The Cost of Air Pollution

Strengthening the Economic Case for Action

WORLD BANK GROUP

IHME

The Cost of Air Pollution

Strengthening the Economic Case for Action

The World Bank and Institute for Health Metrics and Evaluation
University of Washington, Seattle

WORLD BANK GROUP

IHME

© 2016 International Bank for Reconstruction and Development/The World Bank
1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

Some rights reserved
1 2 3 4 19 18 17 16

This work is a product of the staff of The World Bank with external contributions. The findings, interpretations, and conclusions expressed in this work do not necessarily reflect the views of The World Bank, its Board of Executive Directors, or the governments they represent. The World Bank does not guarantee the accuracy of the data included in this work. The boundaries, colors, denominations, and other information shown on any map in this work do not imply any judgment on the part of The World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Nothing herein shall constitute or be considered to be a limitation upon or waiver of the privileges and immunities of The World Bank, all of which are specifically reserved.

Rights and Permissions

This work is available under the Creative Commons Attribution 3.0 IGO license (CC BY 3.0 IGO) http://creativecommons.org/licenses/by/3.0/igo. Under the Creative Commons Attribution license, you are free to copy, distribute, transmit, and adapt this work, including for commercial purposes, under the following conditions:

Attribution—Please cite the work as follows: World Bank and Institute for Health Metrics and Evaluation. 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action*. Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0 IGO

Translations—If you create a translation of this work, please add the following disclaimer along with the attribution: *This translation was not created by The World Bank and should not be considered an official World Bank translation. The World Bank shall not be liable for any content or error in this translation.*

Adaptations—If you create an adaptation of this work, please add the following disclaimer along with the attribution: *This is an adaptation of an original work by The World Bank. Views and opinions expressed in the adaptation are the sole responsibility of the author or authors of the adaptation and are not endorsed by The World Bank.*

Third-party content—The World Bank does not necessarily own each component of the content contained within the work. The World Bank therefore does not warrant that the use of any thirdparty-owned individual component or part contained in the work will not infringe on the rights of those third parties. The risk of claims resulting from such infringement rests solely with you. If you wish to re-use a component of the work, it is your responsibility to determine whether permission is needed for that re-use and to obtain permission from the copyright owner. Examples of components can include, but are not limited to, tables, figures, or images.

All queries on rights and licenses should be addressed to the Publishing and Knowledge Division, The World Bank, 1818 H Street NW, Washington, DC 20433, USA; fax: 202-522-2625; e-mail: pubrights@ worldbank.org.

Cover photo: Chris Stowers/Panos. Used with permission. Further permission required for reuse.
Cover design: Bill Pragluski, Critical Stages, LLC.

Contents

Appendixes

Boxes

Figures

Maps

Tables

Foreword

The science is clear: breathing polluted air increases the risk of debilitating and deadly diseases such as lung cancer, stroke, heart disease, and chronic bronchitis. Air pollution is now the world's fourth-leading fatal health risk, causing one in ten deaths in 2013.

At the same time, air pollution from industries, construction sites, agricultural practices, vehicles, and the combustion of dirty energy sources continues to grow. About 87 percent of the world's population now live in countries in which ambient pollution levels exceed air quality guidelines set by the World Health Organization. In low- and middle-income countries, the danger is even more pronounced: 90 percent of the population in these countries was exposed to dangerous levels of ambient air pollution in 2013.

To reduce the number of people gradually being contaminated by the air they breathe, pollution control would need to be at the top of the agenda for most governments. However, in most countries, such expenditure competes with other budgetary priorities and policy objectives. Demonstrating the economic burden of pollution can help tilt the balance of decisions in favor of investments in clean air.

This study is the result of a collaboration between the World Bank and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, Seattle. It represents an effort to merge cutting edge science and rigorous economic analysis for the good of public health.

The study has found that premature deaths due to air pollution in 2013 cost the global economy about $225 billion in lost labor income, or about $5.11 trillion in welfare losses worldwide. That is about the size of the gross domestic product of India, Canada, and Mexico combined—and a sobering wake-up call.

However impressive and abstract these large numbers are, it is our hope that the cost of premature deaths for countries' economies will leave the pages of this study and inform public debate and policy decisions at the national level. In country after country, the cost of pollution in human lives and on the quality of life is too high. We must work together to reduce it.

Laura Tuck
Vice President, Sustainable Development, World Bank,

Keith Hansen,
Vice President, Human Development, World Bank
Keith E. Hansen

Christopher Murray
Director, Institute for Health Metrics and Evaluation, University of Washington

Acknowledgments

This is a joint report of the World Bank and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, Seattle. The core team, led by Urvashi Narain (World Bank), comprised Christopher Sall (World Bank), Michael Brauer (The University of British Columbia), Aaron Cohen (Health Effects Institute), Kara Estep (IHME), Mohammad Forouzanfar (IHME), Zhiyun Jiang (World Bank), and Kevin O'Rourke (IHME). Contributions were also received from Lelia Croitoru (World Bank), Andreas Kopp (World Bank), and Maria Sarraf (World Bank).

The team thanks Paula Caballero (World Bank), Valerie Hickey (World Bank) and Carter Brandon (World Bank) for their overall support and guidance. The report benefited greatly from discussions with Maureen Cropper (University of Maryland), Alan Krupnick (Resources for the Future (RFF) and peer reviewer), Jostein Nygard (World Bank) and Yewande Awe (World Bank). Constructive comments were received from the following peer reviewers for the study: Anjali Acharya (World Bank), Alan Krupnick, Montserrat Meiro-Lorenzo (World Bank), and Michael Toman (World Bank). The team would also like to acknowledge numerous other colleagues for their suggestions, including Sameer Akbar (World Bank), Michael Brody (World Bank), Gary Kleiman (World Bank), Kseniya Lvovsky (World Bank), Anna Malinovskaya (RFF), Klas Sanders (World Bank), and Elena Strukova (World Bank).

The authors would also like to thank Flore Martinant de Preneuf (World Bank), Adam Broadfoot (World Bank), and Diana Manevskaya (World Bank) for production management. The manuscript was edited by Sabra Ledent. Any remaining errors or omissions are the authors' own.

Last but not least, the team gratefully acknowledges the support of the University of British Colombia and the Health Effects institute, and the financial support provided for the report by the Pollution Management and Environmental Health Program of the World Bank.

Abbreviations

AAP	ambient air pollution
ALRI	acute lower respiratory infection
ANS	adjusted net savings
AOD	aerosol optical depth
APM	ambient $PM_{2.5}$
ASDR	age-standardized death rate
COPD	chronic obstructive pulmonary disease
DALYs	disability-adjusted life years
EPA	Environmental Protection Agency (U.S.)
GBD	Global Burden of Disease
GDP	gross domestic product
GPR	Gaussian process regression
HAP	household air pollution
IARC	International Agency for Research on Cancer
IER	integrated exposure-response
IHD	ischemic heart disease
IHME	Institute for Health Metrics and Evaluation
ILO	International Labour Organization
LFPR	labor force participation rate
LRI	lower respiratory infection
OECD	Organisation for Economic Co-operation and Development
OMB	Office of Management and Budget (U.S.)
PAF	population attributable fraction
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter
PMEH	Pollution Management and Environmental Health (World Bank)
PPP	purchasing power parity
RR	relative risk
RFF	Resources for the Future
SAR	Special Administrative Region
TM5-FASST	FAst Scenario Screening Tool
UI	uncertainty interval
VSL	value of statistical life
VSLY	value per statistical life year
WHO	World Health Organization
WTP	willingness to pay
YLDs	years lived with disability
YLLs	years of life lost

All dollar amounts are U.S. dollars unless otherwise indicated.

Executive Summary

Introduction

Air pollution is recognized today as a major health risk. Exposure to air pollution, both ambient and household, increases a person's risk of contracting a disease such as lung cancer, stroke, heart disease, and chronic bronchitis. According to the latest available estimates, in 2013, 5.5 million premature deaths worldwide, or 1 in every 10 total deaths, were attributable to air pollution. Air pollution has posed a significant health risk since the early 1990s, the earliest period for which global estimates of exposure and health effects are available. In 1990, as in 2013, air pollution was the fourth leading fatal health risk worldwide, resulting in 4.8 million premature deaths.

Air pollution is especially severe in some of the world's fastest-growing urban regions, where greater economic activity is contributing to higher levels of pollution and to greater exposure. But air pollution is also a problem outside cities. Billions of people around the world continue to depend on burning solid fuels such as wood, charcoal, coal, and dung in their homes for cooking and heating. Consequently, the health risk posed by air pollution is the greatest in developing countries. In 2013 about 93 percent of deaths and nonfatal illnesses attributed to air pollution worldwide occurred in these countries, where 90 percent of the population was exposed to dangerous levels of air pollution. Children under age 5 in lower-income countries are more than 60 times as likely to die from exposure to air pollution as children in high-income countries.

Air pollution is not just a health risk but also a drag on development. By causing illness and premature death, air pollution reduces the quality of life. By causing a loss of productive labor, it also reduces incomes in these countries. Air pollution can have a lasting effect on productivity in other ways as well—for example, by stunting plant growth and reducing the productivity of agriculture, and by making cities less attractive to talented workers, thereby reducing cities' competitiveness.

Motivation for This Study

This study sets out to calculate the economic costs of premature mortality from air pollution to strengthen the business case for governments to act ambitiously in reducing pollution. The costs of pollution to society are many, but a full accounting is beyond the scope of this report. Instead, it will focus on what many studies have shown to be the largest and most damaging cost of pollution: premature mortality.

The number of deaths each year attributable to air pollution makes a compelling case for reducing pollution. Valuing the costs of premature deaths associated with pollution helps to further highlight the severity of the problem. Governments face a wide array of competing development challenges, and monetizing the costs of pollution can help them decide how to allocate scarce resources to better the lives of their citizens. Monetary values can also help them measure the benefits of policies to tackle pollution and, when compared with costs of implementation, to devise cost-effective air quality management plans.

This study also presents the results of 2013 Global Burden of Disease Study (GBD 2013 Collaborators 2015). The GBD measures illnesses and premature deaths from a multitude of causes and risk factors around the world, including air pollution. It offers the most extensive estimates of exposure and trends in air pollution levels and their associated burden of disease. The GBD effort dates to the early 1990s when the World Bank commissioned the original GBD study for feature in its *World Development Report 1993: Investing in Health*. Since 2010, the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, Seattle, has steered the GBD study, with the latest set of estimates for 2013.

Methodology

The disease burden attributable to air pollution is estimated by first measuring the severity of air pollution and the extent to which people are exposed to it (Brauer et al. 2016; Cohen et al. n.d.). The GBD evaluates exposure to outdoor (ambient) air pollution as well as indoor air pollution in households cooking with solid fuels. The GBD approach to estimating ambient air pollution aims to make the greatest use of information from different sources in the most reasonable way possible, combining data from ground monitoring with satellite observations and chemical transport models. Exposure to household air pollution is estimated from a combination of data on the proportion of households using solid fuels, estimates of indoor pollution concentrations associated with fuel use, and the ratio of personal to area exposure.

The GBD then evaluates how personal exposure raises people's relative risk of contracting illnesses such as ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, acute lower respiratory infections, and pneumonia. Elevated risk among the exposed population translates into a higher portion of deaths from these conditions each year, which are attributed to air pollution.

Using the GBD estimates of premature mortality attributable to pollution, this study values the economic costs in dollar terms following two different approaches: (1) a welfare-based approach that monetizes the increased fatality risk from air pollution according to individuals' willingness to pay (WTP); and (2) an income-based approach that equates the financial cost of premature mortality with the present value of forgone lifetime earnings. Each of these approaches is given equal weight in this report, although they are tailored to different purposes.

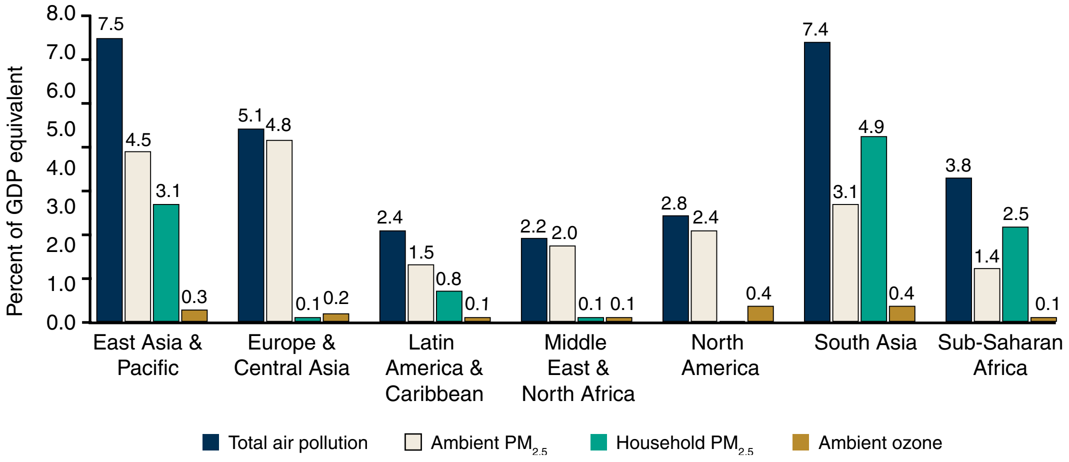
The welfare-based approach is intended to measure the economic costs of fatal health risks to the individuals that make up a society. By increasing people's risk of contracting a deadly illness, air pollution represents a threat to the many things they value, including consumption, leisure, good health, and simply being alive. This value is reflected in the WTP, which captures the trade-offs that individuals are willing to make to reduce their chances of dying. The value of statistical life (VSL) represents the sum of many individuals' WTP for marginal changes in their risk of death. It is *not* the value of any single person's life or death, nor does it represent a society's judgment as to what that value should be. The VSL is also not meant for cross-country comparisons as to the value of life and death in different countries. The WTP-based approach is best suited for analyses of economic welfare, and it has become the standard approach in high-income countries for valuing the mortality risks associated with pollution (see Viscusi 1993; Cropper 2000; OECD 2012).

The income-based approach is more suited to financial analysis and measuring pollution costs within the extended boundaries of the national accounts—for example, as a component of the World Bank's adjusted net savings (ANS) measure. ANS, or "genuine savings," is a measure of the change in the value of a nation's assets, including manufactured capital as well as natural and human capital (see Hamilton and Clemens 1999; World Bank 2005, 2011). Positive savings represents an investment in future well-being as a nation accumulates the assets needed to drive economic growth and at least sustain current levels of consumption. Within the ANS framework, premature mortality due to pollution represents a disinvestment in a nation's human capital stock. As with the degradation of other forms of capital, this disinvestment is valued according to the expected loss of income over the lifetime of the asset. The Ministry of Social Development in Chile, for example, has adopted this approach for valuing premature mortality (Chile MDS 2014).

Key Findings

In 2013 exposure to ambient and household air pollution cost the world's economy some $5.11 trillion in welfare losses. In terms of magnitude, welfare losses in South Asia and East Asia and the Pacific were the equivalent of 7.4 percent and 7.5 percent of the regional gross domestic product (GDP), respectively (figure ES.1).[1] At the low end, losses were still equal to 2.2 percent of GDP in the Middle East and North Africa. Household air pollution from

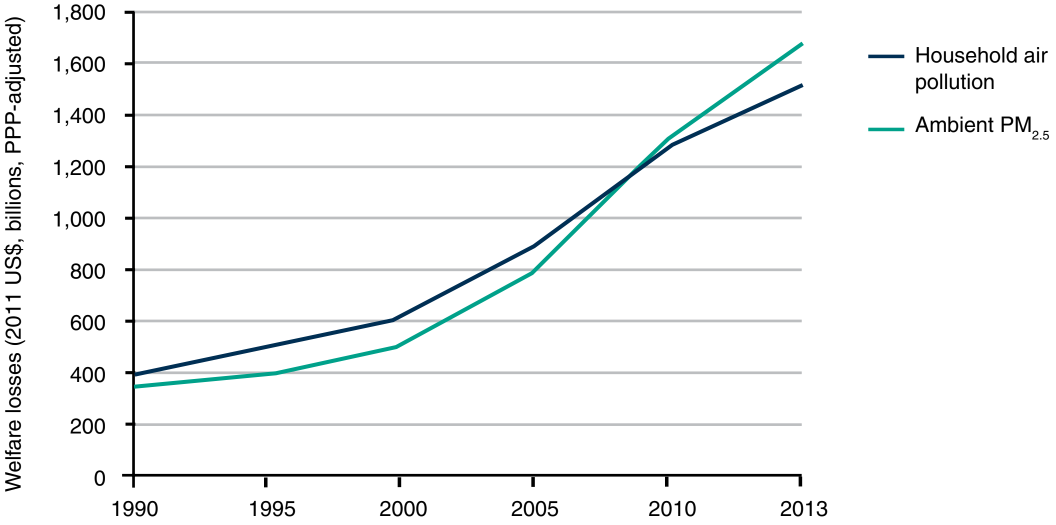
FIGURE ES.1 Welfare Losses Due to Air Pollution by Region, 2013



Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product.

