The Global Health Cost of Ambient $PM_{2.5}$ Air Pollution

POLLUTION MANAGEMENT & ENVIRONMENTAL HEALTH

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Abbreviations

AAP	Ambient Air Pollution
ALRI	Acute Lower Respiratory Infection
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
LMICs	Lower-Middle-Income Countries
$\mu g/m^3$	Micrograms Per Cubic Foot
MNA	Middle East and North Africa
NA	North America
OECD	Organisation for Economic Co-Operation and Development
PM	Particulate Matter—A Mixture Of Solid Particles and Liquid Droplets Found In the Air
$PM_{2.5}$	Particulate Matter Equal to or Less than 2.5 Microns in Diameter
PM_{10}	Particulate Matter Equal to or Less Than 10 Microns in Diameter
PPP	Purchasing Power Parity
SA	South Asia
SSA	Sub-Saharan Africa
UMI	Upper-Middle-Income
VSL	Value of Statistical Life
WHO	World Health Organization
WTP	Willingness to Pay
YLD	Years Lived with Disability

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Figures & Tables

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Acknowledgments

This report was prepared by a team led by **Yewande Awe** with the core team comprising **Bjorn Larsen**, **Shafick Hoossein**, and **Ernesto Sánchez-Triana**. The background document for this report was prepared by **Bjorn Larsen**.

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Executive Summary

Air pollution is a major cause of death and disease. Ambient air pollution refers to the contamination of outdoor air; household air pollution refers to the contamination of indoor air. Ambient (or outdoor) 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), lung cancer, chronic obstructive pulmonary disease (COPD), stroke, and pneumonia. The majority of deaths related to air pollution are caused by human exposure to fine inhalable particles or fine particulate matter, also known as $PM_{2.5}$. "Particulate matter" is a mixture of solid particles and liquid droplets found in the air, and "fine particulate matter ($PM_{2.5}$)" is particulate matter equal to or less than 2.5 microns in diameter.

Many people in developing countries live with ambient concentrations of $PM_{2.5}$ that are multiple times higher than the health-based guideline values for ambient air quality established by the World Health Organization (WHO). About 90 percent of deaths related to air pollution occur in lower-middle-income countries (LMICs) where outdoor air pollution is driven by rapid urbanization, increased motorization and energy use, and the burning of wastes and solid fuels.

An estimated 4.1 million people worldwide died prematurely in 2016 because of exposure to ambient $PM_{2.5}$. About 90 percent of those deaths occurred in LMICs (GBD 2016 Risk Factors Collaborators 2017). The Global Burden of Disease (GBD) studies referred to in this report will be cited as "GBD" followed by the year associated with that particular set of GBD studies. Two-thirds of those deaths occurred in East Asia and Pacific and South Asia. China and India accounted for 52 percent of global deaths from ambient $PM_{2.5}$. There were 11 countries with 50,000 or more deaths from ambient $PM_{2.5}$ and five countries with more than 100,000 deaths.

Besides being a health problem, ambient air pollution contributes to less-livable conditions in cities 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 premature death, illness, 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), preterm delivery, diabetes (Bowe et al. 2018), mental health (Shin et al. 2018), and neurological impairment (Xu et al. 2016; Zhang et al. 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; World Bank 2020a). 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 an 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).

This report provides an estimate of the global, regional, and national costs of health damage—that is, premature mortality and morbidity—from exposure to ambient $PM_{2.5}$ air pollution in 2016. While recognizing the various costs of air pollution to society, this report focuses on the cost of premature mortality and morbidity due to ambient air pollution, the world's leading environmental health risk. 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 ambient air pollution amidst competing development challenges and budgetary and other resource constraints. An earlier study by the World Bank and the IHME (Institute for Health Metrics and Evaluation) (2016) estimated the combined cost of premature mortality from ambient air pollution and household air pollution in 2013.[1]

1 Total air pollution damages in World Bank and IHME (2016) included ambient $PM_{2.5}$, household $PM_{2.5}$, and ambient ozone.

This report estimates the cost of health damages using the estimates of mortality and morbidity from ambient $PM_{2.5}$ published in the GBD 2016 study. The GBD assesses mortality and disability from numerous diseases, injuries, and risk factors, including ambient 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 $PM_{2.5}$, were published for the first time in the GBD 2010 study then followed by the GBD 2013 and annual publications since the GBD 2015.

Methodology

This report uses the GBD 2016 estimates of premature mortality and morbidity attributable to ambient $PM_{2.5}$ air pollution to value the economic cost in dollar terms. The GBD estimates the major health damages of population exposure to ambient $PM_{2.5}$ 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 in a country of premature deaths and disease that result from the population's exposure to given ambient concentrations of $PM_{2.5}$. Population exposure levels are estimated based on a combination of ground-level monitoring of ambient $PM_{2.5}$, satellite imagery, and chemical transport models.

The cost of the health damages from ambient $PM_{2.5}$ 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 (YLD) as estimated by the GBD. YLD is a measure of disease burden that reflects the duration and severity of diseases. YLD from exposure to ambient $PM_{2.5}$ is converted to days lived with disease, with the cost of a day of disease equated to the average daily wage rate in each country.

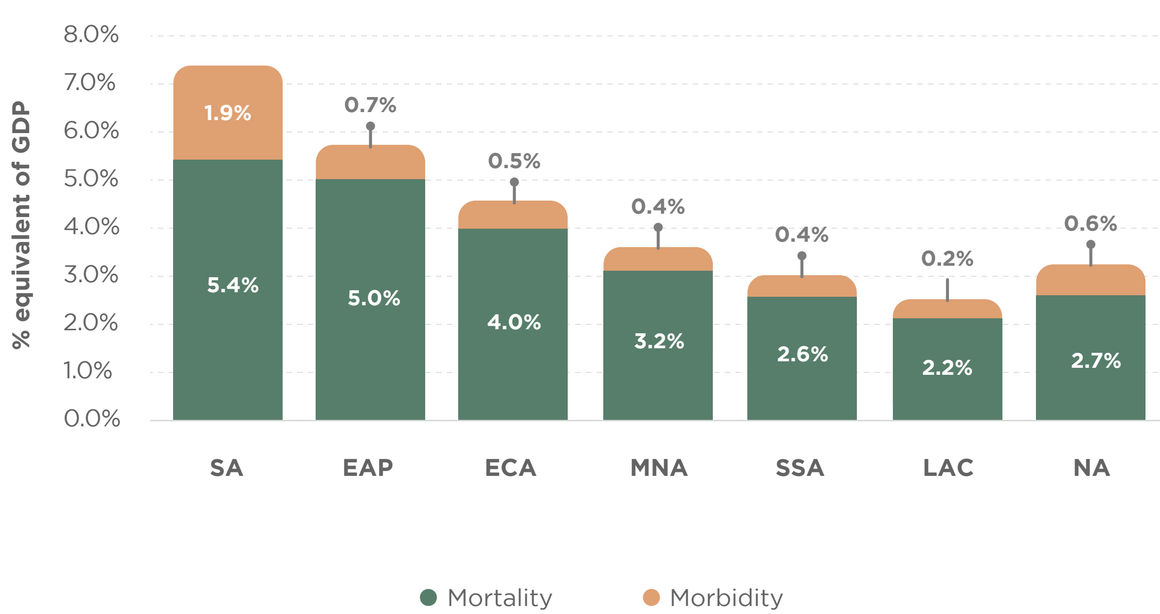
This report recognizes that $PM_{2.5}$ comes from both natural (for example, dust) and anthropogenic (for example, vehicle exhaust and emissions from power generation) origins to varying extents. The epidemiologic literature indicates that short- and long-term exposures to dust have significant health 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 (World Bank 2020b). Epidemiologic evidence supports the 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 the 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 (World Bank 2020c). The estimation of health impacts of natural dust, $PM_{2.5}$ constituents, and $PM_{2.5}$ mass from different sources, at a global level, will require strengthening the measurement of $PM_{2.5}$ constituents and source markers and improving the 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 (World Bank 2020b).

Key Findings

- The global health cost of mortality and morbidity caused by exposure to ambient $PM_{2.5}$ air pollution in 2016 was $5.7 trillion, equivalent to 4.8 percent of global gross domestic product (GDP).[2] By region, the cost ranged from an equivalent of 2.4 percent of GDP in Latin America and the Caribbean, to 5.7 percent in East Asia and Pacific, and 7.3 percent in South Asia (figure 1). The cost was equivalent to 2.7 percent of GDP in low-income countries and rose to 6.0 percent in upper-middle-income countries (figure 2). The cost was equivalent to 7.5–8 percent of GDP in China and India.

- Of the estimated total global health cost of ambient $PM_{2.5}$, about 87 percent is due to premature mortality and 13 percent to morbidity.

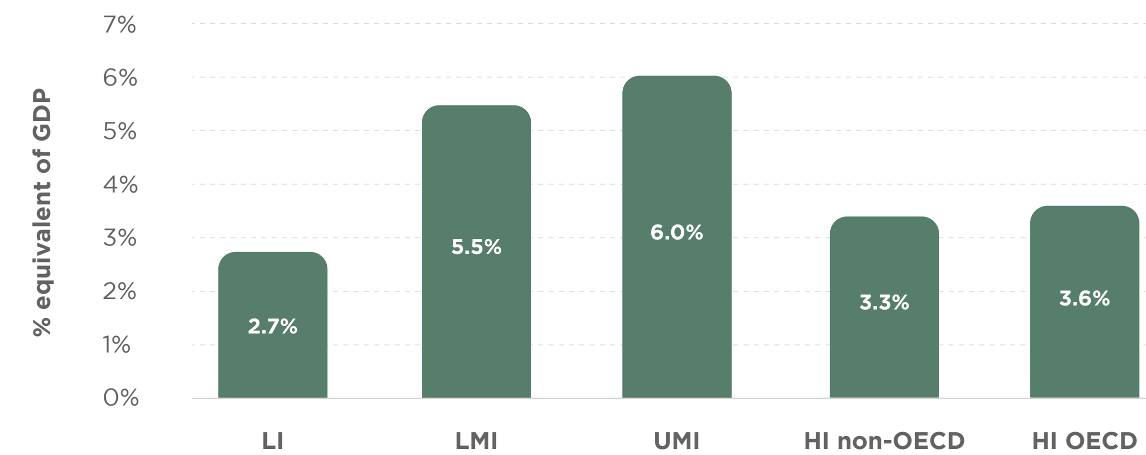
FIGURE 1 Annual Cost of Health Damage from Ambient $PM_{2.5}$ Exposure, % Equivalent of GDP in 2016 by Region



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

2 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.

FIGURE 2 Annual Cost of Health Damage from Ambient $PM_{2.5}$ Exposure, % Equivalent of GDP in 2016 by Income Group



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 classifications.

- In real terms, the estimated global cost of ambient $PM_{2.5}$ air pollution in 2016 is 50 percent higher than the estimate for 2013 in World Bank and IHME (2016).[3] The higher cost estimate in this report is related to two key sets of factors:

  — Improved methodology and availability of data. Specifically, this report uses updated exposure-response functions from the GBD 2016, which quantitatively relate the ambient levels of $PM_{2.5}$ to the risk of health damage (for example, COPD, IHD, ALRI, lung cancer, and stroke). At all exposure levels, the total health damages of $PM_{2.5}$ exposure were larger according to the exposure-response functions used in the GBD 2016 study than according to the exposure-response functions used in the GBD 2013 study.[4] Furthermore, ground-level measurements utilized by the GBD 2016 study came from an expanded WHO Global Ambient Air Quality Database released in 2016 that included data from around 6,000 ground monitors in about 3,000 human settlements.

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

3 World Bank and IHME (2016) provided an estimate of combined cost of $5.11 trillion for ambient air pollution and household air pollution in 2013. The cost of ambient air pollution alone in 2013 was $3.55 trillion (in 2011 $). The cost in 2016 was $5.7 trillion, or $5.31 trillion in 2011 $. The estimated cost in 2016 is therefore 50 percent higher than in 2013.

4 The GBD 2013 study is listed in the Reference section of this report as *GBD 2013 Risk Factor Collaborators 2015.*

- Observations about the reasons for variations between GBD mortality estimates for different years were noted in Ostro et al. (2018), which examined estimates of air pollution–related mortality provided in GBD 2010, GBD 2013, and GBD 2015. 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 air pollution-related mortality in LMICs.

- Although the global availability of exposure data in GBD 2016 increased because of increased ground-level monitoring data, there remains a great need to increase ground-level air quality measurements in LMICs to reduce uncertainties to $PM_{2.5}$ exposure estimates in countries that have limited or no ground-level measurements, particularly of $PM_{2.5}$ which is particulate matter equal to or less than 2.5 microns in diameter. PM_{10} refers to particulate matter equal to or less than 10 microns in diameter. It was found that there was only one $PM_{2.5}$ or PM_{10} ground-level monitor per 54 million people in low-income countries and one monitor per 16 million people in Sub-Saharan Africa, in contrast to one monitor per 300,000 people in high-income countries.[5]

Recommendations for Policy Action

The significant health and economic burdens of ambient $PM_{2.5}$ air pollution call for urgent action from policy makers in LMICs to reduce air pollution and the resulting 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 air quality monitoring networks are also useful for identifying the key sources that contribute to ambient air pollution. Such air quality monitoring networks must be subject to rigorous quality assurance and quality control regimes 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 effective air quality management programs that would also include comprehensive emission inventories; application of models to understand the transport and fate of air pollutants; assessment of costs, health, and other benefits; and public outreach and stakeholder engagement. It is pertinent to note that beyond initial investments in air quality monitoring networks, governments need to ensure effective funding for sustained operation and maintenance of air quality monitoring programs in the long term.

5 The numbers of monitors are based on the WHO Global Ambient Air Quality Database released in 2016. Since the preparation of this report, the WHO has released its 2018 version of the WHO Global Ambient Air Quality Database, which was used by the GBD 2017 study. The 2018 version includes nearly 10,000 ground monitors in nearly 4,400 locations in 108 countries. This represents a substantial improvement in global coverage, although 76 percent of the increase in $PM_{2.5}$ monitors was in high-income countries. Regarding $PM_{2.5}$ monitors, there were 64 million people per ground monitor in low-income countries and 29 million per ground monitor in Sub-Saharan Africa, in contrast to about 370,000 people per monitor in high-income countries. These results continue to underscore the need for establishing and strengthening ground-level monitoring networks in LMICs.

