 | 1,544 | 9,716 | 20,964 | 3,961 | 24,925 | 18.9 | 13                      |
| Seychelles              | 80   | 1    | 81    | 140  | 2    | 141   | 4.8  | 18                      |
| Sierra Leone            | 50   | 257  | 308   | 179  | 913  | 1,092 | 7.8  | 13                      |
| Singapore               | 8,976 | 16  | 8,992 | 13,949 | 25  | 13,974 | 2.4  | 18                      |
| Sint Maarten (Dutch part) | —   | —   | —     | —   | —   | —     | —                       |
| Slovak Republic         | 7,944 | 81  | 8,025 | 14,047 | 143 | 14,191 | 7.6  | 11                      |
| Slovenia                | 2,675 | 216 | 2,891 | 4,226 | 341 | 4,567 | 5.4  | 20                      |
| Solomon Islands         | 15   | 170  | 185   | 18   | 197  | 214   | 13.0 | 9                       |
| Somalia                 | —    | —    | —     | —    | —    | —     | —                       |
| South Africa            | 15,298 | 2,953 | 18,251 | 33,135 | 6,397 | 39,532 | 5.2  | 19                      |
| South Sudan             | 32,814 | 755 | 33,569 | 46,776 | 1,076 | 47,852 | 2.4  | 19                      |
| Spain                   | 3,380 | 3,401 | 6,781 | 11,947 | 12,023 | 23,971 | 8.1  | 33                      |
| Sri Lanka               | 28   | 2    | 30    | 38   | 3    | 42    | 2.9  | 15                      |
| St. Kitts and Nevis     | 101  | 107  | 107   | 8    | 148  | 5.0   | 19   | —                       |
| St. Lucia               | —    | —    | —     | —    | —    | —     | —   | —                       |
| St. Martin (French part)| —    | —    | —     | —    | —    | —     | —   | —                       |
| St. Vincent and the Grenadines | 46   | 3    | 50    | 81   | 6    | 86    | 6.0  | 16                      |
| Sudan                   | 613  | 434  | 1,047 | 5,726 | 4,050 | 9,776 | 5.5  | 21                      |
| Suriname                | 194  | 36   | 231   | 482  | 90   | 572   | 5.8  | 19                      |
| Sweden                  | 3,823 | 19  | 3,842 | 4,135 | 20   | 4,155 | 0.7  | 17                      |
| Switzerland             | 12,661 | 15  | 12,676 | 10,962 | 13  | 10,975 | 1.8  | 19                      |
| Syrian Arab Republic    | —    | —    | —     | —    | —    | —     | —   | —                       |
| Tajikistan              | 307  | 173  | 480   | 1,242 | 698  | 1,941 | 5.9  | 14                      |
| Tanzania                | 473  | 3,007 | 3,480 | 1,168 | 7,424 | 8,592 | 5.3  | 10                      |
| Thailand                | 26,260 | 6,581 | 32,841 | 64,667 | 16,207 | 80,874 | 6.0  | 14                      |
| Timor-Leste             | 20   | 102  | 122   | 51   | 256  | 308   | 7.3  | 17                      |
| Togo                    | 76   | 245  | 320   | 186  | 602  | 788   | 5.9  | 22                      |
| Tonga                   | 8    | 13   | 21    | 12   | 19   | 31    | 4.5  | 21                      |
| Trinidad and Tobago     | 1,878 | 3    | 1,881 | 2,964 | 5    | 2,969 | 7.8  | 10                      |
| Tunisia                 | 2,530 | 8    | 2,538 | 8,543 | 28   | 8,571 | 6.5  | 22                      |
| Turkey                  | 43,168 | 267 | 43,435 | 133,074 | 822 | 133,896 | 5.8  | 15                      |
| Turkmenistan            | 2,408 | 4    | 2,412 | 5,435 | 9    | 5,443 | 5.8  | 9                       |

(continued)
### TABLE A.3, continued

| ECONOMY                  | US$, MILLIONS | $ (PPP), MILLIONS | % OF GDP EQUIVALENT | MORBIDITY COST SHARE (%) |
|--------------------------|---------------|-------------------|----------------------|--------------------------|
|                          | AAP | HAP | TOTAL | AAP | HAP | TOTAL |                           |                          |
| Turks and Caicos Islands | —   | —   | —     | —   | —   | —     | —                       | —                        |
| Tuvalu                   | 1   | 1   | 1     | 1   | 1   | 1     | 2.6                     | 15                       |
| Uganda                   | 246 | 1,245 | 1,491 | 721 | 3,640 | 4,361 | 4.3                     | 15                       |
| Ukraine                  | 14,283 | 935 | 15,218 | 52,077 | 3,409 | 55,486 | 9.4                     | 7                        |
| United Arab Emirates     | 14,748 | 1 | 14,748 | 23,916 | 1 | 23,917 | 3.5                     | 13                       |
| United Kingdom           | 73,528 | 65 | 73,593 | 84,669 | 74 | 84,744 | 2.6                     | 19                       |
| United States            | 371,321 | 1,256 | 372,576 | 371,321 | 1,256 | 372,576 | 1.7                     | 22                       |
| Uruguay                  | 1,473 | 107 | 1,580 | 2,042 | 149 | 2,191 | 2.8                     | 8                        |
| Uzbekistan               | 3,782 | 458 | 4,241 | 15,984 | 1,937 | 17,921 | 7.3                     | 9                        |
| Vanuatu                  | 12 | 82 | 95 | 13 | 88 | 101 | 10.3 | 14 |
| Venezuela, RB            | — | — | — | — | — | — | — | — |
| Vietnam                  | 8,869 | 8,149 | 17,017 | 27,352 | 25,132 | 52,485 | 6.5 | 13 |
| Virgin Islands (US)      | — | — | — | — | — | — | — | — |
| West Bank and Gaza       | 563 | 10 | 573 | 1,056 | 19 | 1,074 | 3.8 | 27 |
| Yemen, Rep.              | — | — | — | — | — | — | — | — |
| Zambia                   | 279 | 849 | 1,128 | 783 | 2,382 | 3,165 | 4.9 | 12 |
| Zimbabwe                 | 271 | 1,060 | 1,331 | 547 | 2,138 | 2,685 | 6.2 | 13 |

Sources: Annual cost is estimated using the methodologies in appendixes B–D.