FIGURE ES.2 Welfare Losses from Ambient $PM_{2.5}$ and Household Air Pollution in Low- and Middle-Income Countries, 1990–2013



Sources: World Bank and IHME.

cooking with solid fuels was the biggest cause of losses in South Asia and Sub-Saharan Africa. In all other regions, losses were largely caused by ambient air pollution from fine particulate matter ($PM_{2.5}$). Labor income losses, while expectedly lower than welfare losses, were nonetheless substantial in regions with younger populations. Lost income for countries in South Asia totaled more than $66 billion in 2013, the equivalent of nearly 1 percent of GDP. Globally, the labor income losses totaled $225 billion in 2013.

Moreover, air pollution costs have grown since 1990. From 1990 to 2013, welfare losses nearly doubled and labor income losses increased by 40 percent, despite countries having made great gains in economic development and health outcomes (figure ES.2). In low-income countries, declines in death rates were more than offset by population growth and greater total exposure to polluted air. In middle-income countries, total exposure and health impacts also increased. However, most of the estimated increase in welfare losses stemmed from people placing a greater value on reducing fatality risks. Similarly, from 1990 to 2013 average wages increased in real terms in all but the high-income countries that are not members of the Organisation for Economic Co-operation and Development (OECD), causing forgone labor income losses per premature death to be higher. Across countries in all income groups, the age profile of people affected by pollution shifted, so that a higher proportion of deaths occurred among people later in their working life, having a countervailing, but not equal or greater, effect on income losses.

Ambient air pollution is becoming a greater challenge, and household air pollution remains a persistent challenge despite some gains. Since the 1990s, exposure to ambient air pollution has grown in most countries (other than high-income), with some of the greatest increases in the heavily populated, fastest-growing regions, including South Asia and East Asia and the Pacific. By 2013 about 87 percent of the world's population was living in areas that exceeded the Air

Quality Guideline of the World Health Organization (WHO), which is an annual average of 10 micrograms per cubic meter ($\mu g/m^3$) $PM_{2.5}$. Although the age-standardized death rate due to ambient $PM_{2.5}$ exposure has decreased in most countries since 1990 because of overall improvements in health, population growth and increased exposure have nonetheless increased the number of premature deaths. From 1990 to 2013, premature mortality attributable to ambient $PM_{2.5}$ increased by 30 percent, from 2.2 million deaths to 2.9 million deaths per year. Global welfare losses from exposure to ambient $PM_{2.5}$ rose 63 percent over the same period, reaching $3.55 trillion—a reflection of worsening exposure in many fast-growing countries as well as the higher marginal costs for fatality risks associated with rising incomes. Labor income losses due to ambient $PM_{2.5}$ climbed from $103 billion to $144 billion per year.

Although two-fifths of the world's population was exposed to household air pollution from cooking with solid fuels in 2013, exposure has declined in most countries since 1990. Declines in exposure ranged from nearly 100 percent in many higher-income countries to under 10 percent across much of Sub-Saharan Africa. The age-standardized death rate from household air pollution decreased from 75 deaths per 100,000 persons in 1990 to 47 per 100,000 in 2013, a 38 percent drop. And yet, despite the reductions in exposure and death rates, the total number of deaths associated with indoor air pollution has mostly remained constant at about 2.9 million per year. Welfare losses due to household air pollution in low- and middle-income countries in 2013 were on the order of $1.52 trillion, while labor income losses reached $94 billion.

The very young and older adults remain particularly vulnerable: in 2013 about 5 percent of deaths of children under 5 and 10 percent of deaths among adults over 50 were attributed to air pollution, compared with less than 1 percent among young adults. This age pattern of mortality has remained unchanged since 1990. Among all ages and over time, a larger share of men than women have died prematurely from air pollution–based illnesses.

Recommendations and Way Forward

The fact that global welfare losses from fatal illness attributable to air pollution are in the trillions of dollars, is a call to action. The additional costs of pollution not captured by this report make reducing exposure all the more urgent for achieving the goals of shared, inclusive, and sustainable prosperity. Furthermore, the growing challenge of ambient air pollution and persistence of household air pollution impacts despite improvements in health services suggest that incremental progress to improve air quality will not be sufficient and that achieving real reductions in the cost of pollution will require more ambitious action.

Meanwhile, by placing air pollution–related health risks in the context of other health risks that, unlike air pollution, are typically within the purview of health agencies, the Global Burden of Disease approach is emphasizing the need for health agencies to consider this important health burden and calling for ministries of environment and health to work together to deal with this challenge.

Notes

1. Here, welfare losses are expressed as a percentage of GDP equivalent only to provide a convenient sense of relative scale and not to suggest that welfare is a share of GDP or that the two are a measure of the same thing.

References

Brauer, Michael, Greg Freedman, Joseph Frostad, Aaron van Donkelaar, Randall V. Martin, Frank Dentener, Rita van Dingenen et al. 2016. "Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013." *Environmental Science and Technology* 50 (1): 79–88. doi:10.1021/acs.est.5b03709.

Chile MDS (Ministerio de Desarrollo Social, Chile). 2014. "Estimación del valor de los costos sociales por fallecimiento prematuro en Chile" (Estimation of the Social Costs of Premature Mortality in Chile). Report by the Division of Social Evaluation of Investments, Sub-Secretary of Social Evaluation, Ministry of Social Development, Government of Chile, March.

Cohen, Aaron, et al. n.d. "The Global Burden of Disease Attributable to Ambient Air Pollution: Estimates of Current Burden and 23-Year Trends from the GBD 2013 Study." In submission.

Cropper, Maureen. 2000. "Has Economic Research Answered the Needs of Environmental Policy?" *Journal of Environmental Economics and Management* 39 (3): 328–50.

GBD 2013 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" *The Lancet* 396 (10010): 2287–2323.

Hamilton, Kirk, and Michael Clemens. 1999. "Genuine Savings Rates in Developing Countries." *World Bank Economic Review* 13 (2): 333–56.

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

Viscusi, W. Kip. 1993. "The Value of Risks to Life and Health." *Journal of Economic Literature* 31: 1912–46.

World Bank. 2005. *Where Is the Wealth of Nations? Measuring Capital for the 21st Century*. Washington, DC: World Bank.

———. 2011. *The Changing Wealth of Nations: Measuring Sustainable Development for the New Millennium*. Washington, DC: World Bank.

1. Introduction

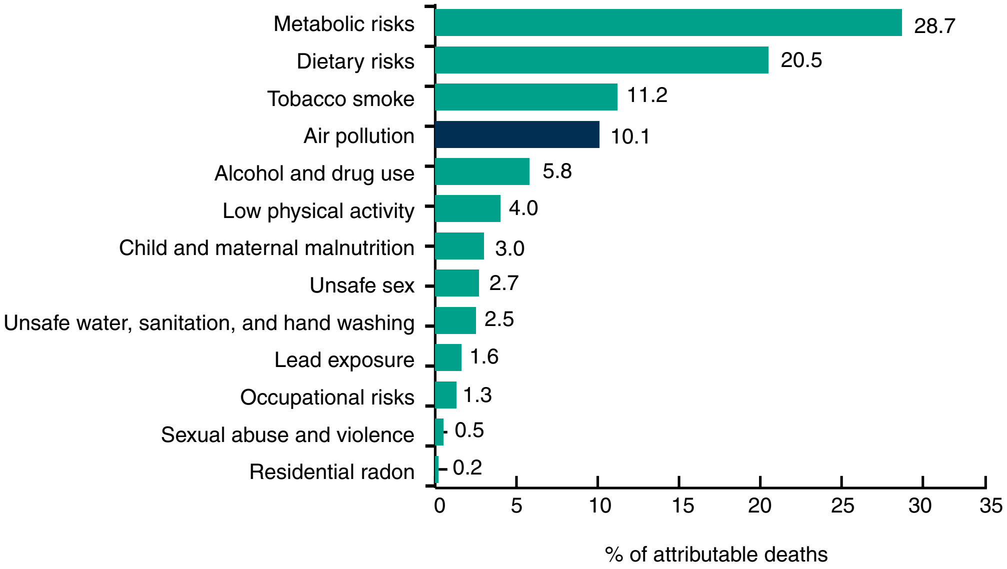
Air Pollution: A Threat to Sustainable Prosperity

Air pollution[1] has emerged as one of the world's leading health risks. Each year, more than 5.5 million people around the world die prematurely from illnesses caused by breathing polluted air. Those illnesses include lung cancer, heart disease, stroke, acute respiratory infections, and chronic obstructive pulmonary diseases such as bronchitis and emphysema (GBD 2013 Collaborators 2015). In fact, exposure to air pollution is now the fourth leading fatal health risk worldwide behind metabolic risks, dietary risks, and tobacco smoke (figure 1.1). More than six times as many people die from air pollution each year as from malaria, and more than four times as many die from air pollution as from HIV/AIDS.

Air pollution takes many forms. One of the most damaging pollutants is $PM_{2.5}$, which is very fine particulate matter (PM) with an aerodynamic diameter of less than 2.5 micrometers, or about one-thirtieth the width of a human hair. Because of their small size, these particles are capable of penetrating deep into the lungs. Their chemical makeup varies, depending on their source. They often consist of carbon, sulfate, and nitrate compounds, but also may include toxic substances such as heavy metals. Very fine particles may be emitted directly from combustion sources such as motor vehicles or power plants, or they may form when gases such as ammonium from fertilizers react with other pollutants in the atmosphere. They may also include concentrations of natural windblown dust.

Air pollution is especially severe in some of the world's fastest-growing urban regions, where the combination of more people, more vehicles, energy derived from dirty fuels, construction,

FIGURE 1.1 Percentage of Attributable Deaths by Risk Factor: Globally, 2013



Sources: World Bank and IHME, using data from IHME, GBD 2013.

improper management of wastes, and other factors have elevated exposure. Exposure has increased most quickly in the developing countries of South Asia and East Asia and the Pacific, reaching 46 micrograms per cubic meter (μg/m^3) and 42 μg/m^3, respectively, or about three times the guideline value of 15 μg/m^3 recommended by the World Health Organization (WHO) as the level below which adverse health effects have not yet been observed (Brauer et al. 2016).[2]

Air pollution is not just a problem in cities. More than 2.8 billion people around the world continue to burn solid fuels such as wood, charcoal, coal, and dung in their homes for cooking and heating (Chafe et al. 2014). Many of these people live in rural areas where they lack access to modern forms of energy such as electricity.

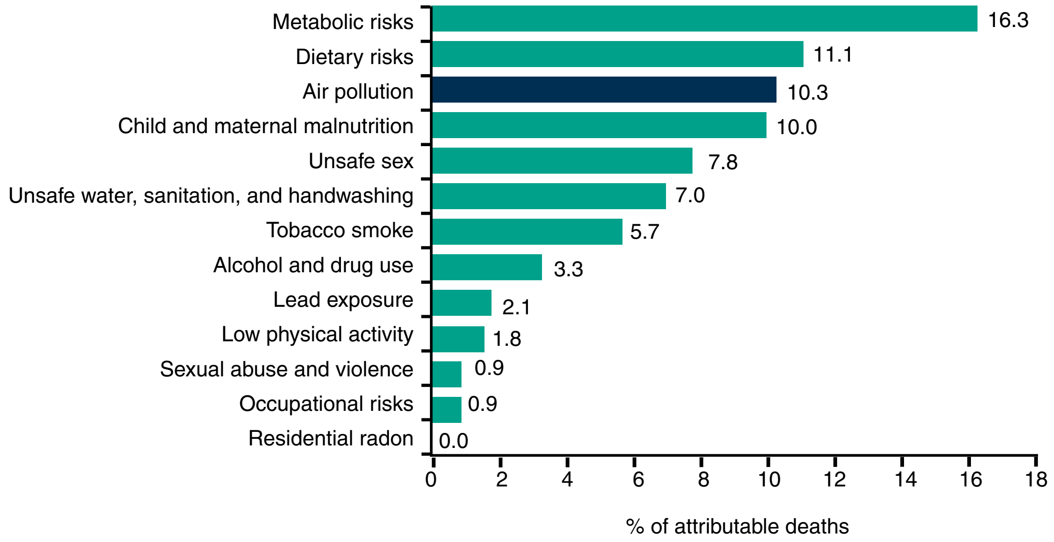
The health risk posed by air pollution is greatest in developing countries. Low- and middle-income countries account for 80 percent of the world's population and for 93 percent of the deaths and nonfatal illness each year from air pollution.[3] Air pollution is the third leading risk factor in these countries behind metabolic risks and dietary risks (figure 1.2). In upper-middle-income countries, as is the case globally, it is the fourth greatest risk factor. Children under age 5 in lower-income countries are more than 60 times as likely to die from exposure to air pollution as children in high-income countries, with the majority of these deaths attributable to household air pollution. Death rates attributable to air pollution exposure among people of all ages are highest in the lower-middle-income countries (GBD 2013 Collaborators 2015).

Air pollution is not just a health risk; it is also an economic burden. By causing illness and premature death, pollution reduces quality of life. By causing a loss of productive labor, pollution also reduces output and incomes in these countries. As will be shown in this report, the annual quality of life or welfare costs of air pollution in low- and middle-income countries are in the trillions of dollars, and lost income is in the hundreds of billions of dollars. The enormity of the costs stems from the widespread nature of exposure to air pollution. Around 87 percent of the world's population is living in areas where $PM_{2.5}$ concentrations exceed the WHO guideline value, and so every day billions of people are breathing polluted air and raising their risk of succumbing to a pollution-caused illness. The economic costs associated with this elevated risk are a real drag on development.

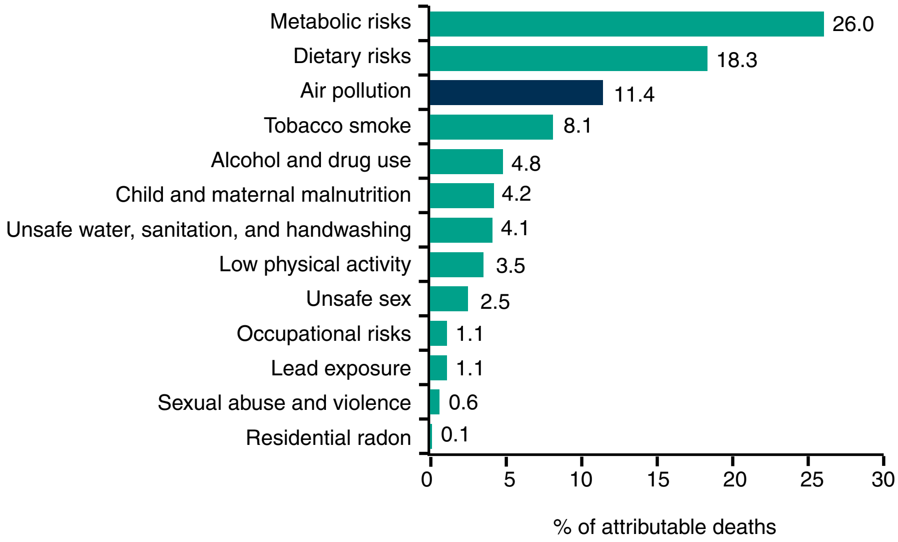
Apart from the sheer magnitude of the costs, the disproportionate impacts on the poorest segments of the population make air pollution a threat to shared and inclusive prosperity. The poor are more likely to live and work in polluted environments, but they are less able to avoid exposure or self-protect. In the United States, research dating back to the 1970s has documented how toxic facilities and sources of air pollution have tended to be sited near poor minority communities.[4] Disparities in exposure continue to exist today in places such as the South Bronx in New York City, where nearly 40 percent of people live below the poverty line and where asthma rates are four times higher than the national average (Katz 2012). Similarly, in China large point sources of pollution such as heavy industry are increasingly moving from city centers to the suburbs, where migrant workers congregate, and from coastal metropolises to second- or third-tier cities and rural towns, where land is cheaper and monitoring by environmental protection authorities may be more lax (Ma and Schoolman 2011; Schoolman and Ma 2012; Zhao, Zhang, and Fan 2014; Zheng et al. 2014a, 2014b).