- **Ensure public access to information on air quality** – To reinforce the impact of air quality monitoring networks, 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 vulnerable groups such as young children, the elderly, and people with health conditions that can be exacerbated by poor air quality.

- **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. Such approaches require governments to collaborate at the national and international levels 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** – Air pollution control efforts 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 climate change mitigation benefits. Notably, reducing $PM_{2.5}$ also means reducing black carbon, a component of $PM_{2.5}$ and a short-lived climate pollutant.

"Global health crises further highlight the need for continued action in addressing a global and cross-cutting challenge such as air pollution."

- **Engage a wide range of instruments that are suited to effectively and efficiently reduce air pollution and ensure that they are enforced** – 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 the establishment of ambient air quality standards, emissions 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, such as by decreasing the sulfur content of fuels. *Economic instruments* such as air pollution charges and repurposing of fossil-fuel subsidies reduce air and climate pollutants to augment the government revenue that can be allocated to education, health care, renewable energy, and interventions to control air pollution. In addition, policies to promote the 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 air-quality management instruments requires that governments put in place adequate enforcement mechanisms that also include incentives to reduce polluting behaviors.

Introduction and Objectives

The detrimental effects of ambient air pollution, notably $PM_{2.5}$, on health are well known. Ambient air pollution refers to the contamination of outdoor air; household air pollution refers to the contamination of indoor air. Ambient (or outdoor) air pollution is the world's leading environmental risk to health and the cause of morbidity and mortality from diseases such as IHD, lung cancer, COPD, stroke, and pneumonia. The majority of deaths related to ambient and household air pollution are caused by human exposure to fine inhalable particulate matter, also known as $PM_{2.5}$. In 2016, about 4.1 million people worldwide died as a result of exposure to ambient air pollution.

Understanding the welfare costs associated with ambient air pollution has been a topic of continued attention in several works. Several of these works have applied methodologies and estimates of exposure to air pollution used in the Global Burden of Disease Project. These works include Larsen (2014), OECD (2016), WHO (2016), World Bank and IHME (2016), and a broader study by the Lancet Commission on pollution and health (Landrigan et al. 2018). Four of these publications provide global estimates of the welfare cost of air pollution, as does a recent World Bank update of the global, regional, and national cost of $PM_{2.5}$ ambient air pollution in 2015 (Larsen 2017). Multiple studies, including ones cited in this paragraph, point to the enormous global welfare cost of ambient air pollution in the trillions of dollars, equivalent in magnitude to 2.5–6 percent of global GDP, depending on the valuation of health damages (table 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).[6]

It is important to note the following two cost-related findings of these studies: (i) The global cost of ambient air pollution is substantially higher than the cost of household air pollution associated with the burning of solid fuels. (ii) However, the cost of household air pollution is still substantially higher than the cost of ambient air pollution in South Asia and Sub-Saharan Africa and nearly as high as the cost of ambient air pollution in East Asia and Pacific (World Bank and IHME 2016).

6 2010 Purchasing Power Parity (PPP) adjusted US$.

TABLE 1 Global Welfare Cost of Air Pollution, $, Trillions, per Year

Study	Domain	Year	$ (PPP)	US$	% of GDP
Larsen (2014)	AAP	2012 in 2012 prices	-	1.7	2.5
World Bank and IHME (2016)	AAP	2013 in 2011 prices	3.6	-	3.5
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*
Larsen (2017)	AAP	2015 in 2015 prices	5.5	3.3	4.5

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 = ambient air pollution; HAP = household air pollution.
* Gross national income.

This report provides an updated estimate of the global, regional, and national cost of ambient $PM_{2.5}$ air pollution in 2016 using the GBD 2016[7] estimates of mortality and morbidity from ambient $PM_{2.5}$. The estimated global cost in 2016 was $5.7 trillion,[8] equivalent to 4.8 percent of global GDP (PPP adjusted).[9] In real terms, the estimated cost of ambient $PM_{2.5}$ air pollution in 2016 is 50 percent higher than the estimate for 2013 in World Bank and IHME (2016).[10] 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 2016, although the exact contribution of each of these two factors is difficult to ascertain.

This report also provides an overview of global and regional ambient $PM_{2.5}$ population exposure and the exposure-response functions developed by the GBD 2016 study.

7 The GBD 2016 study is listed in the References section of this report as *GBD 2016 Risk Factor Collaborators 2017.*

8 International dollars or purchasing power parity adjusted US$. Expressed in US dollars, the global cost in 2016 was US$3.3 trillion, equivalent to 4.4 percent of global GDP.

9 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.

10 The cost of ambient $PM_{2.5}$ in 2013 was $3.55 trillion (in 2011 $ (PPP)) according to World Bank and IHME (2016). The cost in 2016 was $5.7 trillion, or $5.31 trillion in 2011 $ (PPP). The estimated cost in 2016 is therefore 50 percent higher than in 2013.

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 ambient $PM_{2.5}$ air pollution in 2016. While recognizing the various costs of air pollution to society, this report focuses on the cost of premature mortality and morbidity due to ambient air pollution, the world's leading environmental health risk. 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 ambient air pollution amidst competing development challenges and budgetary and other resource constraints.

As a development institution, the cost of ambient air pollution underscores the need for the World Bank's sustained support of governments' efforts to reduce ambient 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 ambient 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 2016 study. Exposure-response functions quantitatively relate the ambient levels of $PM_{2.5}$ to the risk of health damage (for example, COPD, IHD, ALRI, lung cancer, and stroke). The exposure-response functions used in this report differ in important aspects from the functions from the GBD 2013 study[11] used in World Bank and IHME (2016). The GBD 2016 exposure-response functions reveal a much higher risk of COPD and acute lower respiratory infection (ALRI) from $PM_{2.5}$ exposure than the functions used in the GBD 2013 study. The GBD 2016 exposure-response functions are somewhat higher for IHD at higher exposure levels, somewhat lower for stroke, and substantially lower for lung cancer. Lung cancer mortality is, however, a very minor share of total mortality from ambient $PM_{2.5}$. Thus, in aggregate at all exposure levels, the health damages of $PM_{2.5}$ exposure are larger according to the exposure-response functions used in the GBD 2016 study than according to the functions used in the GBD 2013 study.

11 The GBD 2013 study is listed in the References section of this report as *GBD 2013 Risk Factor Collaborators 2015.*

- This report is based on global ambient $PM_{2.5}$ exposure estimates used in the GBD 2016. These exposure estimates are higher than the estimates used in the GBD 2013 and based on a database of ground-level measurements of air quality that are used for calibrating satellite and chemical transport modeling estimates of $PM_{2.5}$. The database of ground-level measurements used by the GBD 2016 is substantially larger than the database used in the GBD 2013 study. Global population-weighted ambient $PM_{2.5}$ exposure was 50 μg/m^3 in 2016 according to the estimates used in the GBD 2016 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 ambient $PM_{2.5}$ exposure estimates from the GBD 2013 study to the GBD 2016 study, this report is based on a global mortality estimate of 4.1 million deaths from ambient $PM_{2.5}$ in 2016 compared to 2.9 million deaths in 2013 used by World Bank and IHME (2016).
- This report also provides an order-of-magnitude estimate of the cost of morbidity of ambient $PM_{2.5}$ based on the morbidity disease burden reported by the GBD 2016 study, which is found to vary substantially across countries and regions.

The remaining sections of this report provide a global and regional overview of $PM_{2.5}$ ambient air quality monitoring, estimates of population exposure to $PM_{2.5}$, estimation of health damages from this exposure, and global costs of these health damages.

Evolution of Estimates of Population Exposure to Ambient $PM_{2.5}$

The GBD project estimates health damages from nationwide population exposure to ambient $PM_{2.5}$. Nationwide exposure is estimated from a combination of satellite imagery, chemical transport modeling, and ground-level $PM_{2.5}$ and PM_{10} measurements.

The evolution in satellite imagery and chemical transport model estimation techniques, the number of ground-level monitoring locations, and the method of calibrating the satellite imagery and chemical transport model estimates with the ground-level measurements has been quite substantial from the GBD 2010 study to the GBD 2016 study. These issues are discussed in some detail in Brauer et al. (2012), Brauer et al. (2016), Shaddick et al. (2018), van Donkelaar et al. (2015), and van Donkelaar et al. (2016).

Ground-level measurements of $PM_{2.5}$ or PM_{10} employed by the GBD 2010 study covered less than 700 locations (Brauer et al. 2012). Two-thirds of the locations were in the high-income countries of East Asia and Pacific, North America, and Western Europe. There were 222 locations in Central Europe (26), the Middle East and North Africa (9), and LMICs of East Asia and Pacific (133), Latin America and the Caribbean (25), South Asia (21), and Sub-Saharan Africa (8). The majority of the locations in East Asia and Pacific were in China.

The ground-level measurements of $PM_{2.5}$ and PM_{10} employed by the GBD 2013 study were expanded to 4,073 data points from 3,387 unique locations (Brauer et al. 2016). This included measurement data used by the GBD 2010 study and new data, especially from China and India, including data compiled from a literature survey (van Donkelaar et al. 2015) and the WHO ambient air pollution database.

The GBD 2015 study[12] utilized the updated and expanded WHO Ambient Air Quality Database released in 2016. This database contained PM measurements from 6,003 ground monitors in about 3,000 human settlements ranging in size from populations ranging from those in the hundreds to those over 10 million (GBD 2015 study; WHO 2016). The GBD 2016 study utilized the same data as the GBD 2015 study.

12 The GBD 2015 study is listed in the References section of this report as *GBD 2015 Risk Factor Collaborators 2016.*

Analysis of the 2016 online version of the WHO database used by the GBD 2015 study and the GBD 2016 study reveals the following:

i. Only 530 (9 percent) of the monitors were in low-income and lower-middle-income countries, although these countries account for nearly 50 percent of the world population and a little over 50 percent of global deaths from ambient $PM_{2.5}$ (figure 3).

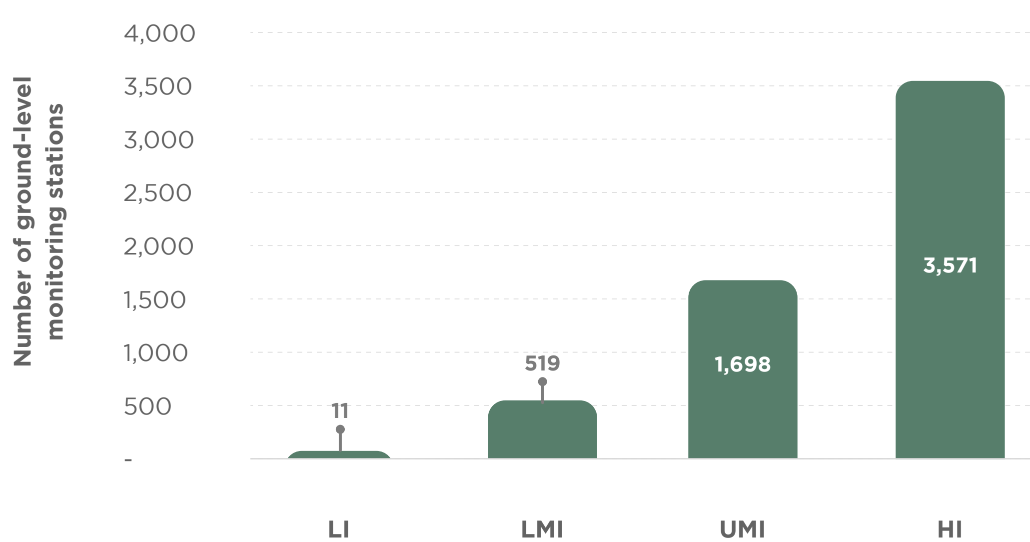
ii. Only 62 of the monitors were in Sub-Saharan Africa, while 270–370 monitors were in each of Middle East and North Africa, Latin America and the Caribbean, and South Asia (figure 4).

iii. There was only one monitor per 54 million people in low-income countries in contrast to one monitor per 300,000 people in high-income countries (figure 5).

iv. Regionally, there was only one monitor per 16 million in Sub-Saharan Africa compared to one monitor per 400,000 in Europe and Central Asia and North America (figure 6).

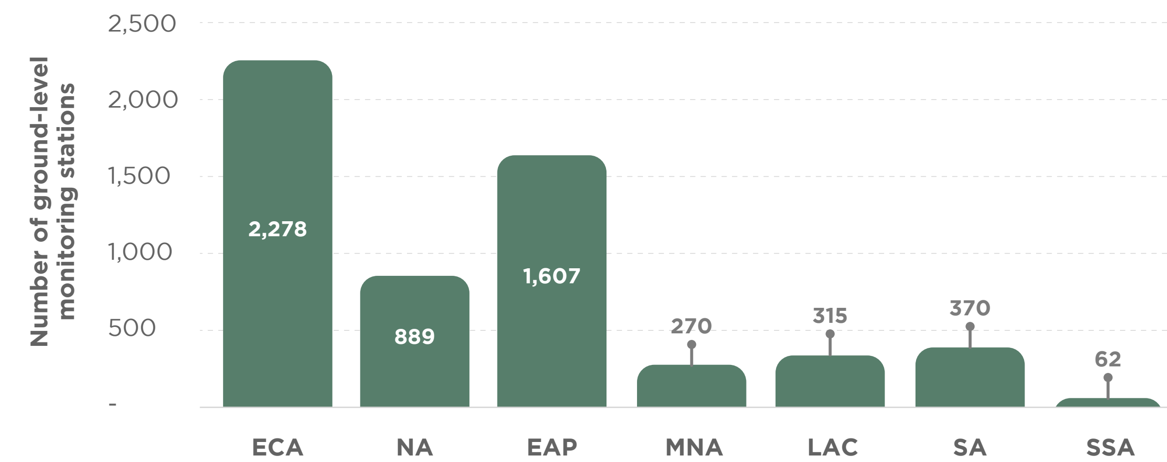
One limitation of the ground-level measurement data is, however, that over half of the measurement points are of coarse particulate matter pollution PM_{10}, rather than the more health-damaging fine particulate matter or $PM_{2.5}$. The measurements of PM_{10} are converted to $PM_{2.5}$ using available, albeit imprecise, information about their ratios. This introduces additional uncertainty to the global $PM_{2.5}$ exposure estimates in countries with relatively few measurement points of $PM_{2.5}$, which was especially the case, at least up until 2016, in the South Asia, Middle East and North Africa, and Latin America and the Caribbean regions, as well as large parts of the Europe and Central Asia region.