Note: HAP = household air pollution; AAP = ambient air pollution; — = not available. Cost of health damages of PM$_{2.5}$ is not estimated for some countries and territories due to lack of estimate of deaths from PM$_{2.5}$ in the GBD 2019 study or absence of GDP per capita (PPP) in the World Development Indicators database.
Particulate matter, and especially fine particulates (PM$_{2.5}$), is the air pollutant that globally is associated with the largest health damages. Health damages of PM$_{2.5}$ exposure include both premature mortality and morbidity. The most substantial health damages of PM$_{2.5}$ are cardiovascular disease, COPD, lung cancer, LRI, type 2 diabetes, and neonatal disorders (GBD 2019 study). The methodologies to estimate these health damages have evolved as the body of research evidence has increased.

Two decades ago, Pope et al. (2002) found elevated risk of cardiopulmonary (CP) and lung cancer mortality from long-term exposure to ambient PM$_{2.5}$ in a study of a large population of adults 30 or more years of age in the United States. CP mortality includes mortality from respiratory infections, cardiovascular disease, and chronic respiratory disease. The World Health Organization used the study by Pope et al. when estimating global mortality from outdoor air pollution (Ezzati et al. 2004; WHO 2009). A decade ago, research suggested that the marginal increase in relative risk of mortality from PM$_{2.5}$ declines with increasing concentrations of PM$_{2.5}$ (Pope et al. 2009, 2011). Pope et al. (2009, 2011) derive a shape of the PM$_{2.5}$ exposure-response curve based on studies of mortality from active cigarette smoking, secondhand cigarette smoking (SHS), and outdoor PM$_{2.5}$ air pollution.

**AN INTEGRATED EXPOSURE-RESPONSE FUNCTION**

The GBD 2010–19 studies take Pope et al. (2009, 2011) some steps further by deriving an integrated exposure-response (IER) function that relates relative risk (RR) of various disease outcomes to the level of exposure to fine particulate matter pollution (PM$_{2.5}$) both in the ambient and household environments (Burnett et al. 2014; Shin et al. 2013).

The parameter values of the IER risk function in the GBD 2019 study are derived from studies of health outcomes associated with long-term exposure to ambient particulate-matter pollution, secondhand tobacco smoking, and household air pollution from solid cooking fuels (GBD 2019 Risk Factors Collaborators 2020, Supplement). This provides a risk function that can be applied to a wide
range of ambient PM$_{2.5}$ concentrations around the world as well as to high household air-pollution levels of PM$_{2.5}$ from combustion of solid fuels.

The disease outcomes assessed using the IER function are IHD, stroke, lung cancer, COPD, LRI, and type 2 diabetes. The relative risks for IHD and stroke are age-specific with five-year age intervals from 25 years of age, while singular age-group risk functions are applied for lung cancer, COPD, LRI, and type 2 diabetes. Estimation of neonatal disorders from PM$_{2.5}$ exposure follows a somewhat different approach (GBD 2019 Risk Factors Collaborators 2020, Supplement).

The method for estimating the health effects of PM$_{2.5}$ exposure is explained in GBD 2019 Risk Factors Collaborators (2020). The GBD 2019 first estimates the total joint health effects of ambient PM$_{2.5}$ and household air pollution PM$_{2.5}$ from household use of solid fuels for cooking, and then apportions the health effects to ambient PM$_{2.5}$ and household air pollution PM$_{2.5}$. The total annual health effects of annual PM$_{2.5}$ exposure are estimated as follows:

\[
B = D \times PAF_{PM}
\]  

where \(B\) is annual number cases of deaths or illness from PM$_{2.5}$ among the exposed population, \(D\) is annual baseline number of cases of deaths or illness among this population, and \(PAF_{PM}\) (population-attributable fraction) is the fraction of baseline cases that is attributable to PM$_{2.5}$ exposure among this population. \(PAF_{PM}\) and \(B\) are calculated for each type of health effect covered by the GBD 2019. Annual baseline cases, \(D\), for each type of health effect for Mexico is taken from the GBD 2019.

The population-attributable fraction (PAF) for each health effect included in the GBD 2019 is calculated as follows:

\[
PAF_{PM} = \frac{P_A (RR_A - 1) + P_H (RR_H - 1)}{P_A (RR_A - 1) + P_H (RR_H - 1) + 1}
\]

where \(P_A\) is the share of the population that is exposed only to ambient PM$_{2.5}$ (that is, the population not using solid fuels for cooking), \(P_H\) is the share of the population that uses solid fuels for cooking, \(RR_A\) is the relative risk of health effects from ambient PM$_{2.5}$ among the population exposed only to ambient PM$_{2.5}$, and \(RR_H\) is the relative risk of health effects from PM$_{2.5}$ among the population exposed to household air pollution PM$_{2.5}$. As the whole population is exposed to at least some level of ambient PM$_{2.5}$, then \(P_A + P_H = 1\).