FIGURE 1.2 Percentage of Attributable Deaths by Risk Factor: Low-, Lower-Middle-Income, and Upper-Middle-Income Countries, 2013

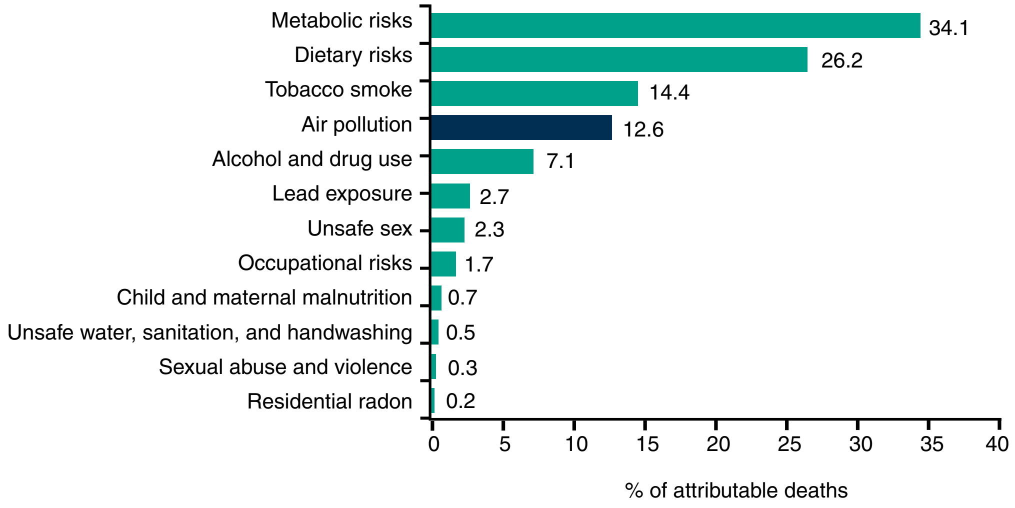
a. Low-income countries



b. Lower-middle-income countries



c. Upper-middle-income countries



Sources: World Bank and IHME, using data from IHME, GBD 2013.

Faced with higher levels of exposure, the poor are also more prone to suffering adverse health effects. In urban areas of Vietnam, for example, the prevalence of acute respiratory illnesses is twice as high in low-income households as in high-income ones (World Bank 2006). The disproportionate health burden suffered by poor households is due not only to higher exposure to air pollution but also to factors such as lower resistance to illness, simultaneous exposure to other environmental health risks, and inequalities in access to and use of basic services (PEP 2008).

By damaging people's health, pollution may have a lasting effect on economic productivity and perpetuate existing inequalities. Prenatal and early childhood exposure to heavy metals and other toxic substances in the environment is especially detrimental. Children are highly sensitive to the effects of toxics, and even small traces in a child's blood of substances such as lead or the polycyclic aromatic hydrocarbons (PAHs) found in polluted air and water can result in cognitive delays, among other health effects (see Grandjean and Landrigan 2014; Tang et al. 2014; Peterson et al. 2015; Vishnevetsky et al. 2015). These health impacts have long-term repercussions for productivity and innovation. A slight shift in average IQs from early exposure to toxics may reduce the number of intellectually "gifted" people and lead to marginally higher rates of crime and societal violence (see Weiss 1988; Wright et al. 2008; GAHP 2013).

Air pollution can have lasting effects on productivity in other ways as well—for example, by degrading natural ecosystems. Pollutants may settle in the air or mix with precipitation and be deposited on plants, in soils, or in waterways. Atmospheric deposition of pollutants has acidified soils and reduced the diversity of plant species and the productivity of grasslands in places such as Mongolia, where many people rely on pastoral livelihoods (Chen et al. 2013). Similar declines in the richness of plant species from the atmospheric deposition of pollutants have been observed in the grasslands of Europe (Duprè et al. 2010). The detrimental effects of air pollutants on aquatic ecosystems include the loss of biota sensitive to the increased acidity of surface waters as well as increased phytoplankton and algal growth, which contributes to the eutrophication of waterways, causing dead zones and harmful algal blooms that hurt fisheries, water-based recreational activities, and tourism (see Greaver et al. 2012).

The Focus of This Report

The costs of pollution to society are many, and a full accounting is beyond the scope of this report. Instead, this report will focus on what many studies have shown to be the largest and most damaging cost of pollution: premature mortality. More specifically, this report evaluates the costs of premature mortality from exposure to ambient concentrations of $PM_{2.5}$, indoor concentrations of $PM_{2.5}$ in households cooking with solid fuels, and ambient ozone pollution. The valuation of mortality risks is supported by a well-developed body of economic theory and empirical evidence. Still, readers should remember that the full costs of air pollution to society are even greater than what is reported here. Examples of other costs not included in this report are discussed in box 1.1.

Calculating the costs of premature mortality due to air pollution is intended to strengthen the business case for governments to act ambitiously in reducing pollution. The number of deaths

BOX 1.1 Air Pollution: Harming Countries' Economies in Many Ways

Beyond its deadly impact on human health, air pollution affects countries' economies in many other ways, from degrading the functioning of natural ecosystems to harming economic competitiveness and the ability of growing cities to attract top talent. Although these costs are beyond the scope of this study, they deserve mention. Two illustrative examples of studies into the additional costs of pollution follow.

Agriculture. The agriculture sector is both a source and a sufferer of air pollution. In the North China Plain, for example, fertilizer use in crop fields is a major contributor to ammonia emissions, which react chemically in the atmosphere with other pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) to form $PM_{2.5}$ (see Guan and Liu 2013). At the same time, pollutants may adhere to plant surfaces and reduce the amount of sunlight reaching crops, stunting their growth (see Chen 2014). In China, surface ozone (a major component of smog) has reduced yields of summer wheat by an estimated 6–12 percent each year and soybeans by an estimated 21–25 percent (Wang and Mauzerall 2004; Avnery et al. 2011). The World Bank and the Chinese environmental authority estimate the cost of acid rain and SO_2 pollution on agricultural output in China at 30 billion yuan a year (2003 prices)—see World Bank–SEPA (2007).

Loss of urban competitiveness. The livability of cities is increasingly believed to affect their economic competitiveness. As the labor force becomes more global, top cities must compete for talented, educated workers who are free to migrate to less polluted, more livable places. Anecdotal evidence abounds of how pollution is harming the ability of firms to attract talent. For example, in a 2012 survey by the American Chamber of Commerce in Hong Kong, around one-third of employers said they were having a harder time recruiting overseas candidates because of concerns about air quality (Pak 2013). Numerous benchmarking indexes have also been created that compare the overall livability or competitiveness of cities, taking into account the severity of air pollution. These include the urban livability rating of the Economist Intelligence Unit (EIU 2014), the City Prosperity Index of the United Nations Human Settlements Programme (UN-HABITAT 2012), and the livability index constructed for South Asian cities by the World Bank (2016). Although these indexes enable urbanites to see how their cities stack up against others, they do not quantify the actual monetary cost of pollution via its effect on competitiveness, demonstrating a causal link between higher levels of pollution and reduced economic competitiveness and quantifying the effect of pollution on cities' competitiveness remain elusive.

each year and the incidence of illness alone make a compelling case for tackling pollution. Why then assign a dollar value to these impacts? The answer is that governments worldwide face a wide array of competing challenges every day, and valuing the costs of pollution helps governments decide how to allocate scarce resources and to measure the results of policies by providing a common basis of comparison. Economic valuation may also help governments measure social costs that are not reflected in existing markets and prices but are nonetheless crucial to people's well-being. An example of how economic valuation has assisted the government of Mongolia in fighting air pollution is provided in box 1.2. And the annual reporting by the U.S. federal government on the benefits and costs of air pollution control is discussed in box 1.3. As economic studies by public agencies in the United States and elsewhere have demonstrated, because large populations are exposed to the health risks of air pollution, these

BOX 1.2 Using an Air Quality Management Study and Economic Valuation to Help Ulaanbaatar Forge a Strategy to Combat Air Pollution

Ulaanbaatar, Mongolia, is one of the world's coldest capital cities. In recent years, it has also become known as one of the world's most polluted cities. Most of the city's air pollution appears during the winters, when the 180,000 or so households living in informal settlements marked by traditional circular tents known as *gers* burn raw coal in stoves for heating and cooking. As a result, despite having a population of only 1.2 million, Ulaanbaatar has experienced levels of air pollution worse than those in much larger cities such as Beijing and Delhi.

In 2007 efforts to replace the traditional heating stoves in the ger areas met with resistance from Ulaanbaatar government officials, who were not certain they wanted to prioritize stove removal, particularly given the cost. This led to a full-scale air quality management study, seeking a complete understanding of the sources, concentration levels, and health impacts of pollution and outlining the most cost-effective abatement options for the short, medium, and long term. The study revealed that switching out existing stoves with cleaner-burning, more efficient ones would yield net health benefits of $1.6 billion. The benefits of pursuing other options, such as moving ger households into apartments, would have come later. However, that delay would result in health-related losses of up to $3.5 billion if more immediate action was not taken. Delaying stove replacement by just three years would lead to health-related losses of about $1.0 billion.

Armed with the results of this analysis, Ulaanbaatar decided to go ahead with the stove replacement program as one of the main pillars of its strategy to reduce air pollution. Since 2010, Ulaanbaatar has replaced nearly 170,000 stoves, reaching more than 90 percent of households in the ger areas. Continued monitoring of $PM_{2.5}$ has revealed a notable reduction in pollution levels since the baseline study; yearly average concentrations declined from over 250 $\mu g/m^3$ in 2008–09 to around 80 $\mu g/m^3$ in 2014–15. Although a longer period of monitoring will be needed to establish definite trends in concentrations, these initial improvements are reason for optimism.

Source: Excerpted and adapted from Awe et al. (2015)

BOX 1.3 Accounting for the Costs and Benefits of Air Pollution Control in the United States

Every year, the U.S. Office of Management and Budget (OMB) reports to Congress on the costs and benefits of federal regulations. OMB has consistently found that rules issued by the U.S. Environmental Protection Agency (EPA) to improve air quality are the most economically beneficial of all federal regulations. Indeed, OMB estimates that EPA regulations issued between 2004 and 2014 to limit air pollution generated between $157 billion and $777 billion (constant year 2010 prices) in benefits to the American economy, mainly by reducing the public health risks of exposure to fine particulate matter (OMB 2015). Implementing these rules costs between $37 billion and $44 billion, meaning the benefits have outweighed the costs by a ratio of at least 4 to 1.

populations also reap the benefits of policies to control pollution, making investing in air quality management highly cost-effective.

The remainder of this report is organized as follows. Chapter 2 details the 2013 estimates of the Global Burden of Disease (GBD) Study of air pollution exposure and health impacts, which form the basis of the valuation exercise. Chapter 3 describes the methods and data for the economic valuation of premature mortality costs and presents the results. Chapter 4 then synthesizes the results and discusses the way forward.

The Context for This Report

This report emerged from a collaborative effort between the World Bank and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, Seattle. IHME has steered the international scientific effort behind the Global Burden of Disease Study since publication of the 2010 study (Murray et al. 2012). GBD 2013 marks the latest stage in the GBD process and represents the state of the art in the evolving science, which will continue to be updated yearly. The GBD estimates currently offer the most extensive estimates of exposure and trends in air pollution levels and their associated burden of disease. The partnership between the World Bank and IHME speaks to the need for the development and scientific communities to work together in solving environmental health problems.

This report also marks part of a renewed commitment by the World Bank to work with countries and stakeholders in tackling air pollution. A Bank-wide review published in early 2015 found that air pollution control is still given “low priority” within the Bank and by developing countries (Awe et al. 2015). Responding to calls for greater action, in April 2015 the Bank launched a new Pollution Management and Environmental Health (PMEH) program. This study aims to further the objectives of the PMEH program by strengthening the economic case for why countries need to take action to reduce air pollution and by raising awareness of the scale of the problem.

A secondary objective of this report is to further the development of a consistent framework for valuing the costs of air pollution across World Bank operations. Assessing potential investments and advising governments on policy are just two of the various activities the Bank undertakes that require it to estimate the economic costs of pollution. Meanwhile, over the past decades tremendous progress has been made in understanding both the epidemiology and economics of health risks from pollution. This report has provided an opportunity to assess what has been done and to bring more uniformity and consistency to the ways in which pollution costs are valued across Bank operations. For example, the need for greater consistency was noted in a 2014 review by Resources for the Future (RFF) of the World Bank’s methodology for estimating damages from particulate emissions for the adjusted net savings (ANS) indicator (Cropper and Khanna 2014). Following the RFF review, the authors of this report undertook an extensive review of methodologies for valuing health risks from air pollution, consulting with experts inside and outside the Bank. The findings of this review are detailed in a technical background paper by Narain and Sall (2016), and its findings are implemented in this report.

Notes

1. Air pollution refers to a combination of ambient air pollution, household air pollution, and pollution caused by ambient ozone.
2. Geographic regions as reported in this study include countries of all income levels and are grouped according to World Bank definitions. See World Bank, "Country and Lending Groups," http://data.worldbank.org/about/country-and-lending-groups.
3. Income groups are according to World Bank definitions. See World Bank, "Country and Lending Groups," http://data.worldbank.org/about/country-and-lending-groups.
4. See Brulle and Pellow (2006) for a review.

References

Avnery, Shiri, Denise Mauzerall, Junfeng Liu, and Larry Horowitz. 2011. "Global Crop Yield Reductions Due to Surface Ozone Exposure: 1. Year 2000 Crop Production Losses and Economic Damage." *Atmospheric Environment* 45 (13): 2284–96.

Awe, Y., J. Nygard, S. Larssen, H. Lee, H. Dulal, and R. Kanakia. 2015. "Clean Air and Health Lungs: Enhancing the World Bank's Approach to Air Quality Management." Environment and Natural Resources Global Practice Discussion Paper 03, World Bank Group Report ACS9035, Washington, DC, February.

Brauer, Michael, Greg Freedman, Joseph Frostad, Aaron van Donkelaar, Randall V. Martin, Frank Dentener, Rita van Dingenen et al. 2016. "Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013." *Environmental Science and Technology* 50 (1): 79–88.

Brulle, Richard, and David Pellow. 2006. "Environmental Justice: Human Health and Environmental Inequalities." *Annual Review of Public Health* 27: 103–24.

Chafe, Z. A., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., Riahi, K. Dentener, F. Smith, K.R. 2014. "Household Cooking with Solid Fuels Contributes to Ambient $PM_{2.5}$ Air Pollution and the Burden of Disease." *Environmental Health Perspectives* 122(12): 1314–1320.

Chen, Dima, Zhichun Lan, Xue Bai, James Grace, and Yongfei Bai. 2013. "Evidence that Acidification-Induced Declines in Plant Diversity and Productivity Are Mediated by Changes in Below-Ground Communities and Soil Properties in a Semi-Arid Steppe." *Journal of Ecology* 101: 1322–34.

Chen, Stephen. 2014. "Agriculture Feels the Choke as China Smog Starts to Foster Disastrous Conditions." *South China Morning Post*, February 25. http://www.scmp.com/news/china/article/1434700/china-smog-threatens-agriculture-nuclear-fallout-conditions-warn.

Cropper, M., and S. Khanna. 2014. "How Should the World Bank Estimate Air Pollution Damages?" Discussion Paper No. 14-30, Resources for the Future, Washington, DC, September.

Duprè, Cecilia, Carly Stevens, Traute Ranke, Albert Bleeker, Cord Peppler-Lisbach, David Gowing, Nancy Dise, et al. 2010. "Changes in Species Richness and Composition in European Acidic Grasslands Over the Past 70 Years: The Contribution of Cumulative Atmospheric Nitrogen Deposition." *Global Change Biology* 16: 344–57.