FIGURE 3 Ground-Level Monitoring Stations in Absolute Numbers by Country Income Level



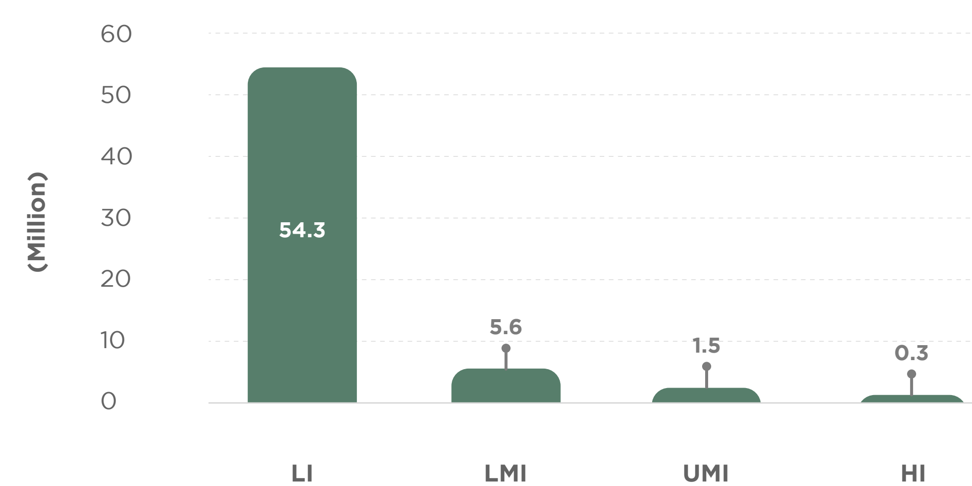
Source: Based on WHO Global Ambient Air Quality Database 2016.
Note: LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Assignment of countries to categories based on World Bank income classifications.

FIGURE 4 Ground-Level Monitoring Stations in Absolute Numbers by Region



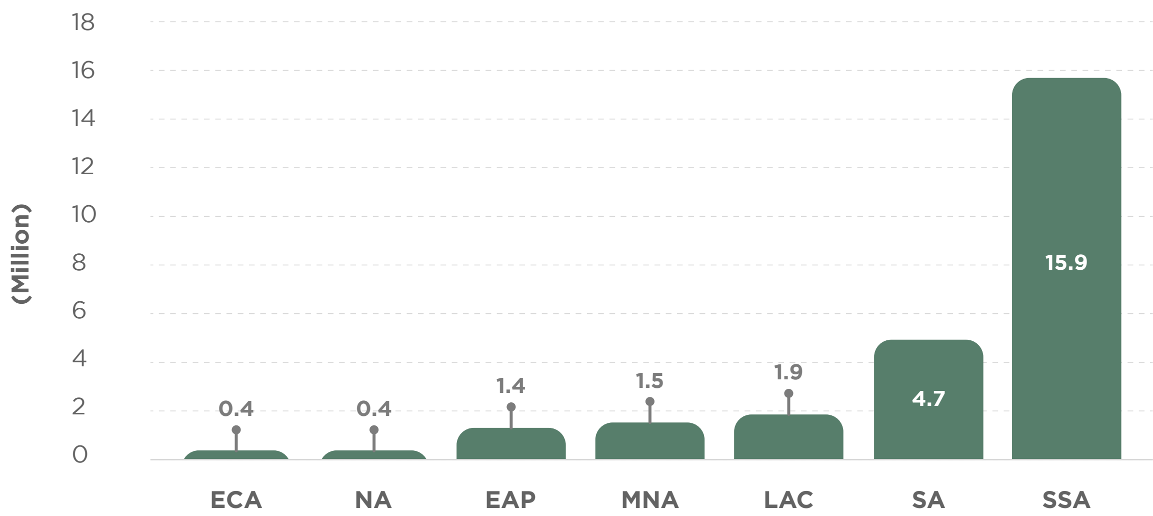
Source: Based on data from WHO Global Ambient Air Quality Database 2016.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

FIGURE 5 Million People per Ground-Level Monitoring Station by Country Income Level



Source: Based on data from WHO Global Ambient Air Quality Database 2016.
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 classifications.

FIGURE 6 Million People per Ground-Level Monitoring Station by Region



Source: Based on data from WHO Global Ambient Air Quality Database 2016.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

Current Ambient $PM_{2.5}$ Population Exposure

Global population exposure to ambient $PM_{2.5}$ was 50 µg/m³ in 2016 according to estimates used by the GBD 2016 study. In contrast, the global population exposure for 2013 was 32 µg/m³ 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 2016 than to actual worsening of global ambient $PM_{2.5}$ air quality from 2013 to 2016, 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 supplemental material of the GBD 2016.

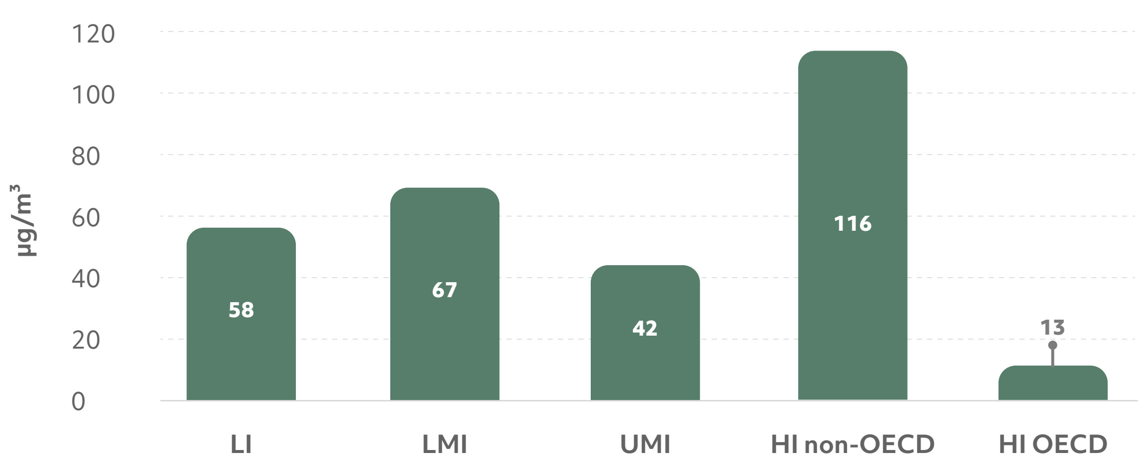
The global population-exposure estimate for 2016 is five times as high as WHO's Air Quality Guideline value of 10 µg/m³ for annual average $PM_{2.5}$. Ambient $PM_{2.5}$ exposures in 2016 were highest in Middle East and North Africa, South Asia, and Sub-Saharan Africa regions—that is, about seven to nine times as high as in North America. $PM_{2.5}$ exposure is also high in East Asia and Pacific, dominated by China at 56 µg/m³ (figure 7).

FIGURE 7 Regional Population-Weighted Ambient $PM_{2.5}$ Exposure in 2016

Source: Based on the GBD 2016 study.
Note: Country-level ambient $PM_{2.5}$ exposure levels are reported by the World Development Indicators Database (http://datatopics.worldbank.org/world-development-indicators/).

By country income group, $PM_{2.5}$ exposure was highest in high-income non-OECD countries, dominated by the countries in the Middle East and North Africa region. Exposure was by far the lowest in high-income OECD countries, followed by upper-middle-income countries, low-income countries, and lower-middle-income countries (figure 8).

FIGURE 8 Population-Weighted Ambient $PM_{2.5}$ Exposure by Country Income Group in 2016



Source: Based on the GBD 2016 study.
Note: Country-level ambient $PM_{2.5}$ exposure levels are reported by the World Development Indicators Database (http://datatopics.worldbank.org/world-development-indicators/). LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; HI = high-income countries; OECD = Organisation for Economic Co-operation and Development member countries. Assignment of countries to categories based on World Bank income classifications.

Risks of Health Damages from Ambient $PM_{2.5}$ Exposure

Exposure-response functions or concentration-response functions are a key input for quantifying the health burden of ambient 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 project estimates the health damages of $PM_{2.5}$ exposure from IER functions for five major health outcomes. 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 10 μg/m^3 to several hundred μg/m^3.

The relative risks from the IER function used by the GBD 2016 study are published in the GBD 2016 study Supplement. They are reproduced in figure 9 for $PM_{2.5}$ concentrations up to 150 μg/m^3. Relative risks of IHD and cerebrovascular disease (stroke) are the smallest for $PM_{2.5}$ concentrations larger than 30 to 50 μg/m^3 and relative risks of ALRI and COPD are the largest at $PM_{2.5}$ concentrations over 20 μg/m^3.[13]

The relative risks are derived from studies of long-term exposure to ambient air $PM_{2.5}$, secondhand tobacco smoke, household use of solid cooking fuels, and active tobacco use (Burnett et al. 2014). This provides risk functions that can be applied to a wide range of

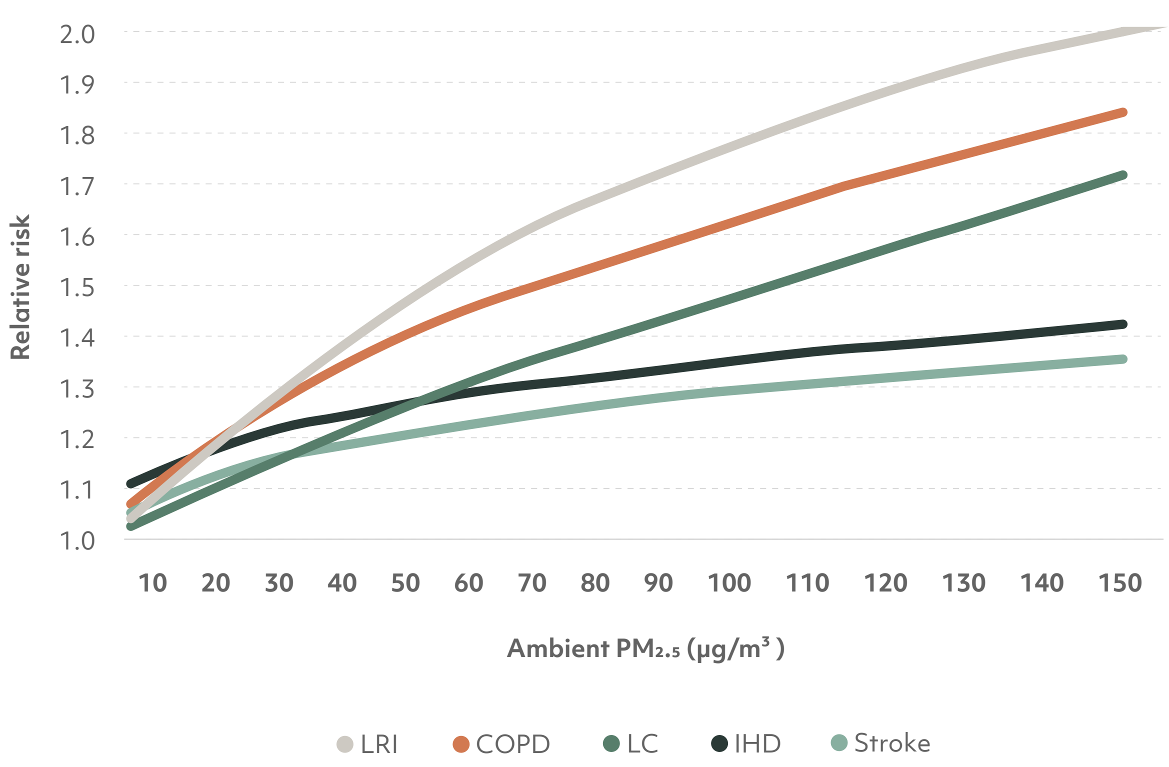
> “Exposure-response functions or concentration-response functions are a key input for quantifying the health burden of ambient air pollution.”

13 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.

ambient $PM_{2.5}$ concentrations around the world as well as to high household air pollution levels of $PM_{2.5}$ from the combustion of solid fuels. The risk functions are nonlinear, with declining marginal health damages at higher $PM_{2.5}$ concentrations.

These GBD 2016 exposure-response functions differ in important aspects from the risk functions from the GBD 2013 study used in World Bank and IHME (2016). The GBD 2016 risk functions reveal a much higher risk of COPD and ALRI from $PM_{2.5}$ exposure than the functions used in the GBD 2013 study. The GBD 2016 risk functions are somewhat higher for IHD at higher exposure levels, somewhat lower for stroke, and substantially lower for lung cancer. Lung cancer mortality is, however, a very minor share of total mortality from ambient $PM_{2.5}$. Thus, in aggregate at all exposure levels, the health damages of $PM_{2.5}$ exposure are larger according to the exposure-response functions used in the GBD 2016 study than according to the functions used in the GBD 2013 study.

FIGURE 9 Relative Risks of Major Health Outcomes Associated with $PM_{2.5}$ Exposure, GBD 2016 Study



Source: Based on the GBD 2016 study Supplement.
Note: COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, LC = lung cancer; LRI = lower respiratory infections.