The size of the relative risks of health effects among the population only exposed to ambient PM$_{2.5}$ is:

\[
RR_A = \frac{RR(AAP)}{RR(TMREL)}
\]

where \(RR(AAP)\) is the relative risk of health effects at annual PM$_{2.5} = AAP$ and \(RR(TMREL)\) is the relative risk at PM$_{2.5} = TMREL$ (theoretical minimum-risk exposure level). These relative risks are reported by the GBD 2019 for each type of health effect for a range of annual PM$_{2.5}$ from 0.01 to 2,500 $\mu g/m^3$. TMREL may be chosen within the range of 2.4–5.9 $\mu g/m^3$ that is used by the GBD 2019 or may be chosen to be larger or smaller. TMREL may also be chosen as zero, in which case \(RR(TMREL) = 1\).

The size of the relative risks of health effects among the population exposed to household air pollution PM$_{2.5}$ is:

\[
RR_H = \frac{RR(HAP + AAP)}{RR(TMREL)}
\]
where $RR(HAP + AAP)$ is the relative risk at exposure level $PM_{2.5} = HAP + AAP$. This exposure level includes both exposure to $PM_{2.5}$ from the use of solid fuels (HAP) and exposure to ambient $PM_{2.5}$ (AAP). HAP + AAP is a so-called personal-exposure level that is typically measured over a 24- to 48-hour period by a measurement device attached to a person (and assumed to reflect long-term exposure). The exposure level is generally different for each household member due to differences in activity patterns. Most studies measuring personal exposure have been for adult women, who usually are exposed to the highest level of $PM_{2.5}$ in households cooking with solid fuels. The GBD 2019 uses a fraction of the adult-women exposure level equal to 0.64 for adult men and 0.85 for children. Because of these differences in exposure levels, PAF is calculated separately for adult females, adult males, and children under the age of five years.

The GBD 2019 then apportions the $PAF_{PM}$ to ambient and household air pollution as follows:

$$ PAF_{AAP} = \frac{AAP}{AAP + P_H HAP} \times PAF_{PM} \quad \text{(B.5)} $$

$$ PAF_{HAP} = \frac{P_H HAP}{AAP + P_H HAP} \times PAF_{PM} \quad \text{(B.6)} $$

where $PAF_{AAP}$ and $PAF_{HAP}$ are the population-attributable fractions of deaths and illnesses due to ambient $PM_{2.5}$ and household air pollution $PM_{2.5}$ from the use of solid fuels, respectively; $AAP$ is annual ambient $PM_{2.5}$; $HAP$ is personal $PM_{2.5}$ exposure from the use of solid fuels; and $P_H$ is the share of the population using solid fuels for cooking.

This approach to apportioning the health effects of $PM_{2.5}$ ensures that

$$ PAF_{PM} = PAF_{AAP} + PAF_{HAP} \quad \text{(B.7)} $$

The GBD 2019 estimates $PAF_{PM}$, $PAF_{AAP}$, and $PAF_{HAP}$ at small geographic units over which health effects are summed to the national, state, province, or city level. Each geographic area is a 0.1° x 0.1° grid (corresponding to 11 km x 11 km at the equator).

However, equations B.5–B.6 are less accurate if the $PAFs$ are estimated for large geographic units with a single population-weighted $PM_{2.5}$ exposure level applied to each unit. In this case, an alternative approach to apportioning the health effects uses the following three steps:

**Step 1:**

$$ PAF_{AAP}^p = \frac{P_A (RR_A - 1)}{P_A (RR_A - 1) + 1} \quad \text{(B.8)} $$

$$ PAF_{HAP}^p = \frac{P_H (RR_H - 1)}{P_H (RR_H - 1) + 1} \quad \text{(B.9)} $$

which are “partial” $PAFs$ for the population exposed only to ambient $PM_{2.5}$ and the population exposed to household air pollution (the population using solid fuels). $RR_H$ in the “partial” $PAF$ for household air pollution is for exposure level $HAP + AAP$. The next step involves separating the effects of $AAP$ and $HAP$ in equation B.9 and adding the effects to the $PAFs$ in equations B.8–B.9.
Step 2:

\[
PAF^F_{AAP} = PAF^p_{AAP} + PAF^p_{HAP} \times (AAP + HAP) \quad (B.10)
\]

\[
PAF^F_{HAP} = PAF^p_{HAP} \times HAP / (AAP + HAP) \quad (B.11)
\]

The result in step 2 is such that

\[
PAF^F_{AAP} + PAF^F_{HAP} > PAF_{PM} \quad (B.12)
\]

The final step involves adjusting the two PAFs downwards so that the sum is equal to \( PAF_{PM} \).

Step 3:

\[
PAF^F_{AAP} = \frac{PAF^F_{AAP}}{PAF^F_{AAP} + PAF^F_{HAP}} \times PAF_{PM} \quad (B.13)
\]

\[
PAF^F_{HAP} = \frac{PAF^F_{HAP}}{PAF^F_{AAP} + PAF^F_{HAP}} \times PAF_{PM} \quad (B.14)
\]

The two approaches give identical PAFs for \( P_{H} = 0 \) and \( P_{H} = 1.0 \). However, for \( 0 < P_{H} < 1 \), the GBD approach results in a smaller PAF for ambient PM\(_{2.5}\) and a larger PAF for household air pollution PM\(_{2.5}\) than the alternative approach described in steps 1–3. The difference can be quite large when PM\(_{2.5}\) exposure from household air pollution is substantially higher than from ambient PM\(_{2.5}\), and increases as \( P_{H} \) approaches 0.5 from 0 and from 1.0. Therefore, the approach in steps 1–3 is recommended if estimation of health effects of air pollution is undertaken with exposure data reflecting relatively large geographic units, such as city by city, state by state, province by province, or urban and rural.

NOTES

1. Supplementary Appendix 1 (pp. 78–115).
2. www.healthdata.org.
3. http://ghdx.healthdata.org/record/ihme-data/global-burden-disease-study-2019-gbd-2019-particulate-matter-risk-curves.