EIU (Economist Intelligence Unit). 2014. "A Summary of the Liveability Ranking and Overview." http://pages.eiu.com/rs/eiu2/images/Liveability_rankings_2014.pdf.

GAHP (Global Alliance on Health and Pollution). 2013. "The Poisoned Poor: Toxic Chemicals Exposures in Low- and Middle-Income Countries." New York.

GBD 2013 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." *The Lancet* 396 (10010): 2287–2323.

Grandjean, Philippe, and Philip Landrigan. 2014. "Neurobehavioral Effects of Developmental Toxicity." *The Lancet Neurology* 13: 330–38.

Greaver, Tara, Timothy Sullivan, Jeffrey Herrick, Mary Barber, Jill Baron, Bernard Cosby, Marion Deerhake et al. 2012. "Ecological Effects of Nitrogen and Sulfur Air Pollution in the US: What Do We Know?" *Frontiers in Ecology and the Environment* 10: 365–72.

Guan, Dabo, and Zhu Liu. 2013. *Tracing Back the Smog: Source Analysis and Control Strategies for* $PM_{2.5}$ *Pollution in Beijing-Tianjin-Hebei*. Beijing: China Environment Press.

Katz, Cheryl. 2012. "Minorities, Poor Breathe Worse Air Pollution, Study Finds." *Environmental Health New*s, November 4. http://www.environmentalhealthnews.org/ehs/news/2012/unequal-exposures.

Lim, Stephen, Theo Vos, Abraham Flaxman, Goodarz Danaei, Kenji Shibuya, 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.

Ma, Chunbo, and Ethan Schoolman. 2011. "Corrigendum to 'Who Bears the Environmental Burden in China—An Analysis of the Distribution of Industrial Pollution Sources?' [*Ecological Economics* 69 (2010) 1869–1876]." *Ecological Economics* 70: 569.

Narain, Urvashi, and Chris Sall. 2016. "Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions." Draft working paper, World Bank, Washington, DC, March.

OMB (U.S. Office of Management and Budget). 2015. "2015 Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance with the Unfunded Mandates Reform Act." https://www.whitehouse.gov/sites/default/files/omb/inforeg/2015_cb/2015-cost-benefit-report.pdf.

Pak, Jennifer. 2013. "Pollution Threatens Hong Kong's Competitiveness," BBC, Hong Kong, 16 January 2013, http://www.bbc.com/news/business-21038495.

PEP (Poverty-Environment Partnership). 2008. "Poverty, Health & Environment: Placing Environmental Health on Countries' Development Agendas." Joint agency paper by Asian Development Bank, Austrian Development Agency, German Federal Ministry for Economic Cooperation and Development, Ministry of Foreign Affairs of Denmark, Department for International Development, European Commission, Finland Ministry of Foreign Affairs, International Institute for Environment and Development, Irish Aid, London School of Hygiene and Tropical Medicine, Norwegian Agency for Development Cooperation, Swedish International Development Cooperation Agency, Swiss Agency for Development and Cooperation, United Nations Development Programme, United Nations Environment Programme, Water Aid, World Bank, World Health Organization, and World Resources Institute.

Peterson, Bradley, Virginia Rauh, Ravi Bansal, Xuejun Hao, Zachary Toth, Giancarlo Nati, Kirwan Walsh et al. 2015. "Effects of Prenatal Exposure to Air Pollutants (Polycyclic Aromatic Hydrocarbons) on Development of Brain White Matter, Cognition, and Behavior in Later Childhood." *JAMA Psychiatry* 72 (6): 531–40.

Schoolman, Ethan, and Chunbo Ma. 2012. "Migration, Class, and Environmental Inequality: Exposure to Pollution in China's Jiangsu Province." *Ecological Economics* 75: 140–151.

Tang, Deliang, Joan Lee, Loren Muirhead, Tingyu Li, Lirong Qu, Jie Yu, and Frederica Perera. 2014. "Molecular and Neurodevelopment Benefits to Children of Closure of a Coal Burning Power Plant in China." *PLoS ONE* 9 (3): e91966.

UN-HABITAT (United Nations Human Settlements Programme). 2012. *State of the World's Cities Report 2012/2013: Prosperity of Cities.* Nairobi, Kenya: UN-HABITAT.

Vishnevetsky, Julia, Deliang Tang, Hsin-Wen Chang, Emily Roen, Ya Wang, Virginia Rauh, Shuang Wang et al. 2015. "Combined Effects of Prenatal Polycyclic Aromatic Hydrocarbons and Material Hardship on Child IQ." *Neurotoxicology and Teratology* 49: 74–80.

Wang, Xiaoping, and Denise Mauzerall. 2004. "Characterizing Distributions of Surface Ozone and Its Impact on Grain Production in China, Japan, and South Korea: 1990 and 2020." *Atmospheric Environment* 38 (26): 4383–402.

Weiss, Bernard. 1988. "Neurobehavioral Toxicity as a Basis for Risk Assessment." *Trends in Pharmacological Sciences* 9 (2): 59–62.

World Bank. 2006. *Poverty Environment Nexus: Sustainable Approaches to Poverty Reduction in Cambodia, Lao PDR, and Vietnam.* Washington, DC: World Bank.

______. 2016. *Leveraging Urbanization in South Asia: Managing Spatial Prosperity and Livability*. Washington, DC: World Bank.

World Bank–SEPA (World Bank and State Environmental Protection Agency, China). 2007. *Cost of Pollution in China: Economic Estimates of Physical Damages*. Washington, DC: World Bank.

Wright, John Paul, Kim Dietrich, M. Douglas Ris, Richard Hornung, Stephanie Wessel, Bruce Lanphear, Mona Ho et al. 2008. "Association of Prenatal and Childhood Blood Lead Concentrations with Criminal Arrests in Early Adulthood." *PLoS Medicine* 5 (5): e101.

Zhao, Xiaoli, Sufang Zhang, and Chunyang Fan. 2014. "Environmental Externality and Inequality in China: Current Status and Future Choices." *Environmental Pollution* 190: 176–79.

Zheng, Siqi, Jing Cao, Matthew Kahn, and Cong Sun. 2014a. "Real Estate Valuation and Cross-Boundary Air Pollution Externalities: Evidence from Chinese Cities." *Journal of Real Estate Finance and Economics* 48: 398–414.

Zheng, Siqi, Cong Sun, Ye Qi, and Matthew Kahn. 2014b. "The Evolving Geography of China's Industrial Production: Implications for Pollution Dynamics and Urban Quality of Life." *Journal of Economic Surveys* 28 (4): 709–24.

2. Health Impacts of Air Pollution

Introduction

The Global Burden of Disease Study 2013 (GBD 2013 Collaborators 2015) estimates the burden of disease attributable to air pollution in 188 countries from 1990 to 2013. The results of this study are presented in this chapter. The health impacts of air pollution include disease and illnesses caused by exposure to ambient concentrations of fine particulate matter ($PM_{2.5}$), indoor concentrations of $PM_{2.5}$ in households cooking with solid fuels, and ambient ozone pollution. The study covers both urban and rural areas and measures changes in the disease burden of air pollution over the extended study period (1990–2013). Global coverage is achieved by integrating data from a wide variety of sources.

The first part of this chapter describes the process of estimating the disease burden attributable to air pollution. The process begins by measuring the severity of air pollution and the extent to which people who live in areas with poor ambient air quality or in households cooking with solid fuels are exposed to this pollution. The study then evaluates how personal exposure raises people's relative risk of contracting illnesses such as ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer, acute lower respiratory infections (LRIs), and pneumonia. Elevated risk among the exposed population translates into a higher portion of deaths from these conditions each year, which are attributed to air pollution.

The second part of the chapter discusses trends in exposure to ambient and household air pollution as well as the resulting health impacts. It reveals that air pollution is ranked fourth in the risk factors leading to premature death worldwide.

Method for Satellite- and Model-Derived Estimates of Ambient Air Pollution

Use of Satellite-Based Estimates for a Global Assessment

To make the greatest use of multiple and complementary sources of information in the most reasonable way possible, the GBD approach to estimating ambient air pollution combines data from ground monitoring with satellite observations and chemical transport models. In doing so, the GBD estimates provide a consistent global picture and trend of exposure to ambient $PM_{2.5}$, which could not be constructed on the basis of any one source of data.

Although important for country- and city-level air quality planning, public communication, and regulatory compliance, ground-level measurements alone are not sufficient to provide global coverage to estimate exposure because of the spatial biases in the availability of ground-level measurements, the differences in measurement approaches among jurisdictions, and the absence of details about measurement data in some instances. Ground-level measurements of air pollution, particularly $PM_{2.5}$, are unavailable in much of the world, and especially in many of the low- and middle-income countries. In addition to the inadequate and highly uneven coverage of ground-level measurements, measurement protocols and techniques are not standardized globally, with different quality control programs and different numbers of samples to arrive at annual averages. Even for measurements made by (similar) filter-based approaches, filters are equilibrated at different relative humidity conditions prior to weighing (for example, 35 percent, 40 percent, and 50 percent relative humidity in the United States, Canada, and European Union, respectively) and therefore are not completely equivalent. In addition, PM_{10} measurements and $PM_{2.5}$ /PM_{10} ratios are commonly used to infer $PM_{2.5}$ concentrations for ground-level estimates. Therefore, surface measurements, although a key component of any global assessment approach, cannot be used solely to derive global exposure estimates.

Satellite-based measurements can help provide estimates for areas with no ground-level monitoring networks. But even in North America, where monitor density is high in populated areas, studies have indicated that satellite-based estimates do provide additional useful information on spatial and temporal patterns of air pollution (Kloog et al. 2011, 2013; Lee et al. 2012). Furthermore, in a large population-based study in Canada the magnitudes of estimated mortality effects of $PM_{2.5}$ derived from ground measurements and satellite-based estimates were identical (Crouse et al. 2012). Satellite-based estimates nonetheless must be used cautiously, as discussed shortly.

Deriving Ambient Air Pollution Concentrations

Long-term average exposure to $PM_{2.5}$ was estimated at $0.1° \times 0.1°$ resolution. Satellite-based estimates that incorporated additional information on temporal trends were applied, as well as chemical transport model simulations incorporating internally consistent emissions trends from 1990 to 2013. Available surface measurements of $PM_{2.5}$ were incorporated to calibrate the estimates based on satellite retrievals and chemical transport model simulations. Data and methodologies are summarized here and reported in more detail in Brauer et al. (2016).

A series of satellite-based estimates for $PM_{2.5}$ were used, which included year-specific estimates for 1998–2012. Satellite-based $PM_{2.5}$ estimates used aerosol optical depth (AOD) retrievals from multiple satellites to estimate near-surface $PM_{2.5}$ by applying the relationship of $PM_{2.5}$ to AOD simulated by the GEOS-Chem chemical transport model. These updated $PM_{2.5}$ estimates used both "unconstrained" and "optimal-estimation" AOD retrievals in combination with the MODIS, MISR, and SeaWiFS satellite-borne instruments. These estimates were combined with information on temporal variation based on SeaWiFS and MISR to estimate global $PM_{2.5}$ at $0.1° \times 0.1°$ for 2000, 2005, 2010, and 2011.

TM5-FASST (FAst Scenario Screening Tool, a reduced-form version of the TM5 chemical transport model) simulations for 1990, 2000, and 2010 were included, using an updated set of emissions inventories and constant meteorological inputs and emissions from dust and sea salt (see box 2.1 for the current understanding of the health impacts of dust and a discussion of why these sources were included in exposure estimates). Emissions of windblown mineral dust and sea salt were estimated in the TM5 model by incorporating information on land cover and wind speed, combined with emission factors. For simulations, a constant "typical" meteorologic year with corresponding emissions from windblown mineral dust and sea salt was used. Year-to-year variations in emissions of windblown mineral dust and sea salt were,

BOX 2.1 Dust and Dust Storm Health Effects

Because there is no evidence that the dust components of $PM_{2.5}$ should be excluded when estimating health impacts, concentrations of windblown mineral dust and sea salt were included in estimating the health impacts of exposure to ambient $PM_{2.5}$ for the GBD 2013 study. The current positions of the U.S. Environmental Protection Agency (EPA), World Health Organization (WHO), and International Agency for Research on Cancer (IARC) are that an insufficient basis exists for using separate indicators for a specific $PM_{2.5}$ component or group of components associated with any source category of fine particles. Many constituents of particulate matter can be linked with differing health effects, and the evidence is not yet sufficient to allow differentiation of those constituents or sources that are more closely related to specific health outcomes (EPA 2009; IARC 2013; WHO 2014). Concentrations of windblown mineral dust and sea salt were therefore included in estimating the health impacts of exposure to ambient $PM_{2.5}$ for the GBD 2013 study.

For windblown mineral dust specifically, there is substantial evidence of its association with mortality and morbidity during episodes of high concentrations such as Saharan dust storms that affect Europe (Perez et al. 2008; Mallone et al. 2011; Karanasiou et al. 2012), Asian dust storms (Chen et al. 2004; Bell, Levy, and Lin 2008), or regional episodes in the Middle East (Thalib and Al-Taiar 2012; Vodonos et al., 2014, 2015). Most of this evidence points to the coarse fraction of particulate matter, or to PM_{10}, and not to the smaller proportion of dust that is in the $PM_{2.5}$ fraction. In toxicology, there is no evidence that dust is more benign than other components of $PM_{2.5}$ (WHO 2014).

however, incorporated into the overall estimates because these sources are also captured by remote sensing observations that contribute to the satellite-based estimates. Furthermore, these sources contribute to ground-level measurements, and their influence is reflected to some degree in the calibration, as described shortly.

A variety of information sources was used to collect updated ground-level $PM_{2.5}$ measurement data for 2010–13. These included national and European Union (EU) measurement databases as well as new data where available, especially from China and India. Input from an international group of GBD collaborators was sought; targeted searches for data were conducted; and measurements were compiled from a literature search and from the 2014 WHO database on ambient air pollution in cities. A final database was constructed, including measurement values, year of annual average (data for 2010–13 were targeted, and other years were used only if no other data were available), site coordinates (if available, or city centroid coordinates if not available), site type (if available), International Standard Organization (ISO) 3 country code, data source, and whether $PM_{2.5}$ was measured directly or estimated from a $PM_{2.5}/PM_{10}$ ratio. The proportion of ground measurements based on direct measurement of $PM_{2.5}$ versus estimated by $PM_{2.5}$ /PM_{10} ratios is presented in appendix table A.1. Although the use of PM_{10} measurements is a balance between provision of spatial coverage and the uncertainty that may be introduced because of the use of a ratio to estimate $PM_{2.5}$ levels, it is important to note that in regions with either low numbers of measurements or a low percentage of direct $PM_{2.5}$ measurements, ground measurements will likely be more uncertain.

This combination of data from ground-level monitoring with satellite observations and chemical transport models provides a globally consistent estimate of $PM_{2.5}$ concentrations. The final $PM_{2.5}$ estimates used in the burden of disease estimation were calibrated against observations from ground-level monitoring from more than 75 countries. The calibration equation was estimated from 4,073 ground-level measurements of annual average concentrations, including significant interaction terms for quality and accuracy of location of ground monitors.

All three sources of information incorporate strengths and limitations with different sources of uncertainty, and so were combined for the exposure estimates. The mean of the TM5-FASST and satellite-derived estimates was calculated for each grid cell, which inherently captures some of the uncertainty between these two input sources. Furthermore, the error from the calibration with ground measurements was used to propagate the uncertainty between the TM5-FASST and satellite-based estimates and the ground measurements into the burden calculations.

This approach has some shortcomings, however, which should be considered when interpreting the modeling results. For one thing, estimates for regions of elevated windblown mineral dust have high levels of uncertainty. This uncertainty is partially driven by the TM5-FASST use of standard dust contributions that do not align with a specific year and the temporally variable levels of re-suspended mineral dust in affected regions. Even with ground-level monitoring, in dusty areas it is hard to get accurate measurements of the dust contribution to $PM_{2.5}$ because much of the dust is in larger size fractions; small errors or between-monitor differences in size fractionation can therefore result in large errors. That said, more surface measurements from such locations will nonetheless be needed to reduce uncertainties related to windblown mineral dust in the future (see appendix map A.1).