Global Health Damages of Ambient $PM_{2.5}$ Exposure

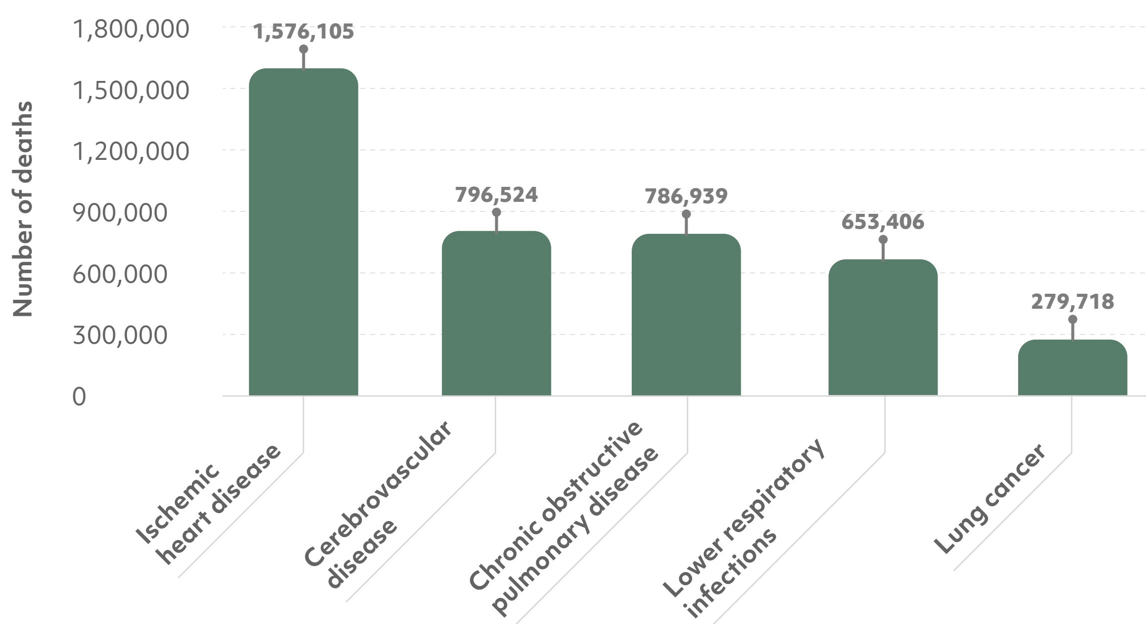
As many as 4.1 million people died from ambient $PM_{2.5}$ air pollution in 2016 according to the GBD 2016 study. This makes ambient $PM_{2.5}$ the seventh-largest health risk factor of global deaths among dozens of risk factors assessed by the GBD 2016 study.

Globally, IHD accounts for 39 percent of deaths from ambient $PM_{2.5}$, stroke for 19 percent, COPD for 19 percent, LRI for 16 percent, and lung cancer for 7 percent according to the GBD 2016 study (see figure 10 for global number of deaths associated with ambient $PM_{2.5}$ and figure 11 for percent share of associated diseases).

For perspective, global deaths from ambient $PM_{2.5}$ air pollution constituted as much as 7.5 percent of all global deaths in 2016. For the five health outcomes of $PM_{2.5}$ exposure, ambient $PM_{2.5}$ caused 14–17 percent of global deaths from IHD, stroke, and lung cancer and 27 percent of global deaths from COPD and LRI (figure 12).

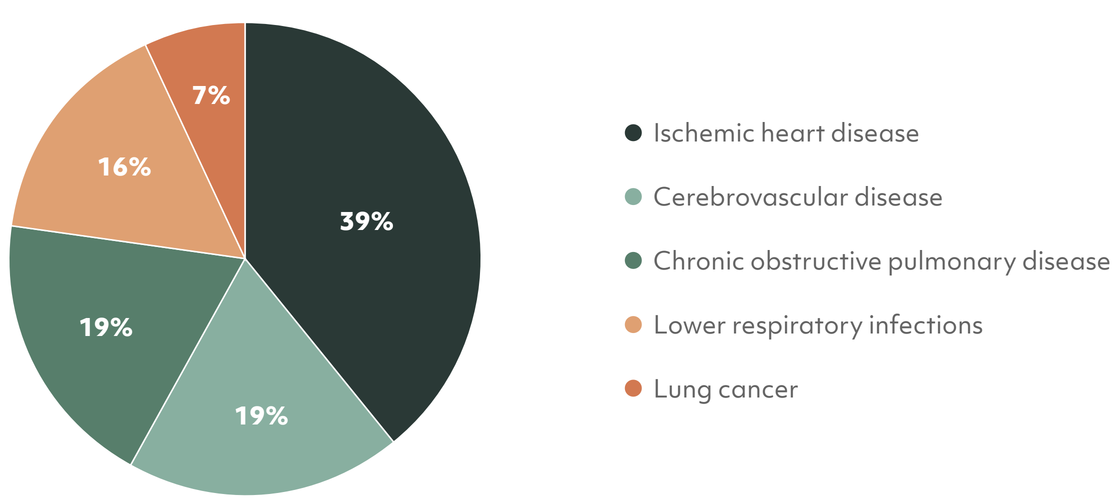
By region, two-thirds of global deaths from ambient $PM_{2.5}$ exposure in 2016 occurred in South Asia and East Asia and Pacific (figure 13). India accounted for 78 percent of these deaths in South Asia and China for 77 percent in East Asia and Pacific. Deaths from ambient $PM_{2.5}$ in these two countries constituted 52 percent of global deaths from ambient $PM_{2.5}$.

FIGURE 10 Global Number of Deaths from Ambient $PM_{2.5}$ Air Pollution in 2016



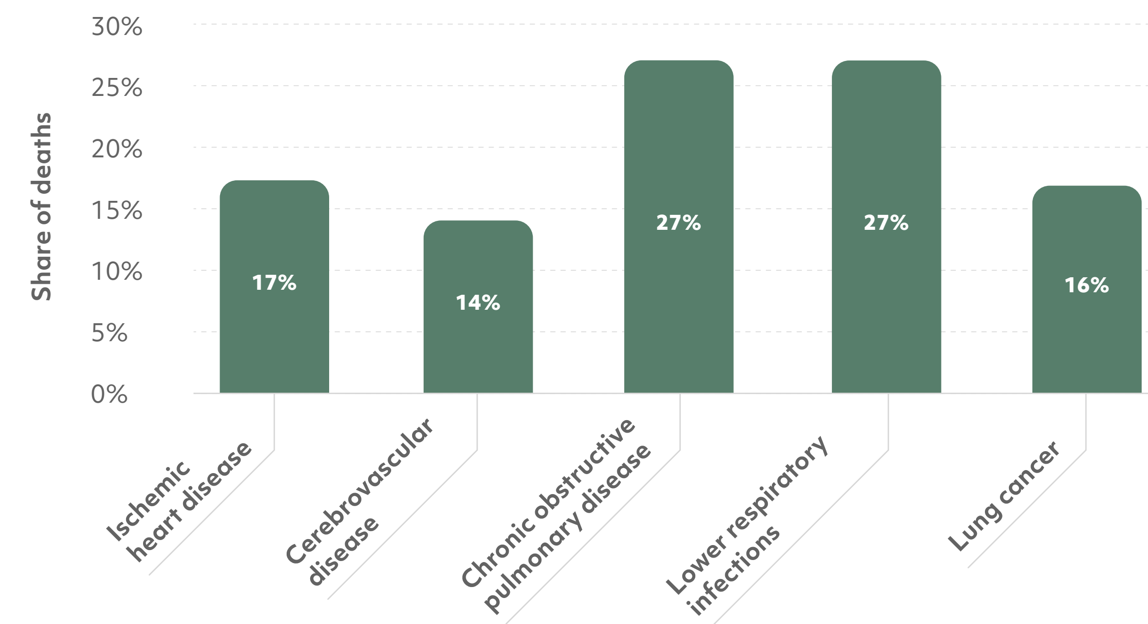
Source: Based on data from IHME, GBD 2016 study.

FIGURE 11 Share of Global Deaths from Ambient $PM_{2.5}$ Air Pollution in 2016



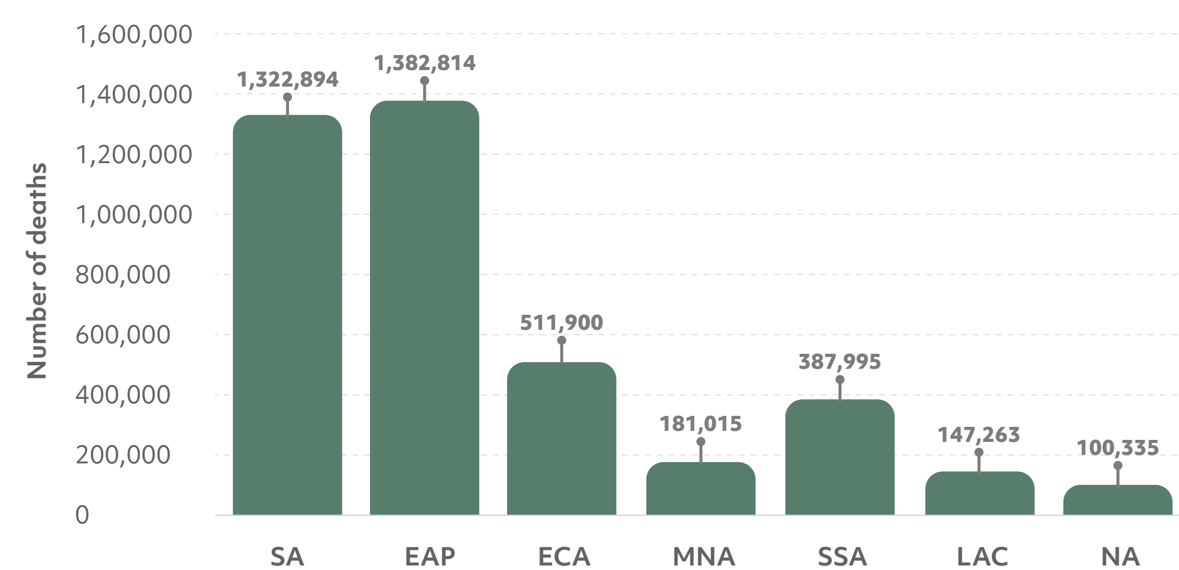
Source: Based on data from IHME, GBD 2016 study.

FIGURE 12 Global Deaths from Ambient $PM_{2.5}$ Air Pollution as a Share of All Global Deaths in 2016



Source: Based on data from IHME, GBD 2016 study.

FIGURE 13 Global Number of Deaths from Ambient $PM_{2.5}$ Exposure by Region in 2016



Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

The three (and, in one case, the two) countries with the most deaths from ambient $PM_{2.5}$ in each region in 2016 are presented in table 2. There are 11 countries with 50,000 or more deaths from ambient $PM_{2.5}$ and five countries with more than 100,000 deaths.

TABLE 2 Number of Deaths from Ambient $PM_{2.5}$ by Region and Country in 2016

Region	Country	Deaths (thousands)	Region	Country	Deaths (thousands)
EAP	China	1,075	NA	United States	93
	Indonesia	80		Canada	7
	Japan	46			
ECA	Russian Federation	125	SA	India	1,034
	Ukraine	54		Pakistan	125
	Germany	37		Bangladesh	109
LAC	Brazil	50	SSA	Nigeria	69
	Mexico	24		Ethiopia	37
	Argentina	16		Congo, Dem. Rep	33
MNA	Egypt, Arab Rep.	68			
	Iran, Islamic Rep.	29			
	Iraq	18			

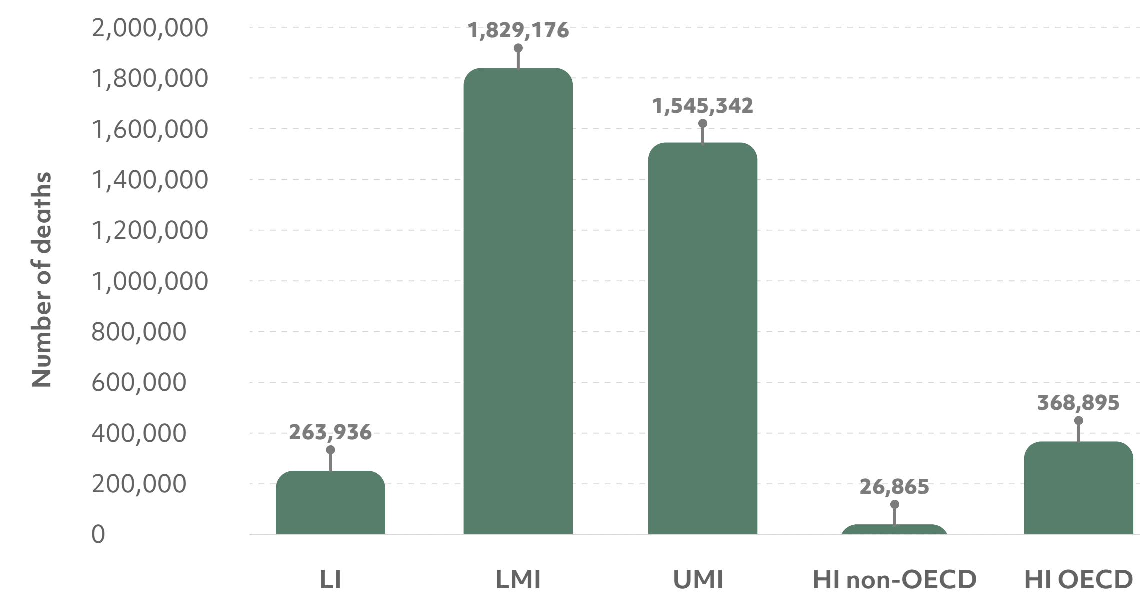
Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

In total, 84 percent of global deaths from ambient $PM_{2.5}$ exposure occurred in middle-income countries, and they were nearly evenly split between lower-middle-income and upper-middle-income countries. About 6.5 percent of deaths were in low-income countries and nearly 10 percent in high-income countries (figure 14).

The majority of deaths from ambient $PM_{2.5}$ exposure in East Asia and Pacific and South Asia, and these regions also have the highest rates of deaths from ambient $PM_{2.5}$, reaching 62 and 75 deaths per 100,000 population, respectively. The lowest death rates are in Latin America and the Caribbean and NA (figure 15).