REFERENCES

Burnett, Richard T., C. Arden Pope III, Majid Ezzati, Casey Olives, Stephen S. Lim, Sumi Mehta, Hwahsin H. Shin, Gitanjali Singh, Bryan Hubbell, Michael Brauer, H. Ross Anderson, Kirk R. Smith, John R. Balmes, Nigel G. Bruce, Haidong Kan, Francine Laden, Annette Prüss-Ustün, Michelle C. Turner, Susan M. Gapstur, W. Ryan Diver, and Aaron Cohen. 2014. “An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure.” Environmental Health Perspectives: 122 (4): 397–403.

Ezzati, M., A. D. Lopez, A. A. Rodgers, and C. J. Murray. 2004. Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. Geneva: WHO.
GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” *Lancet* 396: 1223–49.

Pope, C. A., III, R. T. Burnett, D. Krewski, M. Jerrett, Y. Shi, E. E. Calle, and M. J. Thun. 2009. “Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke: Shape of the Exposure-Response Relationship.” *Circulation* 120: 941–48.

Pope, C. A., III, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. Thurston. 2002. “Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution.” *Journal of the American Medical Association* 287: 1132–41.

Pope, C. A., III, R. T. Burnett, M. Turner, A. Cohen, D. Krewski, M. Jerrett, S. M. Gapstur; and M. J. Thun. 2011. “Lung Cancer and Cardiovascular Disease Mortality Associated with Ambient Air Pollution and Cigarette Smoke: Shape of the Exposure-Response Relationships.” *Environmental Health Perspectives* 119 (11): 1616–21.

Shin, H., A. Cohen, C. A. Pope III, M. Ezzati, S. S. Lim, B. Hubbel, and R. T. Burnett. 2013. “Critical Issues in Combining Disparate Sources of Information to Estimate the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure.” Working Paper prepared for Harvard Center for Risk Analysis “Methods for Research Synthesis: A Cross-Disciplinary Workshop,” October 3.

WHO (World Health Organization). 2009. *Estimated Deaths and DALYs Attributable to Selected Environmental Risk Factors, by WHO Member States, 2004*. http://www.who.int/quantifying_ehimpacts/national/countryprofile/intro/en/index.htm.
The predominant measure of the welfare cost of premature death used by economists is the value of statistical life (VSL). VSL is based on valuation of mortality risk. Everyone in society is constantly facing a certain risk of dying. Examples of such risks are occupational fatality risk, risk of traffic accident fatality, and environmental mortality risks. It has been observed that individuals adjust their behavior and decisions in relation to such risks. For instance, individuals demand a higher wage (a wage premium) for a job that involves a higher occupational risk of fatal accident than in other jobs, individuals may purchase safety equipment to reduce the risk of death, and/or individuals and families may be willing to pay a premium or higher rent for properties (land and buildings) in a cleaner and less polluted neighborhood or city.

Through the observation of individuals’ choices and willingness to pay for reducing mortality risk (or minimum amounts that individuals require to accept a higher mortality risk), it is possible to estimate the value to society of reducing mortality risk, or, equivalently, measure the welfare cost of a particular mortality risk. For instance, it may be observed that a certain health hazard has a mortality risk of 2.5/10,000. This means that 2.5 individuals die from this hazard for every 10,000 individuals exposed. If each individual on average is willing to pay US$40 for eliminating this mortality risk, then every 10,000 individuals are collectively willing to pay US$400,000. Dividing this amount by the risk gives the VSL of US$160,000. Mathematically it can be expressed as follows:

\[ VSL = \frac{WTP_{\text{Ave}}}{R} \]

where \( WTP_{\text{Ave}} \) is the average willingness to pay per individual for a mortality-risk reduction of magnitude \( R \). In the illustration above, \( R = 2.5/10,000 \) (or \( R = 0.00025 \)) and \( WTP_{\text{Ave}} = \text{US$40} \). Thus, if 10 individuals die from the health risk illustrated above, the cost to society is \( 10^* \text{VSL} = 10^* \text{US$0.16 million} = \text{US$1.6 million} \).

The main approaches to estimating VSL are through revealed preferences and stated preferences of people’s WTP for a reduction in mortality risk or their willingness to accept (WTA) an increase in mortality risk. Most of the studies of revealed preferences are hedonic wage studies, which estimate labor market wage differentials associated with differences in occupational mortality risk. Most of the stated-preference studies rely on contingent valuation methods (CVM), which in various forms ask individuals about their WTP for mortality-risk reduction.

APPENDIX C

Valuation of Premature Mortality
Studies of WTP for a reduction in risk of mortality have been carried out in numerous countries. A commonly used approach to estimate VSL in a specific country without such studies is therefore to use a benefit transfer (BT) based on meta-analyses of WTP studies from other countries. Several meta-analyses have been conducted in the last two decades. Meta-analyses assess characteristics that determine VSL, such as household income, size of risk reduction, other individual and household characteristics, and often characteristics of the methodologies used in the original WTP studies.

Most of the meta-analyses of VSL are entirely or predominantly based on hedonic wage studies. However, a meta-analysis prepared for the OECD is exclusively based on stated-preference studies, arguably of greater relevance for valuation of mortality risk from environmental factors than hedonic wage studies (Lindhjem et al. 2011; Navrud and Lindhjem 2010; OECD 2012). These stated-preference studies are from a database of more than 1,000 VSL estimates from multiple studies in over 30 countries, including in developing countries (www.oecd.org/env/policies/VSL).