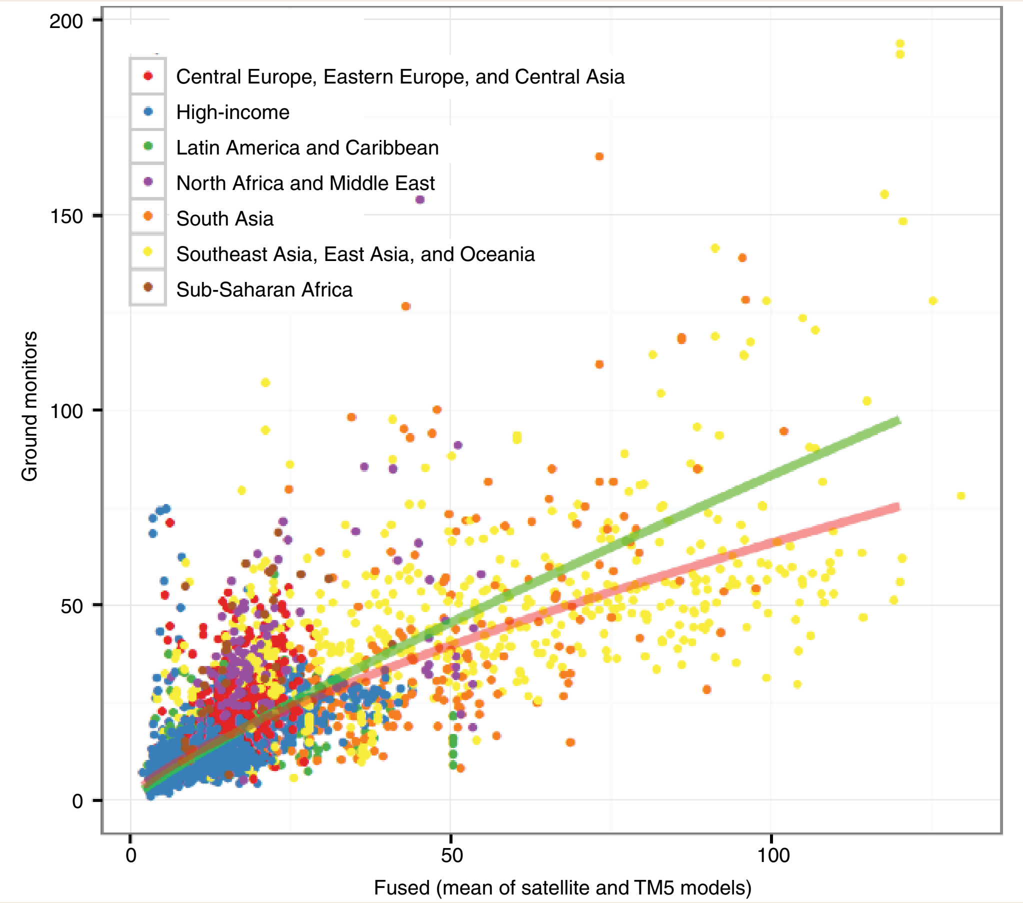
Furthermore, with regard to TM5-FASST, in locations where emissions sources are highly variable and not well characterized, uncertainty is likely to be larger. This suggests, for example, greater uncertainty in rapidly developing regions with high concentration levels. But, as indicated earlier, these uncertainties are mitigated to some degree by the inclusion of both satellite-based estimates and ground-level observations, which may better capture the dynamic nature of emissions sources.

Finally, underestimation of ground measurements has been reported for satellite-based estimates (see box 2.2), which may be more pronounced in locations that experience higher concentrations in wintertime and nighttime, when satellite observations are limited, compared with other seasons in daytime (van Donkelaar et al. 2015). Furthermore, because of the spatial resolution of TM5-FAAST, and to a lesser degree the satellite-based estimates, localized features affecting concentrations, including topography and small emissions sources, are unlikely to be well characterized. For example, underestimation of ground-level measurements in southern Poland and Ulaanbaatar may stem from higher wintertime (and in Ulaanbaatar also nighttime) emissions, when satellite retrievals are more limited because of the more frequent winter cloud cover (or unavailability at night). This underestimation has also been described for the satellite-based estimates alone by van Donkelaar et al. (2015). A similar phenomenon may also contribute to underestimation in Chile, where nighttime wood burning during winter contributes to elevated $PM_{2.5}$ concentrations. These underestimations of ground measurements in specific locations were also evident in TM5-FASST simulations, suggesting that both chemical transport model and satellite-based estimates may fail to accurately estimate ground-level $PM_{2.5}$ in

BOX 2.2 Underestimation of Ground Measurements in Locations with High Concentrations

Figure B2.2.1 depicts the relationship between the fused estimates (satellite-based and from TM5-FAAST) and all available ground measurements. Comparisons of GBD super-regions indicated underestimation by the calibration function in North Africa and the Middle East; Central Europe, Eastern Europe, and Central Asia; and Sub-Saharan Africa. Because of the complete absence of ground-level measurements in specific regions and very limited data in others, comparisons by regions were not feasible.

FIGURE B2.2.1 Calibration Regression Simple (Pink) versus Advanced (Green) Model by Super-Region



Source: Brauer et al. 2016.

Note: The graph is based on calibration of the mean of satellite-based and TM5 grid cell estimates of annual average $PM_{2.5}$ (micrograms per cubic meter, μg/m³), with available ground-level monitoring data color-coded by seven super-regions. Both models are of the form Measured $\ln(PM_{2.5}) = \beta_0 + \beta_1 * \ln(\text{fused})$, with the "simple" model having characteristics of $\beta_0 = 0.82$, $\beta_1 = 0.73$; residual standard error = 0.43; multiple R-squared: 0.60; adjusted R-squared: 0.60. The "advanced" model included additional information on the ground measurements and has characteristics of $\beta_0 = 0.42$, $\beta_1 = 0.87$; residual standard error = 0.41; multiple R-squared: 0.64; adjusted R-squared: 0.64. Reprinted with permission from Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013. Brauer M, Freedman G, Frostad J, van Donkelaar A, Martin RV, Dentener F, van Dingenen R, Estep K, Amini H, Apte JS, Balakrishnan K, Barregard L, Broday D, Feigin V, Ghosh S, Hopke PK, Knibbs LD, Kokubo Y, Liu Y, Ma S, Morawska L, Sangrador JL, Shaddick G, Anderson HR, Vos T, Forouzanfar MH, Burnett RT, Cohen A. Environ Sci Technol. 2016 Jan 5; 50(1):79-88. doi: 10.1021/acs.est.5b03709. Copyright 2016 American Chemical Society.

relatively small areas having very high levels. Improvements in the spatial precision of emissions estimates and satellite retrievals and use of regional models will reduce these uncertainties in the future.

To estimate chronic long-term exposure to ozone, the TM5-FASST chemical transport model and the same set of emissions used for $PM_{2.5}$ were applied to calculate a running three-month average of (daily one-hour maximum values) ozone concentrations for each grid cell over a full year from which the maximum of these values was selected. This metric was chosen to align with epidemiologic studies of chronic exposure, which typically employ a seasonal (summer) average (Jerrett et al. 2009), and to account for global variation in the timing of the ozone (summer) season. These estimates were simulated with TM5-FASST at $0.1° \times 0.1°$ for 1990, 2000, and 2010 using the same emissions and meteorological inputs as for the $PM_{2.5}$ simulations. Estimates for 1995, 2005, 2011, and 2013 were generated with splines and extrapolations as described earlier for $PM_{2.5}$.

Population Exposure to Ambient Air Pollution

Estimates of population exposure to $PM_{2.5}$ were developed in five-year intervals from 1990 to 2010 and for 2013 with $0.1° \times 0.1°$ resolution, using estimates from satellites and chemical transport models, calibrated with surface measurements. Similarly, for ozone, estimates of population exposure for the same five-year intervals and for 2013 were estimated from the TM5-FASST chemical transport model. Gridded exposure concentrations were aggregated to national-level, population-weighted means with the corresponding grid cell population value.[1] National-level, population-weighted means and 95 percent uncertainty interval (UI) concentrations were estimated by sampling 1,000 draws of each grid cell value of the mean of the chemical transport model and satellite-based concentration estimates, in combination with the calibration parameters and the uncertainty of the calibration function. For ozone, population-weighted concentrations and 95 percent UI for each country were estimated as for $PM_{2.5}$, but assuming a normal distribution with a UI of ± 6 percent of the estimated concentration.

Method for Estimating Exposure to Household Air Pollution from Cooking with Solid Fuels

Exposure to household air pollution is defined as the 24-hour average of exposure to $PM_{2.5}$ emitted from cooking with solid fuels such as coal, wood, charcoal, dung, and agricultural residues. Estimates of exposure to household air pollution are not provided for high-income countries. Quantifying exposure to indoor air pollution by the average $PM_{2.5}$ exposure associated with household use of solid cooking fuel makes it possible to utilize the integrated exposure-response (IER) curves needed to calculate the burden of indoor air pollution.

Although solid fuel use is an indirect measure of true exposure, this information is easier to collect and more frequently reported in epidemiological studies than direct measures of household air pollution. Therefore, estimation of exposure to household air pollution starts with data on household use of solid fuels. Such data were extracted from nationally representative household surveys. Fuels such as coal, wood, charcoal, dung, and agricultural residues were classified as solid fuels in this analysis. Data were extracted from 148 countries, and data sources included in the database were primarily population-representative surveys such as the Demographic and Health Survey, Multiple Indicator Cluster Survey, Living Standards Measurement Study, and national censuses. Country-specific data sources were also added for subnational provinces in China and federal states in Mexico.

Next, the methodology requires translating solid fuel use into indoor $PM_{2.5}$ concentrations. Few efforts have been made in the past to systematically consolidate existing published evidence on measured household indoor $PM_{2.5}$ concentrations associated with the use of solid cooking fuel. In its review of the existing $PM_{2.5}$ literature, WHO does a commendable job of consolidating the evidence, but the review is limited in that it only generates pooled regional estimates for $PM_{2.5}$ exposure (Balakrishnan et al. 2014). Therefore, the GBD $PM_{2.5}$ database for household indoor air pollution concentrations was compiled using extractions from the WHO global database of household air pollution measurements (Balakrishnan et al. 2013; Forouzanfar et al. 2015). The WHO $PM_{2.5}$ database was augmented by conducting a systematic search using the search terms and inclusion and exclusion criteria utilized by the WHO database to include additional studies that were published between January 2011 and January 2015.

The final $PM_{2.5}$ mapping data set comprised 66 studies from 16 countries contributing 363 observations of $PM_{2.5}$ measurements (see appendix table A.2). Of the observations, 174 (47.9 percent) were adjusted to ensure that all were as directly comparable as possible—for example, all measures were equivalent to the $PM_{2.5}$ level in the kitchen. For this analysis, the optimal observation measures the $PM_{2.5}$ concentration of the household's kitchen area, averaged over a period of 24 hours or longer so that the measures are representative of an individual's average daily exposure. In the GBD data set, measurements of $PM_{2.5}$ exposure that were averaged over a period of less than 24 hours were adjusted to reflect the reference definition of 24-hour average measurements. Similarly, measurements made during times of unusually high exposure—for example, during meal preparation or any other period of peak concentration—were adjusted to the stated reference definition so that data points would be representative of the average daily exposure.

For the remaining countries, the 24-hour kitchen $PM_{2.5}$ concentration was estimated using models. Modeling the 24-hour kitchen $PM_{2.5}$ concentration involved exploring covariates that were selected based on recommendations in the literature. The selection of covariates was largely limited by data availability. Potential covariates, including household-level cooking-related variables, proportion of households using open or traditional stoves, and proportion of households with kitchens located outdoors, were explored but did not show any significant association. A number of environmental variables were considered at the country level, such as average latitude by country, precipitation, mean temperature, and proportion of the population living above the elevation of 1,500 meters. But none of these covariates showed any significant association either, and no country covariate was used in the end. In the absence of a significant predictor, a linear mixed model approach was used to model the average $PM_{2.5}$ kitchen concentrations in households using solid cooking fuels in log space with random intercepts by country, GBD analytical region, and GBD analytical super-region. The existing published data on measured household $PM_{2.5}$ concentrations were consolidated and then used to generate systematically pooled average $PM_{2.5}$ concentrations for all countries in order to capture to some extent the geographic variation in $PM_{2.5}$ exposure across the globe. This approach resulted in a value for the level of $PM_{2.5}$ for every region. That value was used to quantify exposure to $PM_{2.5}$ for residents of every country in the region that uses solid fuel.

Finally, indoor $PM_{2.5}$ concentrations were translated into personal exposure estimates. Estimation of the ratio of personal to area exposures was based on a subset of seven studies from six countries in Asia, Africa, and the Americas from the larger data set. The level of exposure was defined at the personal level for 24-hour average kitchen exposure.

To cover all developing countries, exposure was modeled using a spatiotemporal Gaussian process regression (GPR), a technique that is useful in estimating time series data because of its ability to maintain correlation with uncertainty over time. This process is used for risk factors for which there is sufficient data density to estimate a flexible time trend (Forouzanfar et al. 2015).

The personal exposure to $PM_{2.5}$ among individuals residing in the same household has been found to vary. Studies suggest that time-activity profiles of different individuals in the household differentially influence levels of personal exposure (Balakrishnan et al. 2013). To capture this variation in personal exposure meaningfully for this analysis the average personal exposure was estimated separately for males and females, and exposure of children under age 5 was estimated with reference to women. The ratios of personal exposure for males, females, and children under 5 to the kitchen $PM_{2.5}$ concentration were calculated from the subset of seven studies reporting both measures using time-activity recalls. The ratios were pooled using random effect meta-analyses. Once the ratios were calculated, the personal exposure for the three demographic groups was calculated by applying the ratios to the modeled estimates of kitchen $PM_{2.5}$ concentrations. One thousand random draws of kitchen $PM_{2.5}$ concentrations were applied to 1,000 draws of personal exposure and kitchen $PM_{2.5}$ ratios to generate 1,000 draws of average personal $PM_{2.5}$ exposure levels for men, women, and children separately. Percentiles at the 2.5th and 97.5th levels were calculated to generate the 95 percent uncertainty intervals for every country-year.

Method for Estimating Health Outcomes from Ambient and Household Air Pollution Exposure

The relative risk of mortality from ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute lower respiratory infections, as well as pneumonia in children and adults from exposure to $PM_{2.5}$ was estimated using cause-specific integrated exposure-response functions (Burnett et al. 2014; Cohen et al. n.d.). The burden attributable to ambient ozone was estimated only for COPD. The IER integrates published relative risk estimates for $PM_{2.5}$ from different sources of exposure (outdoor air pollution, second-hand smoke, household air pollution, and active smoking) to estimate the relative risk of mortality from exposure to $PM_{2.5}$ over the entire global range (see box 2.3). The IERs were fit using a Bayesian Markov Chain Monte Carlo approach and a modified power function.

The effects of household air pollution through $PM_{2.5}$ were mapped and incorporated, so that the same outcomes were included across smoking, second-hand smoke, ambient air pollution, and indoor air pollution. The relative risks applied to cataracts, COPD, and lung cancer were determined using direct epidemiologic evidence.

BOX 2.3 Integrated Exposure-Response (IER)

Currently, there are insufficient epidemiologic data on the magnitude of mortality and disability associated with exposure to the high levels of ambient particulate air pollution in China, India, and other low- and middle-income countries. The IER was designed to allow the relative risk of exposure to be estimated over the entire global range of exposure under assumptions consistent with the most current epidemiologic evidence. The IER estimates appear to predict well the results of the limited studies that have been conducted in China (Burnett et al. 2014).

The IER model uses relative risk estimates from the literature. These estimates allow it to be updated based on systematic reviews of the literature without requiring further analysis of primary data not in the public domain. The IER integrates published evidence on the relative risks associated with cardiovascular disease and the lung cancer burden from four different types of $PM_{2.5}$ exposure—ambient air pollution, second-hand tobacco smoke, active smoking, and household air pollution—to help gain a better understanding of the shape of the exposure-response relationship of air pollution and adverse health outcomes over a broader range of exposures. This model allows estimation of risk over the full range of current human exposure to air pollution in places where no studies have been conducted, such as in much of Asia, Sub-Saharan Africa, and the Middle East and North Africa.