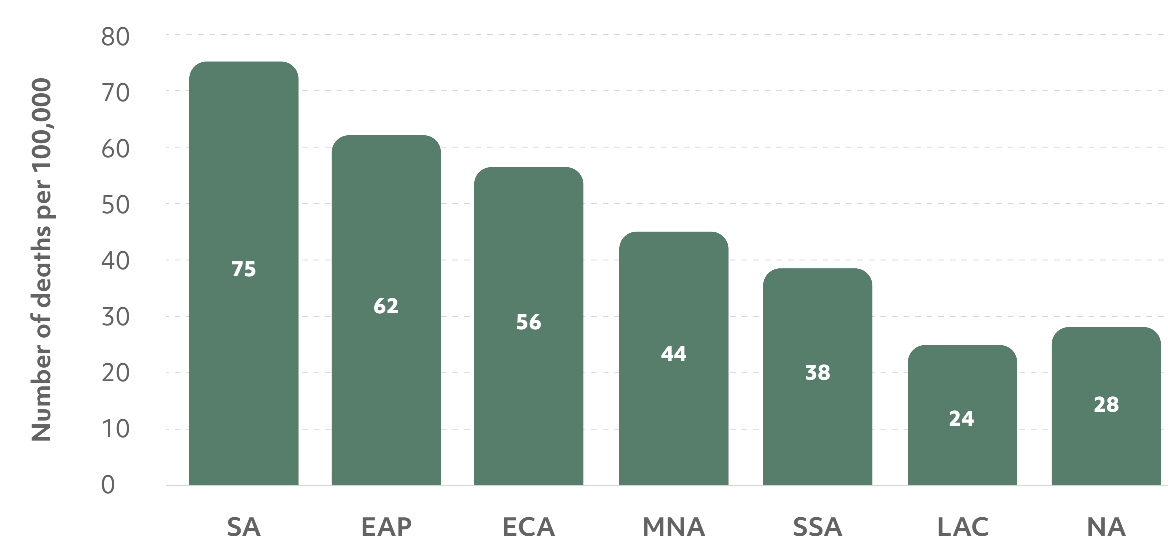
By income group, the highest death rates from ambient $PM_{2.5}$ exposure are in lower-middle-income countries, and lowest in the high-income countries (figure 16).

FIGURE 14 Global Number of Deaths from Ambient $PM_{2.5}$ Exposure by Income Group in 2016



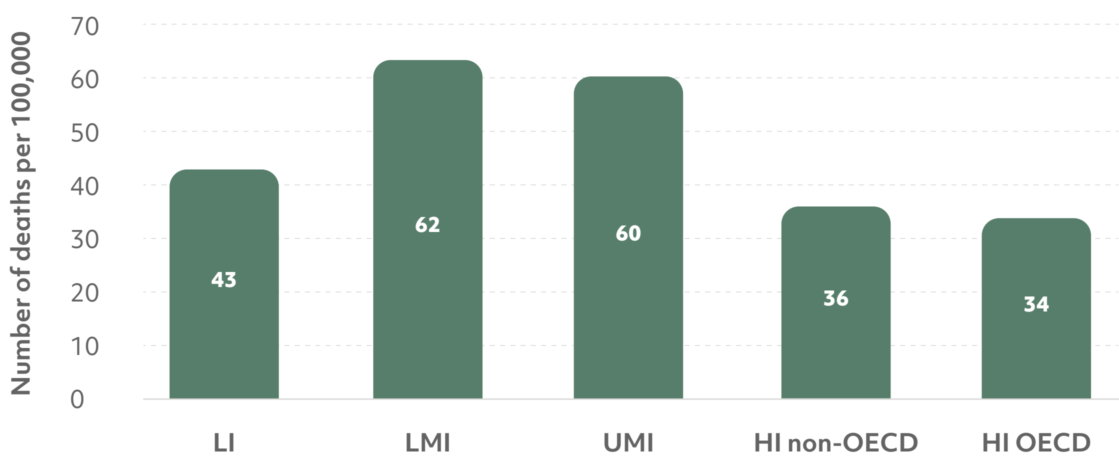
Source: Based on data from IHME, GBD 2016 study.
Note: LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Assignment of countries to categories based on World Bank income classifications.

FIGURE 15 Number of Deaths from Ambient $PM_{2.5}$ Exposure per 100,000 Population in 2016 by Region



Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

FIGURE 16 Number of Deaths from Ambient $PM_{2.5}$ Exposure per 100,000 Population in 2016 by Income Group



Source: Based on data from IHME, GBD 2016 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 classifications.

The three (and, in one case, the two) countries in each region with the highest death rates from ambient $PM_{2.5}$ (expressed as the number of deaths per 100,000 population) are presented in table 3. The countries with the highest death rates are in Europe and Central Asia, East Asia and Pacific, Sub-Saharan Africa, and South Asia. There are as many as 25 countries in Europe and Central Asia with death rates over 50 per 100,000 population. They are all in Central Asia and the eastern part of Europe. The high death rates in these parts of Europe and Central Asia are primarily associated with high baseline cardiovascular death rates.

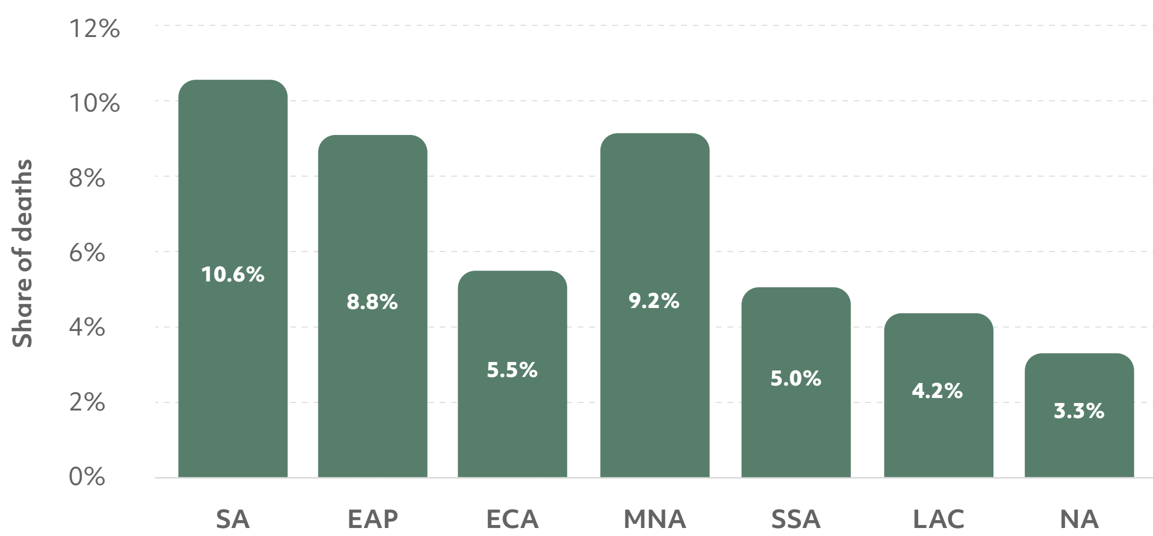
TABLE 3 Number of Deaths from Ambient $PM_{2.5}$ per 100,000 Population in 2016 by Country

Region	Country	Death rate	Region	Country	Death rate
EAP	Korea, Dem. People's Rep.	92	NA	United States	29
	China	78		Canada	19
	Mongolia	51			
ECA	Bulgaria	127	SA	India	78
	Ukraine	119		Afghanistan	78
	Belarus	101		Nepal	71
LAC	Cuba	47	SSA	Central African Republic	90
	Haiti	46		Niger	70
	Guyana	38		Cameroon	68
MNA	Egypt, Arab Rep.	71			
	Iraq	49			
	Djibouti	46			

Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

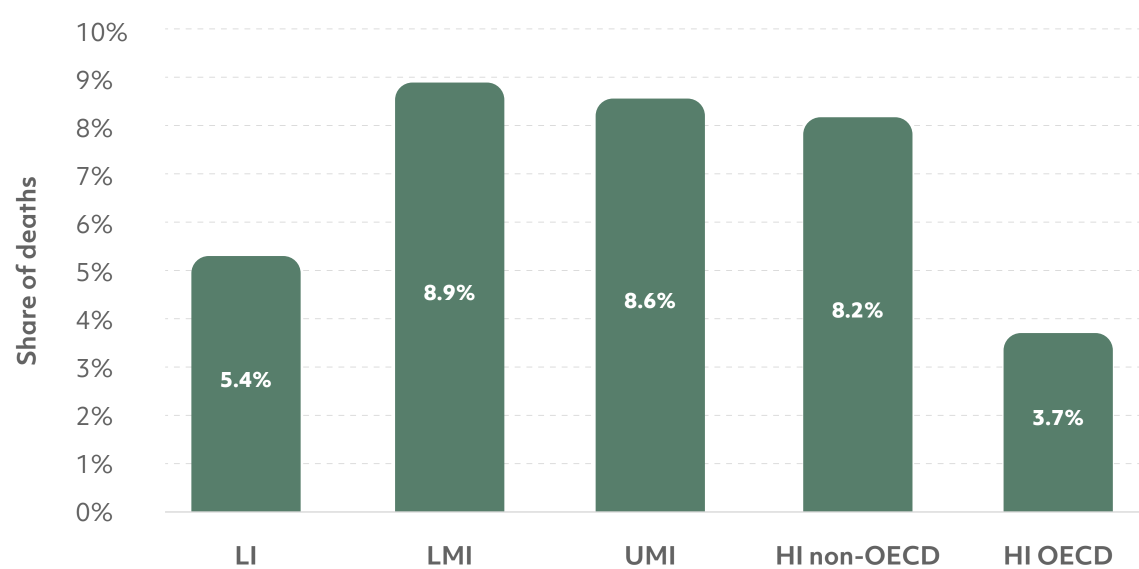
Deaths from ambient $PM_{2.5}$ exposure exceed or approach 10 percent of all deaths in South Asia, Middle East and North Africa, and East Asia and Pacific and 8–9 percent in middle-income and high-income non-OECD countries, compared to 3–4 percent in NA and high-income OECD (figure 17 and figure 18).

FIGURE 17 Deaths from Ambient $PM_{2.5}$ Exposure as a Share of All Deaths in 2016 by Region



Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

FIGURE 18 Deaths from Ambient $PM_{2.5}$ Exposure as a Share of All Deaths in 2016 by Income Group



Source: Based on data from IHME, GBD 2016 study.
Note: LI = low-income countries; LMI = lower-middle-income countries; UMI = upper-middle-income countries; and HI = high-income countries. Classification according to World Bank income taxonomy.

The three (and, in one case, the two) countries in each region with the highest death rates—that is, the number of deaths from ambient $PM_{2.5}$ as a percentage of total deaths—are presented in table 4. The countries with the highest death rates are in Middle East and North Africa, South Asia, Europe and Central Asia, and East Asia and Pacific. There are 10 countries in which deaths from ambient $PM_{2.5}$ exceed 10 percent of total deaths, including Saudi Arabia in Middle East and North Africa.

TABLE 4 Deaths from Ambient $PM_{2.5}$ Exposure as a Share of All Deaths by Country in 2016

Region	Country	Death rate (%)	Region	Country	Death rate (%)
EAP	China	11.1	NA	United States	3.4
	Korea, Dem. People's Rep.	10.0		Canada	2.6
	Mongolia	7.2			
ECA	Tajikistan	11.2	SA	Bangladesh	12.8
	Uzbekistan	9.9		Nepal	11.3
	Turkmenistan	9.7		India	10.6
LAC	Peru	5.8	SSA	Sudan	8.8
	Honduras	5.6		Mauritania	8.8
	Cuba	5.5		Cabo Verde	8.4
MNA	Egypt, Arab Rep.	13.0			
	Kuwait	12.7			
	Saudi Arabia	12.4			

Source: Based on data from IHME, GBD 2016 study.
Note: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; NA = North America; SA = South Asia; SSA = Sub-Saharan Africa.

The GBD 2016 study also estimates that ambient $PM_{2.5}$ air pollution caused morbidity in the magnitude of 6 million YLD in 2016, or about 1.5 YLD per death from ambient $PM_{2.5}$. These YLD are equivalent to nearly 15 billion days of illness, or about 3,600 days of illness per death from ambient $PM_{2.5}$.[14] Morbidity from ambient $PM_{2.5}$ varied substantially relative to mortality across countries, from 0.3–0.5 YLD per death in a dozen countries to as much as 2.0–4.4 in another 11 countries (table D.1, appendix D). YLD per death was lowest in Latin America and the Caribbean (0.73), Sub-Saharan Africa (0.75), Europe and Central Asia (0.80), and Middle East and North Africa (1.07) and highest in East Asia and Pacific (1.60), North America (1.71), and South Asia (1.98).

14 YLD is duration of illness or disability in (fraction of) years multiplied by severity of illness or disability (ranging from 0 to 1).

Global Cost of Ambient $PM_{2.5}$ Exposure

The health damages of ambient $PM_{2.5}$ exposure can be monetized to provide an estimate of the welfare cost of $PM_{2.5}$. The valuation of mortality in this report follows the welfare approach or VSL in World Bank and IHME (2016) (see appendix C). Valuation of morbidity, measured as the cost of days of illness, is valued at wage rates (see appendix D).

The global cost of health damages from ambient $PM_{2.5}$ exposure was $5.7 trillion in 2016, equivalent to 4.8 percent of global GDP (PPP adjusted).[15] This estimate is 50 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, the substantially higher estimate of global ambient $PM_{2.5}$ exposure, and the 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 2016, although the exact contribution of each of these two factors is difficult to ascertain.

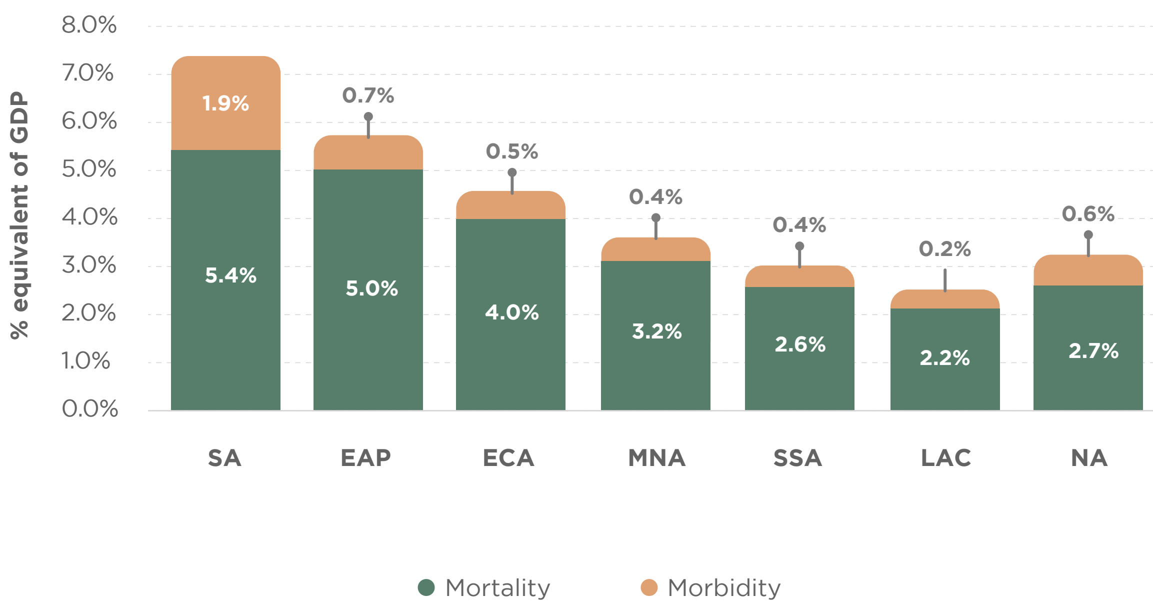
About 87 percent of the total global cost of health damages in 2016 is from premature mortality and 13 percent from morbidity. Cost of morbidity as a share of the total cost of health damages by country varies from as low as 3 percent to as high as 38 percent across countries (see table D.1 in appendix D). Regionally, the morbidity cost-share ranges from 7 percent in Latin America and the Caribbean to 18 percent in NA and 26 percent in South Asia. The share is 10–15 percent in the regions of Europe and Central Asia, Middle East and North Africa, East Asia and Pacific, and Sub-Saharan Africa.