Narain and Sall (2016) present a benefit-transfer methodology for valuing mortality from environmental health risks, drawing on the empirical literature of VSL, especially OECD (2012). The methodology is applied in the publication by the World Bank and IHME (2016) on the global cost of air pollution, and in the recent publication by World Bank (2020) on the global health cost of ambient air pollution. The proposed benefit-transfer function is:

\[
VSL_{c,n} = VSL_{OECD} \left( \frac{Y_{c,n} \cdot 1.2}{Y_{OECD}} \right)
\]

where \(VSL_{c,n}\) is the estimated VSL for country \(c\) in year \(n\), \(VSL_{OECD}\) is the average base VSL in the sample of OECD countries with VSL studies ($3.83 million), \(Y_{c,n}\) is GDP per capita in country \(c\) in year \(n\), \(Y_{OECD}\) is the average GDP per capita for the sample of OECD countries ($37,000), and \(\varepsilon\) is the income elasticity of 1.2 for LMICs and 0.8 for high-income countries. All values are in PPP prices. For VSL in US dollars, \(VSL_{c,n}\) is therefore multiplied by the ratio of PPP conversion factor to nominal exchange rates, available in the World Development Indicators from the World Bank.

REFERENCES

Lindhjem, H., S. Navrud, N. A. Braathen, and V. Biausque. 2011. “Valuing Mortality Risk Reductions from Environmental, Transport, and Health Policies: A Global Meta-Analysis of Stated Preference Studies.” Risk Analysis 31 (9): 1381–407.

Narain, U., and C. Sall. 2016. Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions. A World Bank Study. Washington, DC: World Bank.

Navrud, S., and H. Lindhjem. 2010. Meta-Analysis of Stated Preference VSL Studies: Further Model Sensitivity and Benefit Transfer Issues. ENV/EPOC/WPNEP(2010)10/FINAL. Environment Directorate. Paris: OECD.

OECD (Organisation for Economic Co-operation and Development). 2012. Mortality Risk Valuation in Environment, Health, and Transport Policies. Paris: OECD.

World Bank. 2020. “The Global Health Cost of Ambient PM\(_{2.5}\) Air Pollution.” World Bank, Washington, DC.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. Washington, DC: World Bank.
Two valuation techniques are commonly used to estimate the cost of morbidity or illness. The cost-of-illness (COI) approach includes cost of medical treatment and value of income and time lost to illness. The second approach equates cost of illness to individuals’ WTP for avoiding an episode of illness. Therefore, the latter includes the welfare cost of pain and suffering from illness.

Studies in many countries have found that individuals’ WTP to avoid an episode of an acute illness is generally much higher than the cost of treatment and value of income and time losses (Alberini and Krupnick 2000; Cropper and Oates 1992; Dickie and Gerking 2002; Wilson 2003).

The OECD, in its report on the global economic consequences of outdoor air pollution, includes the cost of both mortality and morbidity (OECD 2016). Mortality is valued using VSL, and the cost of morbidity is estimated both in terms of

- Market impacts or COI (reduced labor productivity and increased health expenditures associated with bronchitis, asthma, hospital admissions, and restricted activity days from illness); and
- Nonmarket impacts (welfare cost of pain and suffering from illness).

Globally, the OECD estimated the cost of market impacts or COI to be about 0.2 percent of GDP or equivalent to 4 percent of the cost of mortality. Expressed in terms of welfare, using the equivalent variation of income, the cost was 0.4 percent of GDP or 8 percent of the cost of mortality. The nonmarket impacts or welfare cost was equivalent to 0.5 percent of GDP or 9 percent of mortality cost. Thus, the total cost of morbidity was estimated at 0.7 to 0.9 percent of GDP or 13 to 17 percent of the cost of mortality according to the OECD report.

The morbidity cost relative to mortality cost may now be expected to be higher than estimated in OECD (2016), since GBD 2019 includes type 2 diabetes as an effect of PM_{2.5} exposure. YLDs from type 2 diabetes constitute as much as 31 percent of YLDs from PM_{2.5} exposure in 2019.

Estimating the cost of morbidity requires much more data—and less accessible data, including baseline health data—than estimating the cost of mortality.
Therefore, a simplified approach is applied in this report using the following steps:

- YLDs from PM$_{2.5}$ exposure from the GBD 2019 study are converted to days of illness by applying the disability weights in the GBD studies.
- The cost of a day of illness is then approximated as a fraction of the average daily wage rates to reflect income losses from illness, health expenditures, time losses, and the welfare costs of pain and suffering.
- The cost of a day of illness is also applied to individuals without income because illness prevents most of these individuals from undertaking household work and other activities with a social value, as well as involves all the non-income impacts of illness.

The cost of morbidity is thus estimated as follows. First, annual disease days (M) in country, $k$, are calculated as:

$$ M_k = \sum_{i} M_i = \sum_{i} (YLD_{ik} * 365 / d_{ik}) $$  \hspace{1cm} (D.1)

where $YLD_{ik}$ is years lost to disease, $i$, from exposure to PM$_{2.5}$, and $d_{ik}$ is the disability weight for disease, $i$, in country, $k$. The disability weight is from the GBD 2019 for each of seven diseases associated with PM$_{2.5}$ exposure.

The disability weight is a measure used in GBD to calculate YLDs from days of illness, disease, or injury. The weighted average global disability weights for the seven diseases associated with exposure to PM$_{2.5}$ range from 0.027 for ischemic heart disease (IHD) to 0.175 for stroke (table D.1).

The cost of a day lived with disease, $i$, or a disease day, in country, $k$, is thus:

$$ c_{ik} = \frac{w_k}{D} \frac{d_{ik}}{D} $$  \hspace{1cm} (D.2)

where $w_k$ and $d_{ik}$ are average daily wage rate and disability weight for disease, $i$, in country, $k$, and $D$ is a disability weight that corresponds to a severity of disease for which the cost of a disease day is assumed equal to the average wage rate. $D$ is here set at 0.4. This is a disability weight (DW) associated with severely restricted work and leisure activity from disease and substantial medical cost, for example, severe COPD (DW = 0.41), distance-vision blindness (DW = 0.19) and stage 5 chronic kidney disease (DW = 0.57) due to diabetes, and stroke with severity level 3 (DW = 0.32) and 4 (DW = 0.55).