The IER model combines information on mortality relative risks from separate types of combustion, equating all types in terms of equivalent ambient $PM_{2.5}$ exposures. Although it is assumed that the toxicity of $PM_{2.5}$ exposure changes with the magnitude of exposure, it is also assumed that at a given exposure level, toxicity is roughly equivalent among all types and temporal patterns of $PM_{2.5}$ exposure (Burnett et al. 2014).

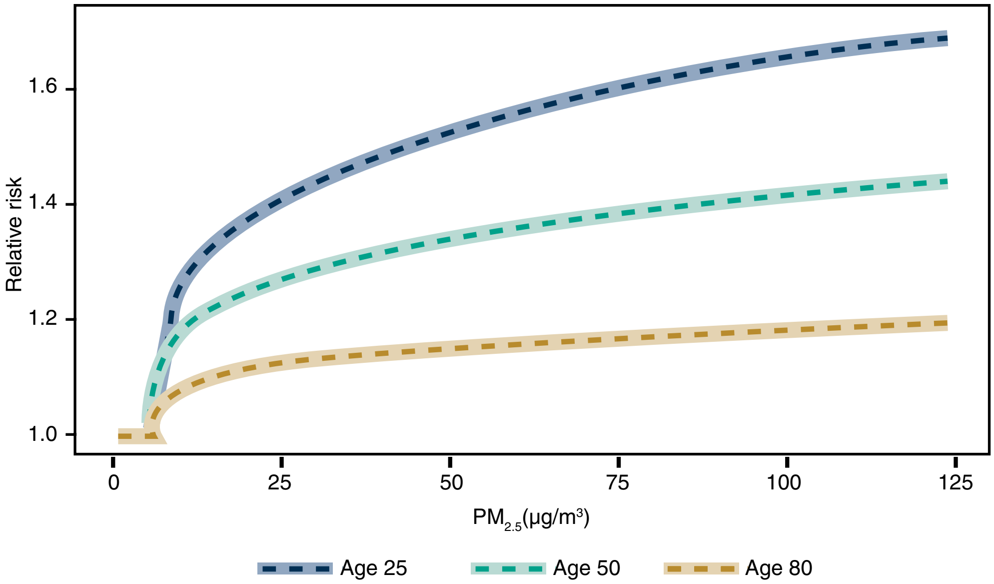
The IER model incorporates four levels of uncertainty: (1) in the model parameters; (2) in the $PM_{2.5}$ exposure estimate; (3) in the counterfactual concentration of exposure; and (4) in the population attributable risk (Burnett et al. 2014). Briefly, uncertainty bounds in the IER are constructed by simulating 1,000 sets of relative risks and fitting the IER model to these values to capture 1,000 sets of parameter values. These parameter estimates are then used to generate 1,000 IER functions over the range of global $PM_{2.5}$ concentrations, as well as estimates of uncertainty for the $PM_{2.5}$ concentrations. Population attributable risk uncertainty is a function of the uncertainty in the model predictions and the exposure estimates.

When direct evidence was not available for outcomes such as ischemic heart disease, cardiovascular disease, and LRIs, risk ratios generated from the IER were used. To utilize evidence from integrated exposure curves, $PM_{2.5}$ mapping values for all country-years were generated using a meta-analysis of published studies that measured $PM_{2.5}$ levels associated with household use of solid cooking fuels. IERs for IHD, stroke, lung cancer and COPD, and LRIs are provided in figure 2.1, and further details on the IERs can be found in Cohen et al. (n.d.).

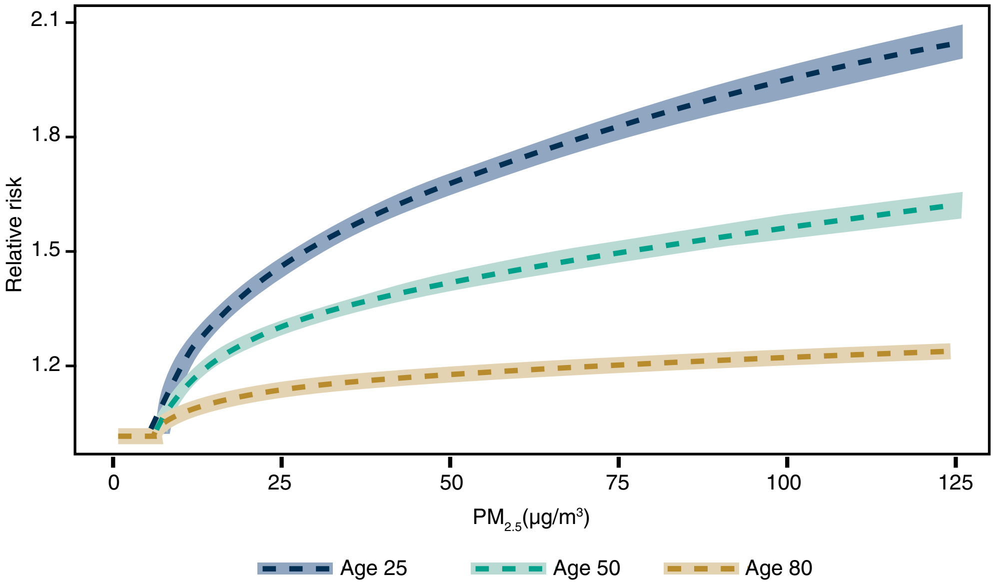
In the absence of empirical studies of their joint effects, the effects of exposure to ambient air pollution (AAP) and household air pollution (HAP) are assumed to be independent. Therefore, although household and outdoor air pollution are related—and sometimes one is the major source of the other—the two exposures are measured independently (AAP by satellite

FIGURE 2.1 Integrated Exposure-Response (IER) Functions for Ischemic Heart Disease (a), Stroke (b), Lung Cancer and COPD (c), and Lower Respiratory Infections (d)

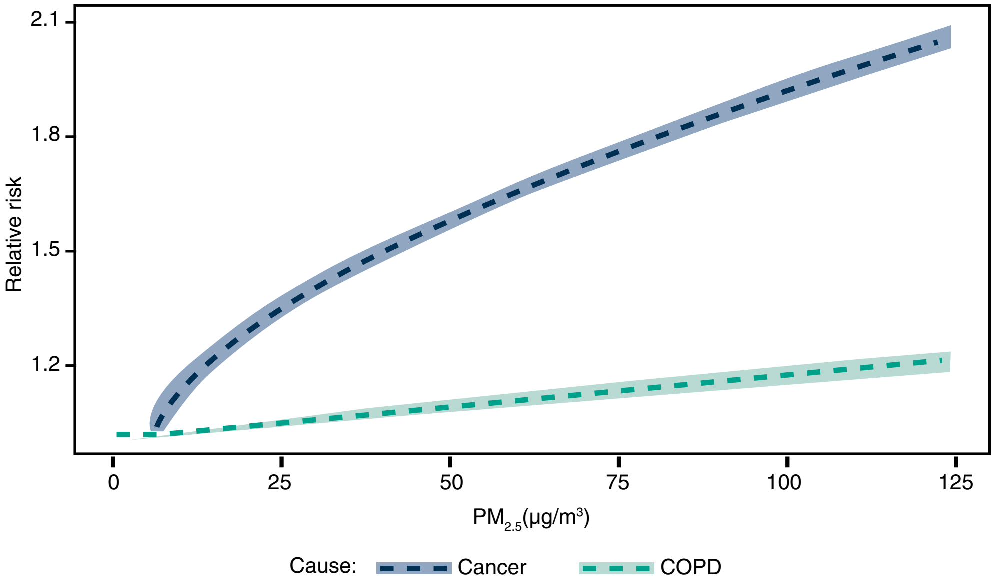
a. Ischemic heart disease



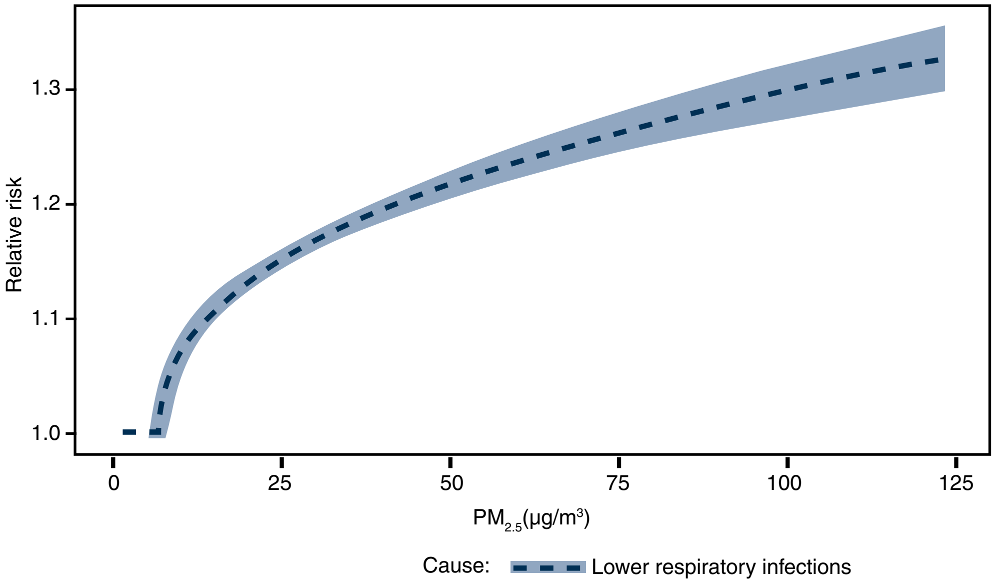
b. Stroke



c. Lung cancer and COPD



d. Lower respiratory infections



Source: Cohen et al. n.d.

Note: Curves depict the central estimate of the IER (dashed line) and their uncertainty (shaded area). COPD = chronic obstructive pulmonary disease.

and ground-level monitors and HAP by household surveys), and their effects are calculated independently. If in some areas solid fuel use is the main source of AAP, both risks affect people living in these areas through ambient exposure and household exposure. However, the correlation between AAP and HAP was not included because it was assumed that exposure to HAP imposes an extra risk on exposure to AAP. Thus assuming there is no interaction between the two exposures (they happen at different times during a 24-hour period rather than stacking on the IER curve), the overall risk is a product of the two relative risks (see appendix A for more details). Similarly, risk of respiratory disease from ozone is assumed to be independent of risk from exposure to $PM_{2.5}$.

The main sources of uncertainty of the exposure-response functions and burden estimates for AAP and HAP are sampling error originating from component studies and the uncertainty of parameters in the IER curve function.

Trends in Exposure and Health Impacts from Ambient and Household Air Pollution

Total Health Impacts of Air Pollution

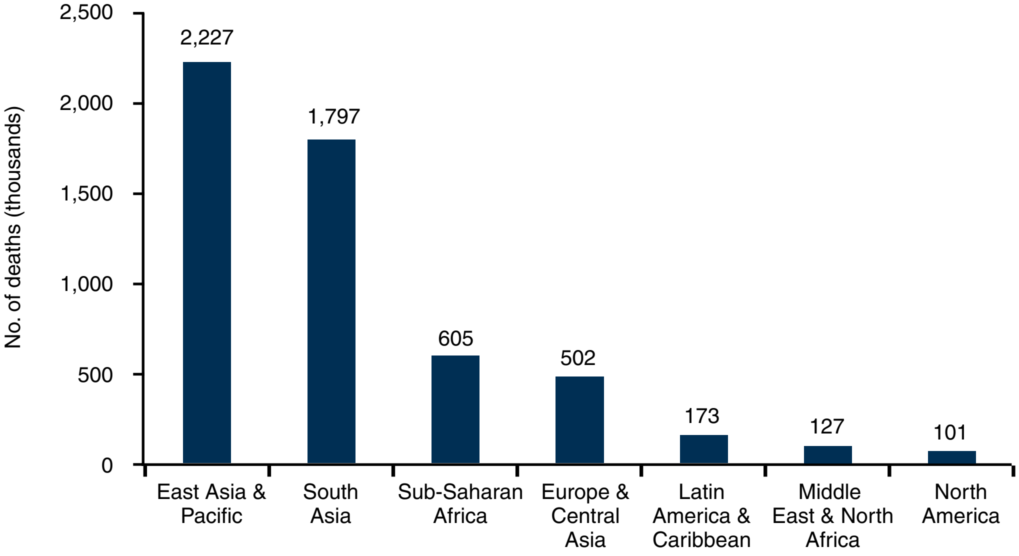
Air pollution (comprising household air pollution, ambient $PM_{2.5}$, and ambient ozone) was the fourth most important risk in 2013 leading to early death. It was associated with 5.5 million premature deaths in 2013—that is, 1 in 10 deaths (see figure 1.1). Air pollution accounted for a larger proportion of total years of life lost (YLLs) than years lived with disability (YLDs); just over 1 percent of total YLDs in 2013 were attributed to air pollution. As a risk factor, its rank has remained unchanged since 1990, when it was also the fourth leading risk factor for premature mortality. Then, air pollution accounted for 4.8 million deaths.

Because of their share in the total population and because of high exposure levels, the majority of deaths attributed to air pollution occurred in East Asia and the Pacific (40 percent) and South Asia regions (33 percent)—see figure 2.2. As a percentage of total deaths, deaths attributable to air pollution were significant in other regions as well. In East Asia and the Pacific and South Asia, about 14 percent of all deaths were attributable to air pollution in 2013; in Sub-Saharan Africa and in the Middle East and North Africa, 7 percent (see figure 2.3). Furthermore, air pollution was the fourth leading cause of premature death in the latter two regions.

From 1990 to 2013, East Asia and the Pacific saw a slight decline in the share of air pollution in total mortality, from 14.9 percent to about 14.4 percent, whereas South Asia saw a significant increase, from 10.5 percent to 13.7 percent.

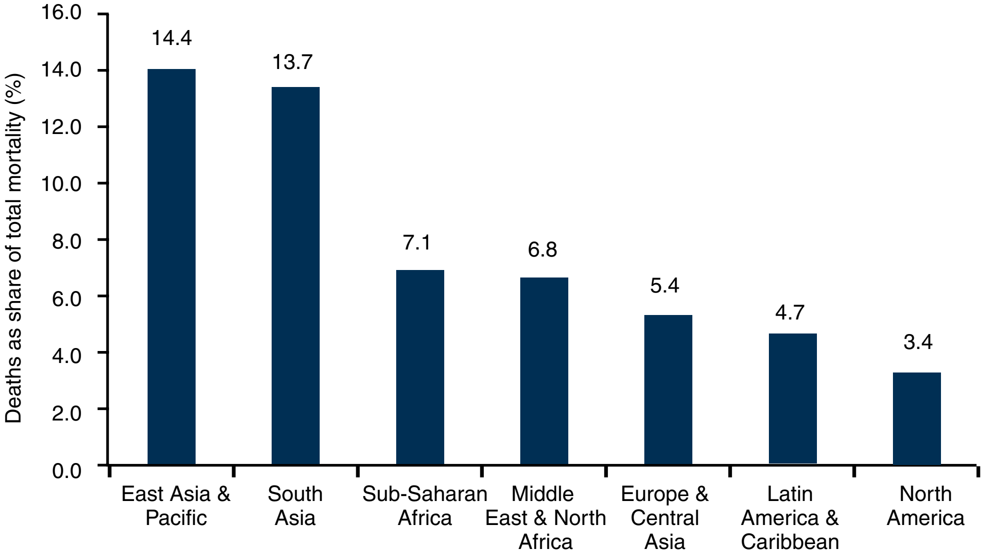
In 2013 South Asia had the most deaths per 100,000 people from air pollution (106 per 100,000 persons), followed by East Asia and the Pacific (99 per 100,000) and Sub-Saharan Africa (64 per 100,000). Latin America and the Caribbean and North America had the lowest deaths per 100,000 people from air pollution in 2013: 28 and 29 per 100,000, respectively. Deaths per 100,000 people from air pollution in East Asia and the Pacific and South Asia have dropped

FIGURE 2.2 Total Deaths from Air Pollution by Region, 2013



Sources: World Bank and IHME, using data from IHME, GBD 2013.