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 total cost of health damages—that is, mortality and morbidity—from ambient $PM_{2.5}$ was the highest in South Asia, at the equivalent of 7.3 percent of GDP, and in upper-middle-income countries, at the equivalent of 6 percent of GDP. The cost was the lowest in Latin America and the Caribbean and Sub-Saharan Africa and low-income countries (figure 19 and figure 20).

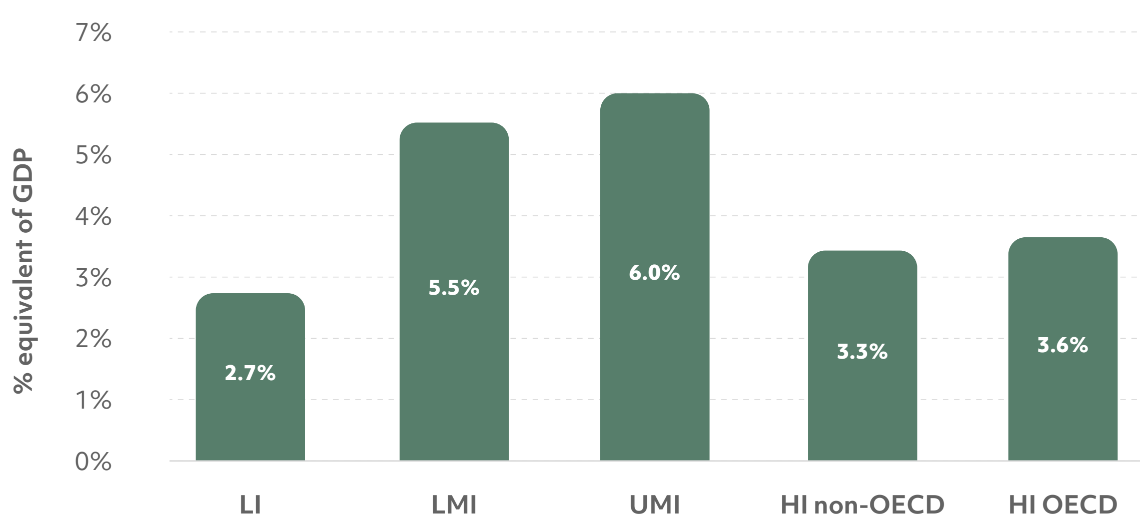
15 Expressed in US dollars, this equates to US$3.3 trillion in 2016, equivalent to 4.4 percent of global GDP.

FIGURE 19 Annual Cost of Health Damage from Ambient $PM_{2.5}$ Exposure, % Equivalent of GDP in 2016 by Region



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

FIGURE 20 Annual Cost of Health Damage from Ambient $PM_{2.5}$ Exposure, % Equivalent of GDP in 2016 by Income Group



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 classifications.

The three (and, in one case, the two) countries in each region with the highest welfare cost of ambient $PM_{2.5}$ as a percentage of GDP are presented in table 5. The countries with the highest costs are in Europe and Central Asia, South Asia, East Asia and Pacific, and Middle East and North Africa. There are 19 countries in which the welfare cost of ambient $PM_{2.5}$ exceeds the equivalent of 7 percent of GDP. Seventeen of these countries are in Europe and Central Asia, and, specifically, in the eastern part of Europe. This is largely associated with the high baseline death rates in this part of Europe. Cost by country is presented in appendix A.

TABLE 5 Annual Cost of Health Damages from Ambient $PM_{2.5}$ by Country, % Equivalent of GDP in 2016

Region	Country	Cost (%)	Region	Country	Cost (%)
EAP	China	7.6	NA	United States	3.4
	Mongolia	4.5		Canada	2.1
	Myanmar	4.3			
ECA	Bulgaria	12.4	SA	India	7.8
	Ukraine	10.4		Pakistan	5.8
	Hungary	9.9		Nepal	5.3
LAC	Cuba	4.3	SSA	Cameroon	4.8
	Trinidad and Tobago	3.6		Central African Republic	4.4
	Barbados	3.5		Chad	4.1
MNA	Egypt, Arab Rep.	6.4			
	Iraq	4.8			
	Tunisia	4.1			

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

The cost of ambient $PM_{2.5}$ air pollution estimated in this report for the year 2016, along with cost estimates in previous reports for previous years, cannot be readily compared to infer whether global air quality has worsened or improved. This is mainly because each cost estimate is based on (i) exposure-response functions that are evolving over time as new evidence becomes available; (ii) 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 (iii) modifications in the valuation in health damages (that is, the inclusion of the 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.

Conclusions

- This report provides an estimate of the global cost of ambient $PM_{2.5}$ air pollution in 2016 based on the GBD 2016 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 2016 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 2016 study that are based on calibration from a substantially larger PM ground-level measurement database than the data used for the GBD 2013 study;
  - Annual deaths of 4.1 million from ambient $PM_{2.5}$ according to the GBD 2016 study, in contrast to 2.9 million according to the GBD 2013 study—a change which is mainly associated with higher health risks of $PM_{2.5}$ and higher estimates of global population exposure to ambient $PM_{2.5}$ in the GBD 2016 study than in the GBD 2013 study, rather than with worsening of air quality; and
  - Inclusion of an estimate of the cost of morbidity based on estimates of YLD from ambient $PM_{2.5}$ reported by the GBD 2016 study.
- Health damages and cost of ambient $PM_{2.5}$ are staggering, especially in developing countries, globally reaching 4.1 million deaths and 15 billion days of illness in 2016, with a welfare cost of $5.7 trillion equivalent to 4.8 percent of global GDP (PPP adjusted).
- This estimated cost for 2016 is 50 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, a 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 an actual worsening of global ambient $PM_{2.5}$ air quality from 2013 to 2016, although the exact contribution of each of these two factors is difficult to ascertain.

- About 87 percent of the total global cost of health damages in 2016 is from premature mortality and 13 percent from morbidity. The cost of morbidity as a share of total cost varies from as low as 3 percent to as high as 27 percent across countries.
- Two-thirds of the health damages occur in the South Asia and East Asia and Pacific regions.
- Costs reach as high as 7.5–8 percent of GDP in China and India, the two countries in which over half of global deaths from ambient $PM_{2.5}$ occur.
- Although the methodology and ground-level measurements data available for the global ambient $PM_{2.5}$ population-exposure estimates from the GBD 2016 study represent important improvements over the estimates from the GBD 2013 study, based on calibration from a larger PM ground-level measurement database, the database nevertheless contains PM measurements from only half of the countries in the world and is almost entirely lacking large parts of Sub-Saharan Africa.
- PM measurements are particularly scarce in low-income countries and Sub-Saharan Africa, with one monitor per 54 and 15 million people, respectively, in contrast to one monitor per 0.3 million people in high-income countries.

Appendixes

Appendix A:
Annual Health Damages and Costs of Ambient $PM_{2.5}$, 2016

TABLE 6 Annual Health Damages and Costs of Ambient $PM_{2.5}$, 2016

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Afganistan	63	26,983	11,838	977	3,265	5.02
Albania	15	1,377	974	521	1,499	4.37
Algeria	37	12,610	15,579	5,165	20,256	3.31
American Samoa	4	2	4	-	-	-
Andorra	11	25	28	-	-	-
Angola	36	7,033	5,941	1,860	3,887	2.08
Antigua and Barbuda	16	19	14	27	43	1.89
Argentina	14	15,611	9,135	18,815	30,127	3.45
Armenia	27	2,075	1,382	640	1,565	6.07
Aruba	-	-	-	-	-	-
Australia	6	3,071	3,226	16,852	15,793	1.40
Austria	15	3,270	3,479	15,834	17,949	4.10
Azerbaijan	33	6,780	4,058	2,406	10,707	6.36
Bahamas, The	13	94	58	257	258	2.84

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Bahrain	80	294	706	748	1,584	2.35
Bangladesh	101	108,687	109,715	11,289	29,749	5.10
Barbados	18	103	70	162	169	3.53
Belarus	20	9,583	5,306	4,605	16,671	9.71
Belgium	16	4,938	5,817	23,324	26,325	5.00
Belize	20	76	45	30	53	1.71
Benin	96	5,630	3,875	305	838	3.55
Bermuda	10	13	10	-	-	-
Bhutan	56	361	697	113	352	5.05
Bolivia	22	3,573	1,831	879	2,048	2.60
Bosnia and Herzegovina	39	3,339	3,308	1,558	3,994	9.41
Botswana	23	602	839	387	953	2.53
Brazil	13	49,724	35,898	40,484	70,801	2.25
Brunei Darussalam	6	39	63	107	307	0.94
Bulgaria	26	9,087	6,178	6,515	17,015	12.43
Burkina Faso	111	10,223	5,130	413	1,094	3.41
Burundi	46	4,730	2,719	74	202	2.47
Cabo Verde	67	238	222	59	130	3.66
Cambodia	26	5,915	7,830	582	1,712	2.91
Cameroon	140	15,986	9,779	1,166	3,708	4.82
Canada	8	6,958	7,410	32,553	33,994	2.13

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Cayman Islands	-	-	-	-	-	-
Central African Republic	66	4,158	1,868	77	140	4.37
Chad	96	9,108	4,174	398	1,194	4.15
Channel Islands	-	-	-	-	-	-
Chile	22	4,918	4,685	6,999	12,158	2.83
China	56	1,075,039	1,644,758	852,964	1,631,202	7.62
Colombia	17	9,668	8,886	5,251	12,806	1.86
Comoros	19	160	131	8	16	1.34
Congo, Dem. Rep.	56	32,664	21,120	822	1,480	2.35
Congo, Rep.	56	1,938	1,655	243	909	3.10
Costa Rica	19	842	992	1,025	1,440	1.78
Côte d'Ivoire	58	12,339	7,314	1,373	3,346	3.80
Croatia	20	3,388	2,749	4,340	8,471	8.61
Cuba	17	5,344	3,193	3,784	7,569	4.34
Curaçao	-	-	-	-	-	-
Cyprus	18	333	305	897	1,254	4.53
Czech Republic	19	6,543	6,226	13,457	25,573	6.98
Denmark	10	1,806	2,042	10,839	10,084	3.54
Djibouti	72	433	359	63	113	3.66
Dominica	17	21	12	13	21	2.54

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Dominican Republic	24	2,964	1,798	1,825	4,128	2.55
Ecuador	13	2,240	1,720	1,144	2,163	1.17
Egypt, Arab Rep.	126	67,555	62,069	21,604	68,429	6.42
El Salvador	33	1,969	1,365	706	1,441	2.64
Equatorial Guinea	71	240	389	217	666	2.14
Eritrea	51	1,832	1,264	-	-	-
Estonia	6	388	271	728	1,216	3.14
Eswatini	24	425	402	111	335	2.99
Ethiopia	50	37,342	27,642	1,683	4,131	2.33
Faroe Islands	-	-	-	-	-	-
Fiji	8	191	183	90	167	1.94
Finland	6	1,099	1,286	5,425	5,420	2.29
France	12	16,444	12,083	67,383	75,814	2.73
French Polynesia	-	-	-	-	-	-
Gabon	47	684	690	482	1,215	3.39
Gambia, The	95	754	579	23	83	2.41
Georgia	21	3,533	1,997	1,142	2,963	7.97
Germany	13	36,938	40,479	170,910	198,597	4.93
Ghana	54	11,803	8,768	1,344	3,814	3.15
Gibraltar	-	-	-	-	-	-

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Greece	11	5,818	6,977	11,661	17,251	5.99
Greenland	4	3	5	-	-	-
Grenada	18	39	18	33	49	3.27
Guam	9	58	71	-	-	-
Guatemala	29	4,105	2,420	1,400	2,683	2.04
Guinea	46	6,585	3,422	196	506	3.11
Guinea-Bissau	59	1,153	619	44	112	3.90
Guyana	20	295	116	106	186	3.07
Haiti	24	4,941	1,613	220	530	2.74
Honduras	29	2,516	1,544	454	911	2.11
Hong Kong SAR, China	-	-	-	-	-	-
Hungary	25	8,999	7,971	12,355	26,028	9.94
Iceland	7	58	78	393	337	1.96
India	76	1,034,420	2,274,778	177,298	681,683	7.83
Indonesia	17	79,739	141,136	28,062	91,270	3.01
Iran, Islamic Rep.	49	28,716	34,603	13,890	47,760	3.53
Iraq	73	18,191	14,795	8,245	31,040	4.81
Ireland	9	1,060	1,258	6,827	7,633	2.32
Isle of Man	-	-	-	-	-	-
Israel	19	1,815	2,399	8,032	8,163	2.52