### TABLE D.1 Disability weights associated with PM$_{2.5}$ Air pollution

| DISEASE                              | AVERAGE DISABILITY WEIGHT |
|--------------------------------------|---------------------------|
| Chronic obstructive pulmonary disease (COPD) | 0.093                     |
| Type 2 diabetes                      | 0.080                     |
| Ischemic heart disease (IHD)         | 0.027                     |
| Lower respiratory infections (LRI)   | 0.060                     |
| Stroke                              | 0.175                     |
| Lung cancer (LC)                     | 0.169                     |
| Cataracts                           | 0.069                     |

Source: Based on data from IHME, GBD 2019 study.
Cost of morbidity \( (C) \) in country, \( k \), is calculated as follows:

\[
C_k = \sum_{j=1}^{n} (c_{ki} M_k)
\]  
(D.3)

Average daily wage rate is estimated as follows:

\[
w_k = \frac{GDP_k}{L_k / 250 * s_k}
\]  
(D.4)

where \( GDP \) is the country’s total GDP, \( L \) is total labor force, \( s \) is labor compensation share of GDP, and annual working days is averaging 250. \( GDP \) and \( L \) are from the World Development Indicators (World Bank) and \( s \) is from Penn World Table, version 9.

REFERENCES

Alberini, A., and A. Krupnick. 2000. “Cost-of-Illness and Willingness-to-Pay Estimates of the Benefits of Improved Air Quality: Evidence from Taiwan.” Land Economics 76: 37–53.

Cropper, M., and W. Oates. 1992. “Environmental Economics: A Survey.” Journal of Economic Literature 30: 675–740.

Dickie, M., and S. Gerking. 2002. “Willingness to Pay for Reduced Morbidity. Paper presented at the Workshop “Economic Valuation of Health for Environmental Policy: Assessing Alternative Approaches,” Orlando, Florida, March 18–19.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” Lancet 396: 1223–49.

OECD (Organisation for Economic Co-operation and Development). 2016. The Economic Consequences of Outdoor Air Pollution. Paris: OECD.

Penn World Table. n.d. Version 9. Groningen Growth and Development Centre. University of Groningen. https://www.rug.nl/ggdc/productivity/pwt/pwt-releases/pwt9.1

Wilson, C. 2003. “Empirical Evidence Showing the Relationships Between Three Approaches for Pollution Control.” Environmental and Resource Economics 24: 97-101.

World Bank. n.d. World Development Indicators. https://datatopics.worldbank.org /world-development-indicators/.
Bibliography

Alberini, A., and A. Krupnick. 2000. “Cost-of-Illness and Willingness-to-Pay Estimates of the Benefits of Improved Air Quality: Evidence from Taiwan.” Land Economics 76: 37–53.

Andrée, P. J. 2020. “Incidence of COVID-19 and Connections with Air Pollution Exposure: Evidence from the Netherlands.” Policy Research Working Paper 9221, World Bank, Washington DC.

Bowe, B., Y. Xie, T. Li, Y. Yan, H. Xian, and Z. Al-Aly. 2018. “The 2016 Global and National Burden of Diabetes Mellitus Attributable to PM$_{2.5}$ Air Pollution.” Lancet Planetary Health 2 (7): e301–e312.

Brauer, M., M. Amann, R. T. Burnett, A. Cohen, F. Dentener, M. Ezzati, S. B. Henderson, M. Krzyzanowski, R. V. Martin, R. Van Dingenen, A. van Donkelaar, and G. D. Thurston. 2012. “Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution.” Environ Sci Technol 46 (2): 652–60.

Brauer, M., G. Freedman, J. Frostad, A. van Donkelaar, R. V. Martin, F. Dentener, R. van Dingenen, K. Estep, H. Amini, J. S. Apte, K. Balakrishnan, L. Barregard, D. Broday, V. Feigin, S. Ghosh, P. K. Hopke, L. D. Knibbs, Y. Kokubo, Y. Liu, S. Ma, L. Morawska, J. L. Sangrador, G. Shaddick, H. R. Anderson, T. Vos, M. H. Forouzanfar, R. T. Burnett, and A. Cohen. 2016. “Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013.” Environ Sci Technol 50 (1): 79–88.

Burnett, Richard T., C. Arden Pope III, Majid Ezzati, Casey Olives, Stephen S. Lim, Sumi Mehta, Hwashin H. Shin, Gitanjali Singh, Bryan Hubbell, Michael Brauer, H. Ross Anderson, Kirk R. Smith, John R. Balmes, Nigel G. Bruce, Haidong Kan, Francine Laden, Annette Prüss-Ustün, Michelle C. Turner, Susan M. Gapstur, W. Ryan Diver, and Aaron Cohen. 2014. “An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure.” Environmental Health Perspectives: 122 (4): 397–403.

Carey, I. M., H. R. Anderson, R. W. Atkinson, S. D. Beevers, D. G. Cook, D. P. Strachan, D. Dajnak, J. Gulliver, and F. J. Kelly. 2018. “Are Noise and Air Pollution Related to the Incidence of Dementia? A Cohort Study in London, England.” BMJ Open 8: e022404.

Chen, J., and G. Hoek, 2020, “Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-analysis.” Environment International, Volume 143, https://doi.org/10.1016/j.envint.2020.105974.

Cropper, M., and W. Oates. 1992. “Environmental Economics: A Survey.” Journal of Economic Literature 30: 675–740.

Dickie, M., and S. Gerking. 2002. “Willingness to Pay for Reduced Morbidity. Paper presented at the Workshop “Economic Valuation of Health for Environmental Policy: Assessing Alternative Approaches,” Orlando, Florida, March 18–19.
Ezzati, M., A. D. Lopez, A. A. Rodgers, and C. J. Murray. 2004. *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors.* Geneva: WHO.