FIGURE 2.3 Percentage of Total Deaths from Air Pollution by Region, 2013

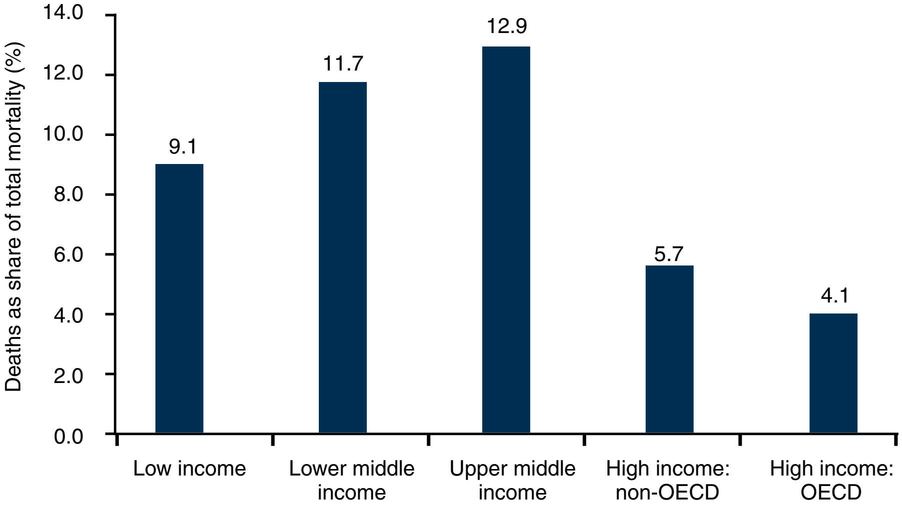


Sources: World Bank and IHME, using data from IHME, GBD 2013.

only slightly since 1990, although the total number of air pollution deaths in these regions has grown substantially. Declines in deaths per capita were greatest for Europe and Central Asia, at 56 per 100,000, and for North America, at 29 per 100,000.

In 2013 air pollution accounted for more than 9 percent of all deaths in countries at all income levels except the high-income countries. The largest proportion of deaths attributable to air

FIGURE 2.4 Percentage of Total Deaths from Air Pollution by Income Group, 2013



Sources: World Bank and IHME, using data from IHME, GBD 2013.
Note: OECD = Organisation for Economic Co-operation and Development.

pollution was found in the upper-middle-income countries (12.9 percent)—see figure 2.4. The share of air pollution in all-cause mortality has increased for low- and lower-middle-income countries and decreased for all other income levels.

Deaths per 100,000 people were highest for the lower-middle-income countries (88 per 100,000 persons) in 2013, followed by the upper-middle-income countries (85 per 100,000) and low-income countries (80 per 100,000). On a more disaggregated basis, the health burden of air pollution was particularly heavy for low-income countries (164 deaths per 100,000) and upper-middle-income countries (116 deaths per 100,000) in East Asia and the Pacific in 2013, followed by low-income and lower-middle-income countries in South Asia, each of which saw 106 deaths per 100,000 in 2013.

Male deaths per 100,000 from air pollution (85 per 100,000 persons) were higher than female deaths (68 per 100,000) in 2013. Although male deaths were also higher in 1990, so were deaths per 100,000 for both men and women, at 93 per 100,000 for males and 88 per 100,000 for females. In 2013 about 5 percent of deaths of children under 5 were attributed to air pollution, compared with less than 3 percent among older children and young adults and more than 10 percent for older adults in every age group above 50. The same age patterns of mortality risks were found in 1990 as well.

Trends in Ambient Air Pollution Exposure and Health Impacts

Exposure

Based on the grid-cell concentration estimates and corresponding population data for 2013, about 87 percent of the world's population lived in areas that exceeded the World Health Organization's Air Quality Guideline of an annual average of 10 micrograms per cubic meter (μg/m^3) for PM$_{2.5}$. Thirty-five percent of the global population resided in areas with concentrations above the WHO Interim Target 1 of an annual average of 35 μg/m^3 PM$_{2.5}$, with nearly all of the most extreme (higher than 65 μg/m^3) concentrations experienced by populations in China and India.

The highest concentrations of PM$_{2.5}$ in 2013 were in North Africa and the Middle East because of emissions of windblown mineral dust, and in South Asia and East Asia and the Pacific, especially in northern India and eastern China, because of combustion emissions from multiple sources, including household solid fuel use, coal-fired power plants, agricultural burning, and industrial and transportation-related sources (see map 2.1). At the country level, the highest population-weighted mean concentration estimated for 2013 was in Mauritania (70 μg/m^3), followed by China (55 μg/m^3) and Saudi Arabia (54 μg/m^3). The lowest country-level population-weighted estimates (at or below 6 μg/m^3) were for several Pacific and Caribbean island nations, Australia, and Norway.

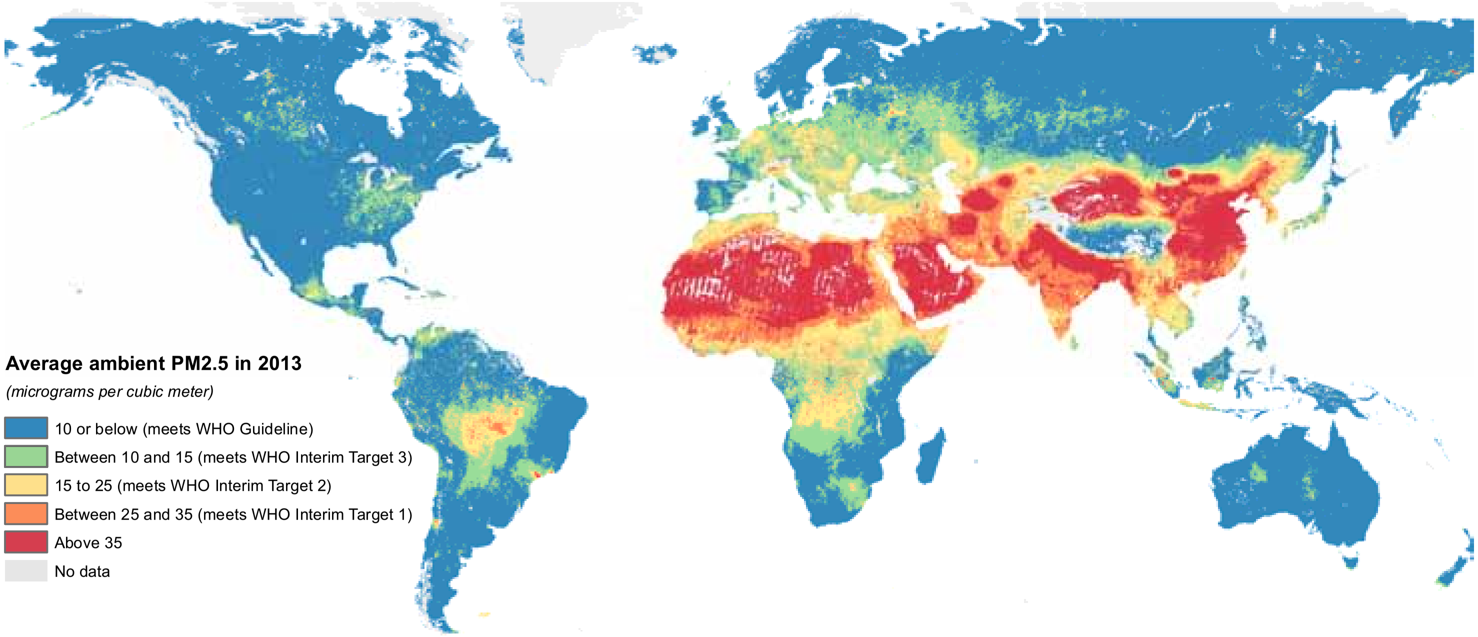
Between 1990 and 2013, decreases in population-weighted mean concentrations of PM$_{2.5}$ were reported in most high-income countries, in contrast to the increases estimated in South Asia, throughout much of Southeast Asia, and in China. There were large relative decreases in concentrations in the eastern United States, Europe, and the Russian Federation, and in parts of East Asia and the Pacific. By contrast, large relative increases were apparent in western Canada, parts of South America, the Middle East, India, and China (map 2.2).

Between 1990 and 2013, population-weighted ozone concentrations increased by 8.9 percent. Some regions saw an increase; others saw a decline. Increases of 10–20 percent were observed in China, India, Pakistan, Bangladesh, and Brazil, while decreases were observed in the United States and Indonesia, for example.

Health Impacts

Ambient PM$_{2.5}$ (APM) pollution was responsible for more than 2.9 million deaths in 2013 (a 30 percent increase from 1990). Of those deaths, 1.7 million were males and 1.2 million were females.

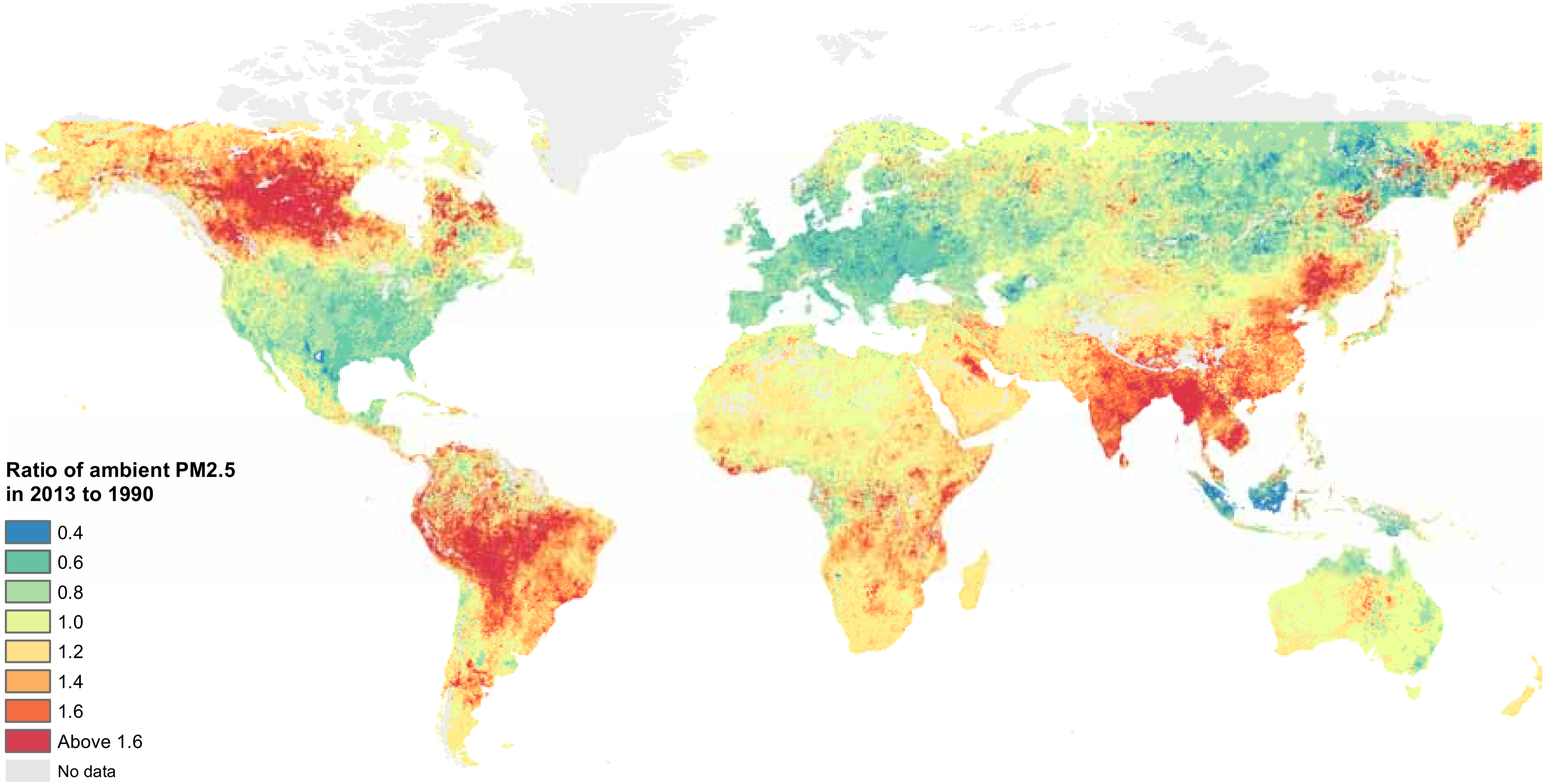
MAP 2.1 Locations Where 2013 Annual Average $PM_{2.5}$ Concentrations (µg/m^3) Meet or Exceed World Health Organization's (WHO) Air Quality Guideline or Exceed Interim Targets



Source: Brauer et al. 2016.

Note: Reprinted with permission from Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013. Brauer M, Freedman G, Frostad J, van Donkelaar A, Martin RV, Dentener F, van Dingenen R, Estep K, Amini H, Apte JS, Balakrishnan K, Barregard L, Broday D, Feigin V, Ghosh S, Hopke PK, Knibbs LD, Kokubo Y, Liu Y, Ma S, Morawska L, Sangrador JL, Shaddick G, Anderson HR, Vos T, Forouzanfar MH, Burnett RT, Cohen A. Environ Sci Technol. 2016 Jan 5; 50(1):79–88. doi: 10.1021/acs.est.5b03709. Copyright 2016 American Chemical Society.

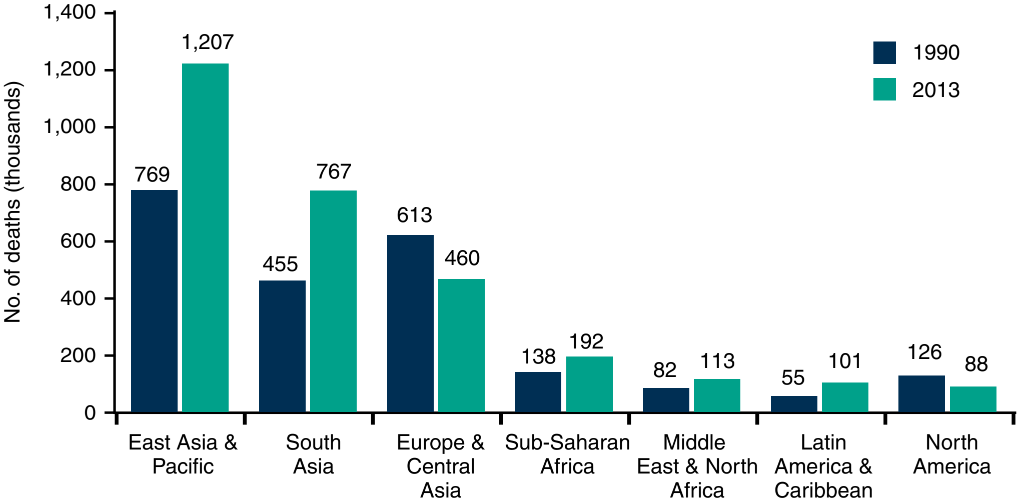
MAP 2.2 Ratio of Estimated 2013:1990 Annual Average $PM_{2.5}$ Concentrations at 0.1° × 0.1° Resolution



Source: Brauer et al. 2016.

Note: Areas of darker red indicate regions with the largest relative increases in annual average $PM_{2.5}$, with areas of darker blue indicating regions with the largest relative decreases. White areas indicate no data. Reprinted with permission from Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013. Brauer M, Freedman G, Frostad J, van Donkelaar A, Martin RV, Dentener F, van Dingenen R, Estep K, Amini H, Apte JS, Balakrishnan K, Barregard L, Broday D, Feigin V, Ghosh S, Hopke PK, Knibbs LD, Kokubo Y, Liu Y, Ma S, Morawska L, Sangrador JL, Shaddick G, Anderson HR, Vos T, Forouzanfar MH, Burnett RT, Cohen A. Environ Sci Technol. 2016 Jan 5; 50(1):79–88. doi: 10.1021/acs.est.5b03709. Copyright 2016 American Chemical Society.