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (µg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Italy	15	24,555	22,019	85,764	107,210	4.64
Jamaica	15	802	504	330	599	2.35
Japan	13	45,783	71,794	207,804	221,564	4.21
Jordan	37	1,621	2,398	696	1,540	1.80
Kazakhstan	20	9,360	6,341	7,105	23,901	5.32
Kenya	16	6,509	6,142	748	1,621	1.06
Kiribati	4	8	7	1	1	0.48
Korea, Dem. People's Rep.	36	23,360	22,642	-	-	-
Korea, Rep.	29	16,803	40,527	59,523	77,273	4.22
Kosovo	-	-	-	-	-	-
Kuwait	111	860	2,115	2,498	6,363	2.19
Kyrgyz Republic	18	2,480	1,347	191	628	2.91
Lao PDR	28	3,183	3,786	631	1,658	3.97
Latvia	15	1,670	1,166	2,457	4,530	8.88
Lebanon	33	1,796	2,697	1,453	2,570	3.06
Lesotho	27	1,021	759	74	226	3.38
Liberia	17	968	635	25	45	1.21
Libya	64	2,421	3,204	-	-	-
Liechtenstein	-	-	-	-	-	-
Lithuania	17	2,496	1,687	3,945	7,945	9.23

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (µg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Luxembourg	16	175	239	1,758	1,810	2.93
Macao SAR, China	-	-	-	-	-	-
Madagascar	21	8,500	5,226	207	777	2.07
Malawi	28	5,126	3,231	91	354	1.67
Malaysia	18	10,461	18,160	11,693	34,060	3.95
Maldives	27	84	221	80	123	2.23
Mali	92	6,385	5,165	350	948	2.49
Malta	12	150	146	429	649	3.92
Marshall Islands	11	15	17	4	5	2.22
Mauritania	124	1,762	1,650	153	546	3.29
Mauritius	14	420	833	441	966	3.62
Mexico	19	24,390	22,256	19,333	42,106	1.85
Micronesia, Fed. Sts.	9	25	22	6	7	1.79
Moldova	20	3,175	1,639	477	1,340	7.07
Monaco	-	-	-	-	-	-
Mongolia	30	1,536	879	503	1,669	4.51
Montenegro	20	421	322	277	696	6.63
Morocco	25	12,406	12,305	3,138	8,684	3.09
Mozambique	21	6,689	4,596	150	477	1.36
Myanmar	49	25,280	55,512	2,932	13,273	4.35

	Annual $PM_{2.5}$ (µg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	Cost of health damages from $PM_{2.5}$ US$, Millions	$ (PPP), Millions	% of GDP equivalent
Namibia	26	657	816	266	680	2.59
Nauru	-	-	-	-	-	-
Nepal	78	20,453	33,528	1,117	3,780	5.28
Netherlands	15	6,337	9,031	32,458	36,474	4.21
New Caledonia	-	-	-	-	-	-
New Zealand	6	552	511	2,413	2,391	1.30
Nicaragua	23	1,017	892	176	454	1.33
Niger	204	14,390	7,582	302	814	4.02
Nigeria	122	68,887	59,119	12,313	33,170	3.04
North Macedonia	32	1,599	1,447	814	2,351	7.47
Northern Mariana Islands	11	11	37	-	-	-
Norway	8	1,097	1,411	8,299	6,950	2.24
Oman	78	1,193	1,910	2,059	5,873	3.11
Pakistan	76	124,577	174,172	16,486	58,943	5.81
Palau	-	-	-	-	-	-
Panama	14	653	626	908	1,528	1.65
Papua New Guinea	14	3,312	2,904	517	654	3.06
Paraguay	24	1,881	1,245	662	1,553	2.41
Peru	26	7,526	5,549	4,004	8,624	2.08
Philippines	23	44,389	71,263	11,837	31,312	3.88

	Annual $PM_{2.5}$ (µg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	Cost of health damages from $PM_{2.5}$ US$, Millions	$ (PPP), Millions	% of GDP equivalent
Poland	26	26,382	23,847	35,256	79,248	7.51
Portugal	9	3,576	2,918	7,807	12,067	3.82
Puerto Rico (US)	20	1,358	1,036	-	-	-
Qatar	148	290	1,263	1,570	3,374	1.03
Romania	19	16,933	12,553	16,474	41,082	8.82
Russian Federation	16	125,455	78,840	111,381	294,897	8.68
Rwanda	53	3,765	3,088	179	488	2.14
Samoa	4	10	10	4	6	0.46
Saint Martin (French)	-	-	-	-	-	-
San Marino	-	-	-	-	-	-
São Tomé and Principe	15	41	33	6	11	1.64
Saudi Arabia	188	11,210	18,537	24,473	66,510	3.79
Senegal	57	6,219	4,431	412	1,105	2.79
Serbia	19	5,968	5,472	3,158	8,570	8.37
Seychelles	15	30	58	53	101	3.74
Sierra Leone	42	3,049	1,669	95	283	2.60
Singapore	25	1,373	2,143	7,187	11,922	2.42
Sint Maarten (Dutch)	-	-	-	-	-	-
Slovak Republic	20	3,614	2,970	6,456	11,989	7.21
Slovenia	18	905	1,065	2,356	3,636	5.36

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Solomon Islands	9	144	115	20	22	1.66
Somalia	24	4,024	1,749	-	-	-
South Africa	36	21,061	32,619	11,669	29,264	3.96
South Sudan	49	6,926	3,620	348	882	3.85
Spain	10	12,289	9,448	37,072	50,740	3.01
Sri Lanka	26	7,330	16,965	3,470	11,144	4.27
St. Kitts and Nevis	-	-	-	-	-	-
St. Lucia	17	44	34	30	45	2.21
St. Vincent and the Grenadines	17	38	18	23	38	2.98
Sudan	78	19,046	14,805	3,784	7,411	3.96
Suriname	22	191	109	114	248	3.14
Sweden	5	1,384	1,796	8,061	7,682	1.58
Switzerland	11	2,041	3,177	17,900	14,282	2.71
Syrian Arab Republic	44	6,789	5,486	-	-	-
Tajikistan	61	4,651	2,679	245	919	3.53
Tanzania	22	14,314	9,080	850	2,693	1.79
Thailand	23	25,432	65,373	15,832	45,334	3.89
Timor-Leste	17	256	433	28	56	1.97
Togo	84	3,603	2,437	138	357	3.15
Tonga	4	5	6	2	3	0.42

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Trinidad and Tobago	17	473	299	761	1,580	3.63
Tunisia	36	4,932	5,483	1,736	5,460	4.13
Turkey	37	27,103	45,783	32,340	72,681	3.77
Turkmenistan	38	3,185	1,417	1,903	5,029	5.26
Turks and Caicos Islands	-	-	-	-	-	-
Tuvalu	-	-	-	-	-	-
Uganda	74	14,566	10,568	584	1,754	2.29
Ukraine	19	53,665	26,015	9,715	36,765	10.42
United Arab Emirates	105	3,093	6,732	11,794	22,702	3.38
United Kingdom	12	24,231	22,706	108,127	115,470	4.13
United States	9	93,376	164,451	622,383	622,383	3.35
Uruguay	12	1,188	887	1,799	2,555	3.43
Uzbekistan	47	20,297	9,605	3,365	10,385	5.01
Vanuatu	9	83	63	17	18	2.19
Venezuela, RB	26	8,559	7,319	-	-	-
Vietnam	26	40,170	78,104	7,835	23,030	3.87
Virgin Islands (British)	-	-	-	-	-	-
Virgin Islands (US)	18	61	31	-	-	-
West Bank and Gaza	19	1,289	876	286	286	2.14
Yemen, Rep.	73	12,562	9,531	911	2,308	3.34

				Cost of health damages from $PM_{2.5}$		
	Annual $PM_{2.5}$ (μg/m³)	Deaths from $PM_{2.5}$	YLD from $PM_{2.5}$	US$, Millions	$ (PPP), Millions	% of GDP equivalent
Zambia	31	5,713	3,431	495	1,647	2.53
Zimbabwe	25	4,552	3,772	308	613	1.89

Source: Ambient $PM_{2.5}$ is from the World Development Indicators (database), http://datatopics.worldbank.org/world-development-indicators/. Annual deaths from $PM_{2.5}$ are from the GBD 2016 study. The annual cost is estimated using the methodology applied in World Bank and IHME (2016).
Note: Cost of health damages of $PM_{2.5}$ is not estimated for some countries and territories due to lack of estimate of deaths from ambient $PM_{2.5}$ in the GBD 2016 study or absence of GDP per capita (PPP) in the World Development Indicators Database.

Appendix B: Health Damages of Ambient $PM_{2.5}$

Particulate matter, and especially $PM_{2.5}$, is the ambient air pollutant that is associated globally 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, and ALRI (Lim et al. 2012; Mehta et al. 2013; GBD 2013 Risk Factors Collaborators 2015; GBD 2015 Risk Factors Collaborators 2016; GBD 2016 Risk Factors Collaborators 2017; Pope et al. 2009; Pope et al. 2011). The methodologies to estimate these health damages have evolved as the body of research evidence has increased.

Ambient PM air pollution

Over a decade ago, Pope et al. (2002) found an elevated risk of cardiopulmonary and lung cancer mortality from long-term exposure to outdoor $PM_{2.5}$ in a study of a large population of adults 30 or more years of age in the United States. Cardiopulmonary mortality includes mortality from respiratory infections, cardiovascular disease, and chronic respiratory disease. The WHO used the findings of research by Pope and his colleagues—see Pope et al. (2009) and Pope et al. (2011)—when estimating global mortality from outdoor air pollution (Ezzati et al. 2004; WHO 2009). Since then, recent research suggests that the *marginal increase* in the relative risk of mortality from $PM_{2.5}$ declines with increasing concentrations of $PM_{2.5}$ (Pope et al. 2009; Pope et al. 2011). Pope et al. (2009) and Pope et al. (2011) derive a shape of the $PM_{2.5}$ exposure-response curve based on studies of mortality from actively smoking cigarettes, secondhand smoke, and outdoor $PM_{2.5}$ air pollution.

An integrated exposure-response function

The GBD 2010–2016 studies take Pope et al. (2009) and Pope et al. (2011) some steps further by deriving an IER relative risk function, *RR*, for disease outcome, *k*, in age group, *l*, associated with exposure to fine particulate matter pollution ($PM_{2.5}$) both in the ambient and household environments:

$$RR(x)_{kl} = 1 \quad \text{for } x < xcf \quad \text{(A2.1a)}$$

$$RR(x)_{kl} = 1 + \alpha_{kl}\left(1 - e^{-\beta_{kl}(x - x_{cf})^{\rho_{kl}}}\right) \quad \text{for } x \geq xcf \quad \text{(A2.1b)}$$

where *x* is the ambient concentration of $PM_{2.5}$ in *μg/m³* and x_{cf} is a counterfactual concentration below which it is assumed that no association exists. The function allows for the prediction of relative risks over a very large range of $PM_{2.5}$ concentrations, with $RR(xcf + 1) \sim 1 + \alpha\beta$ and $RR(\infty) = 1 + \alpha$ being the maximum risk (Burnett et al. 2014; Shin et al. 2013).

The parameter values of the risk function are derived based on studies of health outcomes associated with long-term exposure to ambient PM pollution, secondhand tobacco smoke, household air pollution from solid cooking fuels, and active tobacco smoking (Burnett et al. 2014). 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 the combustion of solid fuels.

The disease outcomes assessed are IHD, cerebrovascular disease (stroke), lung cancer, COPD, and ALRI. The risk functions for IHD and cerebrovascular disease 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, and ALRI.

The attributable fraction of disease from $PM_{2.5}$ exposure is calculated by the following expression:

$$AF = \sum_{i=1}^{n} P_i\left[RR\left(\frac{x_i + x_{i-1}}{2}\right) - 1\right] / \left(\sum_{i=1}^{n} P_i\left[RR\left(\frac{x_i + x_{i-1}}{2}\right) - 1\right] + 1\right) \quad \text{(A2.2)}$$

where P_i is the share of the population exposed to $PM_{2.5}$ concentrations in the range x_{i-1} to x_i. This attributable fraction is calculated for each disease outcome *k* and age group *l*. The disease burden (*B*) in terms of annual cases of disease outcomes due to $PM_{2.5}$ exposure is then estimated by:

$$B = \sum_{k=1}^{t} \sum_{l=1}^{s} D_{kl} AF_{kl} \quad \text{(A2.3)}$$

where D_{kl} is the total annual number of cases of disease *k* in age group *l*, and AF_{kl} is the attributable fraction of these cases of disease *k* in age group *l* due to $PM_{2.5}$ exposure.

Appendix C: Valuation of Premature Mortality

The predominant measure of the welfare cost of premature death used by economists is VSL. VSL is based on the 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 accidents than 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 (WTP) 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:

$$VSL = WTP_{Ave} \times 1/R \qquad \text{(A3.1)}$$

where WTP_{Ave} is the average WTP 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_{Ave} = US$40. Thus, if 10 individuals die from the health risk illustrated above, the cost to society is 10 x VSL = 10 x US$0.16 million = US$1.6 million.

The main approaches to estimating VSL are through the revealed preferences and the stated preferences of people's WTP for a reduction in mortality risk or their willingness to accept 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, which in various forms ask individuals about their WTP for mortality risk reduction.

Studies of WTP for a reduction in the 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 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. A meta-analysis prepared for the OECD is, however, exclusively based on stated-preference studies, which are arguably of greater relevance for the 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 recent publication by the World Bank and IHME (2016) on the global cost of air pollution. The proposed benefit transfer function is:

$$VSL_{c,n} = VSL_{OECD} * \left(\frac{Y_{c,n}}{Y_{OECD}}\right)^{\epsilon} \qquad \text{(A3.2)}$$

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, and Y_{OECD} is the average GDP per capita for the sample of OECD countries ($37,000), and ε an 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 Database from the World Bank.

Appendix D: Valuation of Morbidity

Two valuation techniques are commonly used to estimate the cost of morbidity or illness. The cost-of-illness approach includes the cost of medical treatment, the value of income, and the time lost to illness. The second approach equates the cost of illness to individuals' WTP for avoiding an episode of illness. The latter therefore 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 both the cost of mortality and morbidity (OECD 2016). Mortality is valued using VSL, and the cost of morbidity is estimated both in terms of

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

ii. Nonmarket impacts (welfare cost of pain and suffering from illness).

Globally, the OECD estimated the cost of market impacts or cost-of-illness to 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 0.7–0.9 percent of GDP or 13–17 percent of the cost of mortality according to OCED report.