Ezziane, Z. 2013. “The Impact of Air Pollution on Low Birth Weight and Infant Mortality.” *Review of Environmental Health* 28 (2–3): 107–15.

GBD 2013 Risk Factors Collaborators. 2015. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013.” *Lancet* 386: 2287–323.

GBD 2015 Risk Factors Collaborators. 2016. “Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2015: A Systematic Analysis for the Global Burden of Disease Study 2015.” *Lancet* 388: 1659–724.

GBD 2016 Risk Factors Collaborators. 2017. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks, 1990–2016: A Systematic Analysis for the Global Burden of Disease Study 2016.” *Lancet* 390: 1345–422.

GBD 2017 Risk Factors Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” *Lancet* 392: 1923–94.

GBD 2019 Risk Factors Collaborators. 2020. “Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019.” *Lancet* 396: 1223–49.

GBD 2019 Viewpoint Collaborators. 2020. “Five Insights from the Global Burden of Disease Study 2019.” *Lancet.* 396: 1135–59.

Heft-Neal, S., J. Burney, E. Bendavid, and M. Burk. 2018. “Robust Relationship Between Air Quality and Infant Mortality in Africa.” *Nature* 559 (7713): 254–58.

HEI (Health Effects Institute). 2020. *State of Global Air 2020.* Boston: HEI. www.stateofglobalair.org.

Landrigan, P. J., R. Fuller, N. J. R. Acosta, O. Adeyi, R. Arnold, N. N. Basu, A. B. Balde, R. Bertollini, S. Bose-O’Reilly, J. J. Boufford, P. N. Breysse, T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, A. Haines, D. Hanrahan, D. Hunter, M. Khare, A. Krupnick, B. Lanphear, B. Lohani, K. Martin, K. V. Mathiasen, M. A. McTeer, C. J. L. Murray, J. D. Ndahimananjara, F. Perera, J. Potočnik, A. S. Preker, J. Ramesh, J. Rockström, C. Salinas, L. D. Samson, K. Sandilya, P. D. Sly, K. R. Smith, A. Steiner, R. B. Stewert, W. A. Suk, O. C. P. van Schayck, G. N. Yadama, K. Yumkella, and M. Zhong. 2018. “The Lancet Commission on Pollution and Health.” *Lancet* 391 (10119): 462–512.

Larsen, B. 2014. “Benefits and Costs of the Air Pollution Targets for the Post-2015 Development Agenda.” Air Pollution Assessment Paper, Post-2015 Consensus Project. Copenhagen: Copenhagen Consensus Center. https://www.copenhagenconsensus.com/sites/default/files/air_pollution_assessment_-_larsen.pdf.

Larsen, B. 2017. *Global Ambient Air Pollution: New Perspectives on Exposure, Health Effects and Costs – Global, Regional and National Estimates for 2015.* A World Bank Study. Washington, DC: World Bank.

Larsen, B. 2018. *The Global Cost of Ambient PM_{2.5} Air Pollution in 2017.* A World Bank Study. Washington, DC: World Bank.

Lim, S. S., T. Vos, A. D. Flaxman, et al. 2012. “A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010.” *Lancet* 380: 2224–60.

Lindhjem, H., S. Narvud, N. A. Braathen, and V. Biausque. 2011. “Valuing Mortality Risk Reductions from Environmental, Transport, and Health Policies: A Global Meta-Analysis of Stated Preference Studies.” *Risk Analysis* 31 (9): 1381–407.

Mehta, S., H. Shin, R. Burnett, T. North, and A. Cohen. 2013. “Ambient Particulate Air Pollution and Acute Lower Respiratory Infections: A Systematic Review and Implications for Estimating the Global Burden of Disease.” *Air Qual Atmos Health* 6: 69–83.
Narain, U., and C. Sall. 2016. *Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions*. A World Bank Study. Washington, DC: World Bank.

Navrud, S., and H. Lindhjem. 2010. *Meta-Analysis of Stated Preference VSL Studies: Further Model Sensitivity and Benefit Transfer Issues*. ENV/EPOC/WPNEP(2010)10/FINAL. Environment Directorate. Paris: OECD.

OECD (Organisation for Economic Co-operation and Development). 2012. *Mortality Risk Valuation in Environment, Health, and Transport Policies*. Paris: OECD.

OECD (Organisation for Economic Co-operation and Development). 2016. *The Economic Consequences of Outdoor Air Pollution*. Paris: OECD.

Orellano, P., J. Reynoso, N. Quaranta. 2021. “Short-Term Exposure to Sulphur Dioxide (SO2) and All-Cause and Respiratory Mortality: A Systematic Review and Meta-Analysis.” *Environment International*, Volume 150. https://doi.org/10.1016/j.envint.2021.106434.

Orellano, P., J. Reynoso, N. Quaranta, A. Bardach, and A. Ciapponi, 2020. “Short-Term Exposure to Particulate Matter (PM10 and PM2.5), Nitrogen Dioxide (NO2), and Ozone (O3) and All-Cause and Cause-Specific Mortality: Systematic Review and Meta-Analysis.” *Environment International*, Volume 142. https://doi.org/10.1016/j.envint.2020.105876.

Ostro, B., J. V. Spadaro, S. Gumy, P. Mudu, Y. Awe, F. Forastiere, and A. Peters. 2018. “Assessing the Recent Estimates of the Global Burden of Disease for Ambient Air Pollution: Methodological Changes and Implications for Low- and Middle-Income Countries.” *Environmental Research* 166: 713–25.

Ostro, B., Y. Awe, and E. Sánchez-Triana. 2021. *Implications of Exposure to Dust on the Burden of Disease from Air Pollution*. A World Bank Study. Washington, DC: World Bank.

Pope, C. A., III, R. T. Burnett, D. Krewski, M. Jerrett, Y. Shi, E. E. Calle, and M. J. Thun. 2009. “Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke: Shape of the Exposure-Response Relationship.” *Circulation* 120: 941–48.

Pope, C. A., III, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. Thurston. 2002. “Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution.” *Journal of the American Medical Association* 287: 1132–41.

Pope, C. A., III, R. T. Burnett, M. Turner, A. Cohen, D. Krewski, M. Jerrett, S. M. Gapstur, and M. J. Thun. 2011. “Lung Cancer and Cardiovascular Disease Mortality Associated with Ambient Air Pollution and Cigarette Smoke: Shape of the Exposure-Response Relationships.” *Environmental Health Perspectives* 119 (11): 1616–21.

Sánchez-Triana, E., S. Enriquez, B. Larsen, P. Webster, and J. Afzal. 2015. *Sustainability and Poverty Alleviation: Confronting Environmental Threats in Sindh, Pakistan*. Directions in Development. Washington, DC: World Bank.

Shaddick, G., M. L. Thomas, A. Green, M. Brauer, A. van Donkelaar, R. Burnett, H. Chang, A. Cohen, R. Van Dingenen, C. Dora, S. Gumy, Y. Liu, R. Martin, L. A. Waller, J. West, J. V. Zidek, and A. Prüss-Ustün. 2018. “Data Integration Model for Air Quality: A Hierarchical Approach to the Global Estimation of Exposures to Ambient Air Pollution.” *Journal of the Royal Statistical Society. Series C, Applied Statistics* 2018 67: 231–53.

Shin, H., A. Cohen, C. A. Pope III, M. Ezzati, S. S. Lim, B. Hubbel, and R. T. Burnett. 2013. “Critical Issues in Combining Disparate Sources of Information to Estimate the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure.” Working Paper prepared for Harvard Center for Risk Analysis “Methods for Research Synthesis: A Cross-Disciplinary Workshop,” October 3.

Shin J., J. Y. Park, and J. Choi. 2018. “Long-Term Exposure to Ambient Air Pollutants and Mental Health Status. A Nationwide Population-Based Cross-Sectional Study.” *PLOS One* 13 (4): e0195607.

Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluwegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler. 2012. “Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security.” *Science* 335: 183–89.
Shupler, M., W. Godwin, J. Frostad, P. Gustafson, R. E. Arku, and M. Brauer. 2018. “Global Estimation of Exposure to Fine Particulate Matter (PM$_{2.5}$) from Household Air Pollution.” *Environment International* 120: 354–63.

Thurston, G., Y. Awe, and E. Sánchez-Triana. 2021. *Are All Air Pollution Particles Equal? How Constituents and Sources of Fine Air Pollution Particles (PM$_{2.5}$) Affect Health.* A World Bank Study. Washington, DC: World Bank.

Van Donkelaar, A., R. Martin, M. Brauer, and B. Boys. 2015. “Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter.” *Environmental Health Perspectives* 123: 135–43.

Van Donkelaar, A., R. V. Martin, M. Brauer, N. C. Hsu, R.A. Kahn, R. C. Levy, A. Lyapustin, A. M. Sayer, and D. M. Winker. 2016. “Global Estimates of Fine Particulate Matter Using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors.” *Environmental Science and Technology* 50: 3762–72.

WHO (World Health Organization). 2009. *Estimated Deaths and DALYs Attributable to Selected Environmental Risk Factors, by WHO Member States, 2004.* http://www.who.int/quantifying_ehimpacts/national/countryprofile/intro/en/index.htm.

WHO (World Health Organization). 2016. *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease.* Geneva: WHO.

Wilson, C. 2003. “Empirical Evidence Showing the Relationships Between Three Approaches for Pollution Control.” *Environmental and Resource Economics* 24: 97–101.

World Bank. 2020. *The Global Health Cost of Ambient PM$_{2.5}$ Air Pollution.* Washington, DC: World Bank.

World Bank and IHME (Institute for Health Metrics and Evaluation). 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action.* Washington, DC: World Bank.

Xu, X., S. U. Ha, and R. Basnet. 2016. “A Review of Epidemiological Research on Adverse Neurological Effects of Exposure to Ambient Air Pollution.” *Frontiers in Public Health* 4:157.

Zhang, X., X. Chen, and X. Zhang. 2018. “The Impact of Exposure to Air Pollution on Cognitive Performance.” *Proceedings of the National Academy of Sciences* 115 (37): 9193–97.
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According to the Global Burden of Disease 2019 study, air pollution from fine particulate matter caused 6.4 million premature deaths and 93 billion days lived with illness in 2019. Over the past decade, the toll of ambient air pollution has continued to rise. Air pollution’s significant health, social, and economic effects compel the World Bank to support client countries in addressing air pollution as a core development challenge.

This publication estimates that the global cost of health damages associated with exposure to air pollution is $8.1 trillion, equivalent to 6.1 percent of global GDP. People in low- and middle-income countries are most affected by mortality and morbidity from air pollution. The death rate associated with air pollution is significantly higher in low-and lower-middle income countries than in high-income countries.

This publication further develops the evidence base for air-quality management through up-to-date estimates of air pollution’s global economic costs. The analyses presented here build on previous cost estimates by the Bank and its partners, as well as on more comprehensive air-quality data from monitoring stations in many cities across the world.

By providing monetary estimates of air pollution’s health damages, this publication aims to support policy makers and decision-makers in client countries in prioritizing air pollution amid competing development challenges. Its findings build a robust economic case to invest scarce budgetary resources in the design and implementation of policies and interventions for improving air quality. Such investments will deliver benefits for societies at large, and particularly for vulnerable groups. This publication builds a strong case for scaling up investments for air pollution control in low-and middle-income countries.