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

i. Estimates of YLD from ambient $PM_{2.5}$ from the GBD 2016 study are converted to days of illness by applying the disability weights in the GBD studies.

ii. The cost of a day of illness is then approximated as the average daily wage rates to reflect income losses from illness, health expenditure, time losses, and the welfare cost of pain and suffering.

iii. 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 (D) in country k are calculated as:

$$D_k = YLD_k * 365 / d$$

where YLD is years lost to disease from exposure to ambient $PM_{2.5}$, taken from the GBD 2016 study, and d is the disability weight of disease, here applied a weight of 0.15.

The disability weight is a measure used in the GBD studies to calculate YLD from days of illness, disease, or injury. The weight for diseases associated with exposure to ambient $PM_{2.5}$ ranges from 0.006 to 0.133 for infectious diseases (for example, ALRI); from 0.036 to 0.569 for cancers (for example, lung cancer); from 0.033 to 0.224 for heart disease; from 0.019 to 0.588 for stroke; and from 0.019 to 0.408 for COPD, with the ranges reflecting various degrees of severity and stages of illness and treatments (Salomon et al. 2015). A disability weight of 0.15, as applied here, is the weighted average for mild, moderate, and severe illness (with frequency distributions of 45 percent, 45 percent, and 10 percent respectively) weighted by each illness's share of global YLD from ambient $PM_{2.5}$ exposure.

Cost of morbidity (C) in country k is calculated as follows:

$$C_k = D_k * w_k \quad \text{(A4.2)}$$

or

$$C_k = YLD_k * 365 * (w_k/d) \quad \text{(A4.3)}$$

where w is the average daily wage rate, or the cost per day of illness.[16] The average daily wage rate is estimated as follows:

$$w_k = GDP_k / L_k / 250 * s_k \quad \text{(A4.4)}$$

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 Database (http://datatopics.worldbank.org/world-development-indicators/) and s is from PENN World Table, version 8.

This provides an estimated global cost of morbidity from ambient $PM_{2.5}$ equivalent to 0.6 percent of GDP in 2016 or 16 percent of the cost of mortality. This is very close to the estimates by OECD presented above.

The cost of morbidity, as a share of the total cost of health damages of ambient $PM_{2.5}$, varies from 3 percent to 38 percent across countries. The share is mainly determined by YLD per death from ambient $PM_{2.5}$ as well as wage rate relative to GDP per capita. YLD per death varies from 0.33 to 4.36 across countries (table D.1).

TABLE 7 Years of Life Lived with Disability (YLD) from Ambient $PM_{2.5}$ in 2016

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Afghanistan	11,838	0.44	113	12
Albania	974	0.71	50	10
Algeria	15,579	1.24	972	19
American Samoa	4	1.60	-	-
Andorra	28	1.13	-	-

16 Note that the cost of morbidity, C_k, is independent of the numerical value of d if the cost per day of illness, w_k, varies in proportion to the disability of illness, d (that is, $w_k = w_k(d) = \beta k\ d$ where βk is a constant). This can be seen by substituting $\beta^k d$ for w_k in equation A4.3.

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Angola	5,941	0.84	261	14
Antigua and Barbuda	14	0.74	2	8
Argentina	9,135	0.591	1,039	6
Armenia	1,382	0.67	59	9
Aruba	-	-	-	-
Australia	3,226	1.05	1,709	10
Austria	3,479	1.06	1,757	11
Azerbaijan	4,058	0.60	70	3
Bahamas, The	58	0.62	9	4
Bahrain	706	2.41	102	14
Bangladesh	109,715	1.01	1,707	15
Barbados	70	0.68	15	10
Belarus	5,306	0.55	317	7
Belgium	5,817	1.18	3,246	14
Belize	45	0.59	2	8
Benin	3,875	0.69	44	14
Bermuda	10	0.77	-	-
Bhutan	697	1.93	34	30
Bolivia	1,831	0.51	50	6
Bosnia and Herzegovina	3,308	0.99	257	16
Botswana	839	1.39	26	7

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Brazil	35,898	0.72	3,253	8
Virgin Islands (British)	-	-	-	-
Brunei Darussalam	63	1.62	13	13
Bulgaria	6,178	0.68	451	7
Burkina Faso	5,130	0.50	41	10
Burundi	2,719	0.57	10	13
Cabo Verde	222	0.93	7	12
Cambodia	7,830	1.32	91	16
Cameroon	9,779	0.61	113	10
Canada	7,410	1.06	3,224	10
Cayman Islands	-	-	-	-
Central African Republic	1,868	0.45	2	3
Chad	4,174	0.46	49	12
Channel Islands	-	-	-	-
Chile	4,685	0.95	562	8
China	1,644,758	1.53	93,045	11
Colombia	8,886	0.92	457	9
Comoros	131	0.82	1	18
Congo, Dem. Rep.	21,120	0.65	123	15
Congo, Rep.	1,655	0.85	32	13
Costa Rica	992	1.18	147	14

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Côte d'Ivoire	7,314	0.59	142	10
Croatia	2,749	0.81	465	11
Cuba	3,193	0.60	264	7
Curaçao	-	-	-	
Cyprus	305	0.91	72	8
Czech Republic	6,226	0.95	1,243	9
Denmark	2,042	1.13	1,423	13
Djibouti	359	0.83	12	18
Dominica	12	0.59	1	8
Dominican Republic	1,798	0.61	98	5
Ecuador	1,720	0.77	52	5
Egypt, Arab Rep.	62,069	0.92	2,276	11
El Salvador	1,365	0.69	63	9
Equatorial Guinea	389	1.62	25	12
Eritrea	1,264	0.69	-	-
Estonia	271	0.70	54	7
Eswatini	402	0.95	21	19
Ethiopia	27,642	0.74	202	12
Faroe Islands	-	-	-	-
Fiji	183	0.95	12	13
Finland	1,286	1.17	670	12

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
France	12,083	0.73	6,064	9
French Polynesia	-	-	-	-
Gabon	690	1.01	41	8
Gambia, The	579	0.77	3	14
Georgia	1,997	0.57	57	5
Germany	40,479	1.10	19,157	11
Ghana	8,768	0.74	142	11
Gibraltar	-	-	-	-
Greece	6,977	1.20	1,439	12
Greenland	5	1.40	-	-
Grenada	18	0.47	2	6
Guam	71	1.23	-	-
Guatemala	2,420	0.59	105	7
Guinea	3,422	0.52	19	9
Guinea-Bissau	619	0.54	5	10
Guyana	116	0.39	6	6
Haiti	1,613	0.33	14	6
Honduras	1,544	0.61	47	10
Hong Kong SAR, China	-	-	-	-
Hungary	7,971	0.89	1,304	11
Iceland	78	1.35	58	15

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
India	2,274,778	2.20	47,747	27
Indonesia	141,136	1.77	4,689	17
Iran, Islamic Rep.	34,603	1.21	1,270	9
Iraq	14,795	0.81	785	10
Ireland	1,258	1.19	855	13
Isle of Man	-	-	-	-
Israel	2,399	1.32	1,059	13
Italy	22,019	0.90	8,647	10
Jamaica	504	0.63	27	8
Japan	71,794	1.57	27,633	13
Jordan	2,398	1.48	178	26
Kazakhstan	6,341	0.68	363	5
Kenya	6,142	0.94	148	20
Kiribati	7	0.84	0	14
Korea, Dem. People's Rep.	22,642	0.97	-	-
Korea, Rep.	40,527	2.41	11,294	19
Kosovo	-	-	-	-
Kuwait	2,115	2.46	251	10
Kyrgyz Republic	1,347	0.54	18	9
Lao PDR	3,786	1.19	89	14
Latvia	1,166	0.70	182	7

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Lebanon	2,697	1.50	242	17
Lesotho	759	0.74	10	14
Liberia	635	0.66	4	16
Libya	3,204	1.32	-	-
Liechtenstein	-	-	-	-
Lithuania	1,687	0.68	260	7
Luxembourg	239	1.36	244	14
Macao SAR, China	-	-	-	-
Madagascar	5,226	0.61	21	10
Malawi	3,231	0.63	11	12
Malaysia	18,160	1.74	1,983	17
Maldives	221	2.64	19	24
Mali	5,165	0.81	59	17
Malta	146	0.97	43	10
Marshall Islands	17	1.16	1	16
Mauritania	1,650	0.94	28	18
Mauritius	833	1.98	67	15
Mexico	22,256	0.91	1,434	7
Micronesia, Fed. Sts.	22	0.86	1	13
Moldova	1,639	0.52	53	11
Monaco	-	-	-	-

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Mongolia	879	0.57	34	7
Montenegro	322	0.76	27	10
Morocco	12,305	0.99	471	15
Mozambique	4,596	0.69	16	11
Myanmar	55,512	2.20	630	22
Namibia	816	1.24	47	18
Nauru	-	-	-	-
Nepal	33,528	1.64	219	20
Netherlands	9,031	1.43	4,584	14
New Caledonia	-	-	-	-
New Zealand	511	0.93	185	8
Nicaragua	892	0.88	21	12
Niger	7,582	0.53	41	13
Nigeria	59,119	0.86	1,568	13
North Macedonia	1,447	0.91	90	11
Northern Mariana Islands	37	3.28	-	-
Norway	1,411	1.29	981	12
Oman	1,910	1.60	154	7
Pakistan	174,172	1.40	3,675	22
Palau	-	-	-	-
Panama	626	0.96	67	

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Papua New Guinea	2,904	0.88	72	14
Paraguay	1,245	0.66	56	8
Peru	5,549	0.74	182	5
Philippines	71,263	1.61	1,904	16
Poland	23,847	0.90	3,344	9
Portugal	2,918	0.82	746	10
Puerto Rico (US)	1,036	0.76	-	-
Qatar	1,263	4.36	180	11
Romania	12,553	0.74	1,293	8
Russian Federation	78,840	0.63	7,931	7
Rwanda	3,088	0.82	28	16
Samoa	10	0.99	1	21
San Marino	-	-	-	-
São Tomé and Principe	33	0.82	1	21
Saudi Arabia	18,537	1.65	2,958	12
Senegal	4,431	0.71	50	12
Serbia	5,472	0.92	419	13
Seychelles	58	1.95	10	18
Sierra Leone	1,669	0.55	13	14
Singapore	2,143	1.56	856	12
Sint Maarten (Dutch)	-	-	-	-

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Slovak Republic	2,970	0.82	513	8
Slovenia	1,065	1.18	311	13
Solomon Islands	115	0.80	3	14
Somalia	1,749	0.43	-	-
South Africa	32,619	1.55	2,310	20
South Sudan	3,620	0.52	46	13
Spain	9,448	0.77	3,199	9
Sri Lanka	16,965	2.31	1,135	33
St. Kitts and Nevis	-	-	-	-
St. Lucia	34	0.77	2	8
Saint Martin (French)	-	-	-	-
St. Vincent and the Grenadines	18	0.48	1	6
Sudan	14,805	0.78	628	17
Suriname	109	0.57	8	7
Sweden	1,796	1.30	1,078	13
Switzerland	3,177	1.56	2,922	16
Syrian Arab Republic	5,486	0.81	-	-
Tajikistan	2,679	0.58	14	6
Tanzania	9,080	0.63	73	9
Thailand	65,373	2.57	2,533	16
Timor-Leste	433	1.69	11	38

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Togo	2,437	0.68	25	18
Tonga	6	1.13	0	17
Trinidad and Tobago	299	0.63	30	4
Tunisia	5,483	1.11	243	14
Turkey	45,783	1.69	4,529	14
Turkmenistan	1,417	0.44	103	5
Turks and Caicos Islands	-	-	-	-
Tuvalu	-	-	-	-
Uganda	10,568	0.73	74	13
Ukraine	26,015	0.48	716	7
United Arab Emirates	6,732	2.18	1,263	11
United Kingdom	22,706	0.94	10,834	10
United States	164,451	1.76	113,746	18
Uruguay	887	0.75	117	6
Uzbekistan	9,605	0.47	232	7
Vanuatu	63	0.77	2	12
Venezuela, RB	7,319	0.86	-	-
Vietnam	78,104	1.94	1,432	18
Virgin Islands (US)	31	0.51	-	-
West Bank and Gaza	876	0.68	49	17

	YLD from $PM_{2.5}$	YLD per death from $PM_{2.5}$	Cost of morbidity (US$, millions)	Cost of morbidity (% of total cost of health damages)
Yemen, Rep.	9,531	0.76	160	18
Zambia	3,431	0.60	50	10
Zimbabwe	3,772	0.83	43	14

Source: Annual YLD from $PM_{2.5}$ is from the GBD 2016 study. The annual cost is estimated using the methodology presented in this annex.
Note: Cost of morbidity of $PM_{2.5}$ is not estimated for some countries and territories due to lack of estimate of YLD from ambient $PM_{2.5}$ in the GBD 2016 study or absence of GDP per capita in the World Development Indicators Database (http://datatopics.worldbank.org/world-development-indicators/).

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.

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 RW, 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.

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, 2002.

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 2010 Risk Factors Collaborators. 2012. "GBD 2010: A Multi-Investigator Collaboration for Global Comparative Descriptive Epidemiology." *Lancet* 380 (9859): 2055–58.

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.

Heft-Neal, S., J. Burney, E. Bendavid, and **M. Burk.** 2018. "Robust Relationship Between Air Quality and Infant Mortality in Africa." *Nature* 559(7713): 254–8.

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. 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. Poto nik, 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 Consensus Center, Copenhagen. 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." Report prepared for the World Bank, Washington, DC.

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.* 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.

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.

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.

Salomon, J. A., J. A. Haagsma, A. Davis, C. M. de Noordhout, S. Polinder, A. H. Havelaar, A. Cassini, B. Devleesschauwer, M. Kretzschmar, N. Speybroeck, C. J. Murray, and **T. Vos.** 2015. "Disability Weights for the Global Burden of Disease 2013 Study." *Lancet Global Health* 3: e712–23.

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, 2013.

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.

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

World Bank. 2020a. *Air Pollution and Climate. How Many Stones to Hit Both Targets?* Washington, DC: World Bank.

World Bank. 2020b. *Implications of Exposure to Dust on the Burden of Disease from Air Pollution*. Washington, DC: World Bank.

World Bank. 2020c. *Are All Air Pollution Particles Equal? – How Constituents and Sources of Fine Air Pollution Particles ($PM_{2.5}$) Affect Health.* 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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