FIGURE 2.5 Total Deaths from Ambient $PM_{2.5}$ Pollution by Region, 1990 and 2013



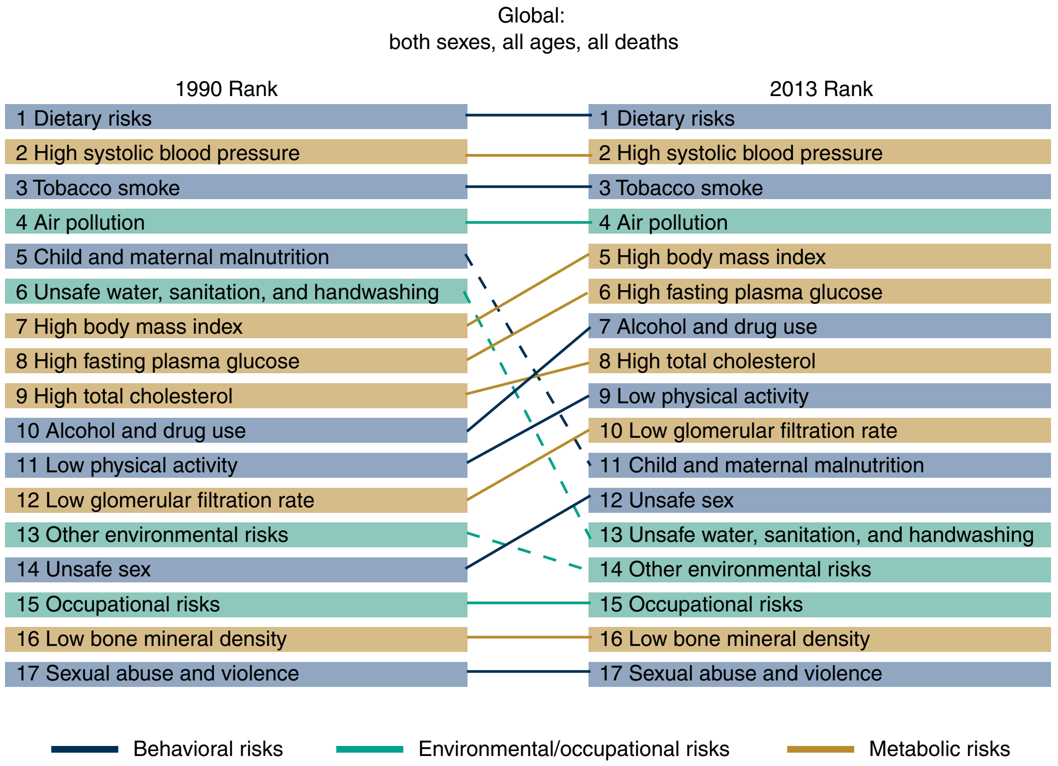
Sources: World Bank and IHME, using data from IHME, GBD 2013.
Note: Data are for a balanced sample of countries for which data are available for both 1990 and 2013.

The strong rising trend in total deaths accelerated after 2000, driven largely by China. In 1990 there were 2.2 million APM-associated deaths, increasing 8 percent, to 2.4 million, in 2000, followed by a 21 percent increase to 2.9 million deaths in 2013. Four factors played a role in the upward trend in the number of APM deaths, including increases in $PM_{2.5}$ exposure in a number of countries with very large populations (China, India, Bangladesh, and Pakistan), population growth, population aging, and changes in the prevalence of diseases affected by air pollution. Although the majority of deaths were in East Asia and the Pacific and South Asia, all regions other than Europe and Central Asia and North America saw an increase in the number of deaths (figure 2.5).

Exposure to ambient $PM_{2.5}$ was the seventh-ranked risk associated with death in 2013 (see figure 2.6). More than 5.3 percent of deaths in 2013 worldwide were attributable to exposure to $PM_{2.5}$. The $PM_{2.5}$ risk increased from 4.7 percent of deaths in 1990, when it was the 10th highest ranked risk factor. The main outcome of $PM_{2.5}$ risk is cardiovascular disease, including IHD and stroke, and cancers. In 1990 lower respiratory infections were the second most important outcome of $PM_{2.5}$ risk, with about 1 percent of total deaths caused by pneumonia attributable to $PM_{2.5}$. Two million cardiovascular disease deaths (3.7 percent of global deaths) and 387,000 cancer deaths (0.7 percent of global deaths) were attributable to $PM_{2.5}$ risk in 2013. Globally in 2013, $PM_{2.5}$ exposure caused 13.6 percent of IHD deaths, 14.5 percent of stroke deaths, 23.6 percent of lung cancer deaths, 5.7 percent of COPD deaths, and 12.4 percent of pneumonia deaths.

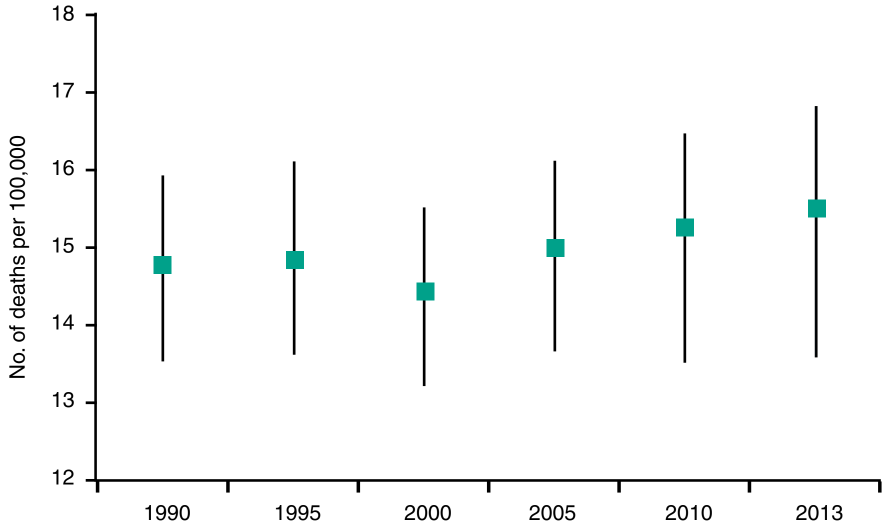
Globally, exposure to $PM_{2.5}$ and the fraction of outcomes attributable to $PM_{2.5}$ have not improved over the last 23 years. The trend line for the cause-specific attributable fraction shows the trend in exposure. The global population attributable fraction for ischemic heart disease decreased between 1990 and 2000, revealing a brief improvement in air quality and reduction in exposure (figure 2.7). However, exposure increased from 2000 to 2010, with the

FIGURE 2.6 Leading Modifiable Risks by Number of Deaths: Globally, 1990 and 2013



Source: IHME, GBD 2013.

FIGURE 2.7 Trends in Ischemic Heart Disease Death Rates from Ambient $PM_{2.5}$ Pollution, 1990–2013



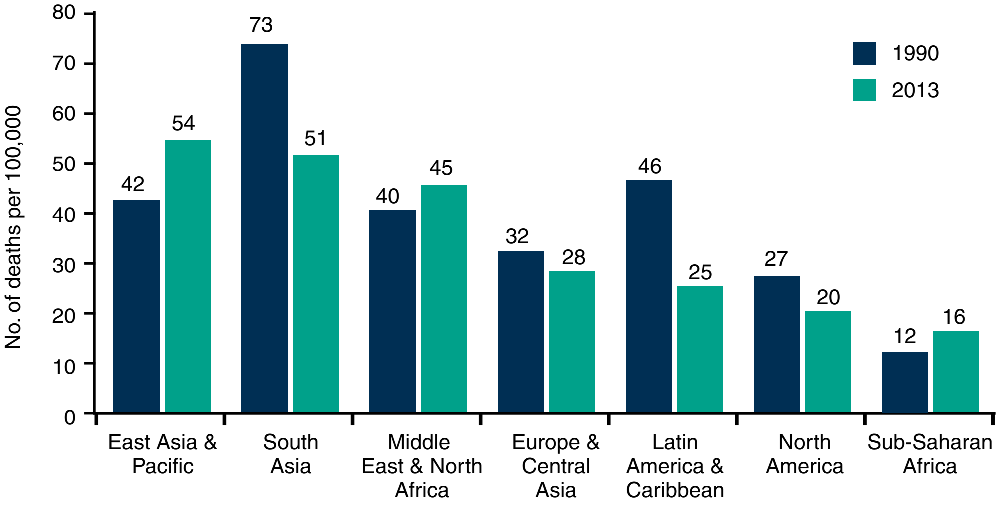
Source: IHME, GBD 2013.

trend slowing after 2010. The increase is more prominent among younger populations in the world. The change in the all-age attributable rate is a function of three factors: (1) population aging, which tends to increase rates because cardiovascular outcome rates are higher in older ages; (2) changes in the baseline rate unrelated to air pollution—examples are other risk factors such as smoking or access to care and better survival of patients; and (3) changes in the exposure to air pollution. It appears that since 2005 the increase in global exposure to air pollution and population aging has outpaced the decrease in the baseline trend that began before the 1990s, changing the trend to slightly upward. The role of different factors is discussed further in Cohen et al. (n.d.).

Deaths per 100,000 people for all ages decreased slightly between 1990 and 2000, from 42 deaths per 100,000 persons to 40 per 100,000, but rose slightly to 41 deaths per 100,000 in 2013, revealing that the trend in the 1990s was mainly driven by population growth. All regions other than Middle East and North Africa and Sub-Saharan Africa saw a decrease in number of deaths per capita from $PM_{2.5}$ pollution between 1990 and 2013 (figure 2.8).

Global age-standardized death rates (ASDRs), which are adjusted for population growth and aging change by time and are suitable for comparing the per capita disease burden for different years, reveal a somewhat different picture. Since 1990, there has been a monotonic decrease, from 62 deaths per 100,000 persons in 1990 to 48 per 100,000 in 2013, with an annual decline of about 1.1 percent. The decline in the ASDR reflects overall improvement in health in these

FIGURE 2.8 **Deaths per 100,000 People from Ambient $PM_{2.5}$ Pollution by Region, 1990 and 2013**



Sources: World Bank and IHME, using data from IHME, GBD 2013.

countries—for example, a decline in the impact of childhood respiratory diseases. The exceptions are countries in East Asia and the Pacific (including Cambodia and the Marshall Islands), Latin America and the Caribbean (including Bolivia, the Dominican Republic, and Uruguay), and South Asia (including Bangladesh and Pakistan). Bolivia has experienced the greatest rate of change, with a 6.3 percent increase, followed by Mozambique (4.2 percent) and Zambia (2.9 percent). The greatest decline from 1990 to 2013 occurred in Norway, with an 8.2 percent decrease, followed by Australia (–7.4 percent) and Ireland (–6.9 percent). The age-standardized death rates from $PM_{2.5}$ are highest in developing countries in South Asia (77 deaths per 100,000), East Asia and the Pacific (56 per 100,000), and the Middle East and North Africa (52 per 100,000)—see map 2.3. People living in Afghanistan, Turkmenistan, and Yemen are at the highest risk of death from $PM_{2.5}$ exposure.

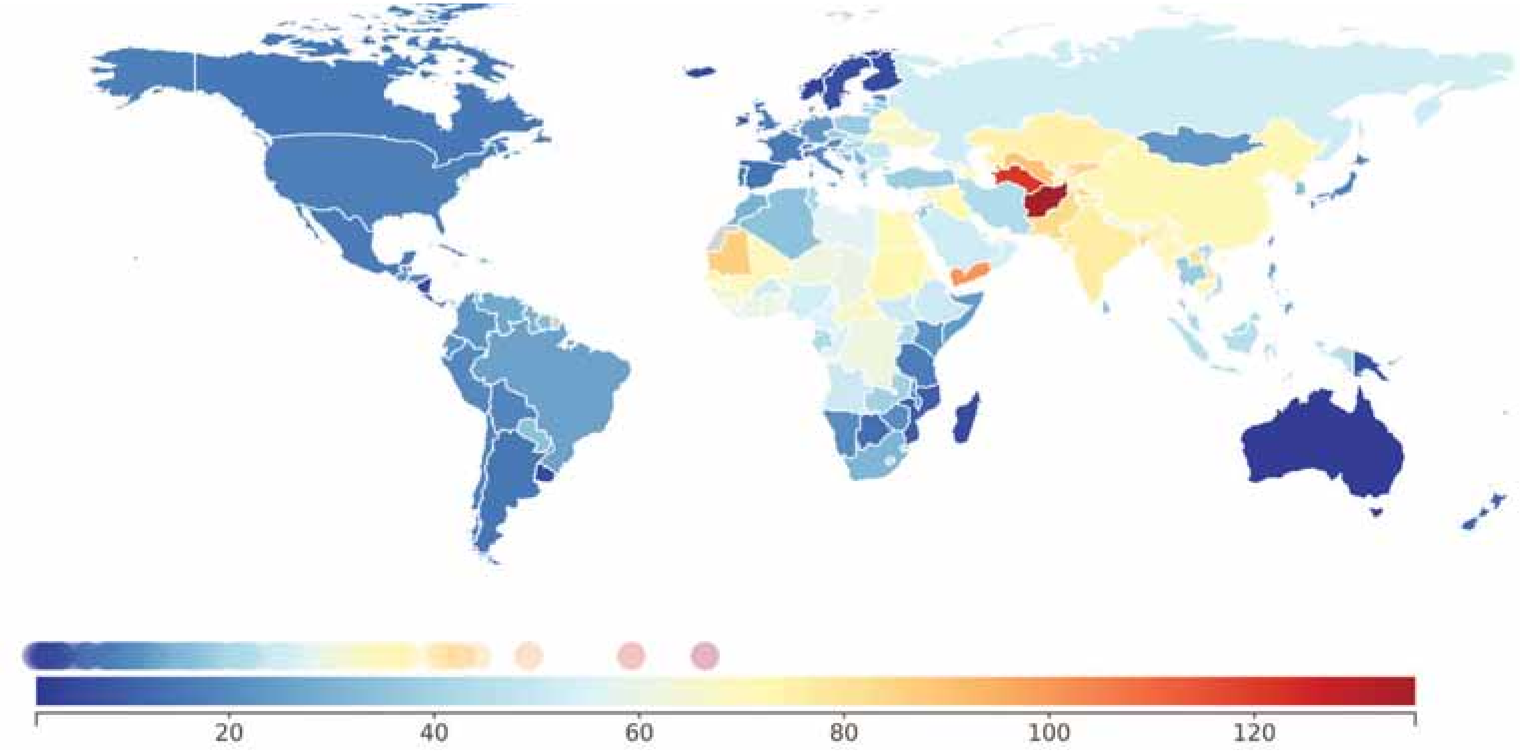
The total deaths and deaths per 100,000 people associated with APM increase by age. In 2013 there were just over 120,000 deaths from APM among children under 5 (a figure that declined to fewer than 10,000 deaths among older children) and substantially higher rates in the middle-aged and older groups (figure 2.9). The mortality rate in 2013 was 18 deaths per 100,000 persons under age 5 (driven mostly by lower respiratory infections), increasing to 397 per 100,000 in people over age 70 (driven largely by cardiovascular diseases and cancers). The age pattern in the burden of DALYs (disability-adjusted life years) shifted somewhat, with a higher peak among young children and then again among adults ages 60–64. For younger children, this increase in burden is explained by the greater loss of life years from premature death and more years lived with disabilities.

The level of exposure and adverse health effects of $PM_{2.5}$ differ greatly among income groups. In 2013 ambient air pollution exposure was associated with 4.1 percent of all deaths in high-income countries, where the percentage of deaths has been declining since 1990. In all other regions, the percentage of total deaths attributable to APM has increased, from 2.3 percent in 1990 to 3.5 percent in 2013 in low-income countries, from 4.0 percent to 5.1 percent in lower-middle-income countries, and from 5.7 percent to 7.4 percent in upper-middle-income countries (see figure 2.10). In 2013, 75 percent of $PM_{2.5}$ deaths occurred in middle-income countries, and the age-standardized attributable death rate was nearly three times higher in lower-middle-income countries than in high-income countries. Death rates for lower respiratory infections attributable to $PM_{2.5}$ among children under 5 were more than 60 times higher in low-income countries than in high-income countries.

The burdens associated with $PM_{2.5}$ in high-income countries compared with low- and middle-income countries have changed in different ways. In high-income countries, the proportion of $PM_{2.5}$-attributable IHD deaths decreased from 12.3 percent in 1990 to 9.4 percent in 2013. In low-income countries, it increased from 13.6 percent to 15.5 percent, and in lower- and upper-middle-income countries it increased slightly as well, from 15.7 percent to 16.3 percent and from 13.9 percent to 14.4 percent, respectively.

MAP 2.3 Age-Standardized Death Rates from Ambient $PM_{2.5}$ Pollution, 2013

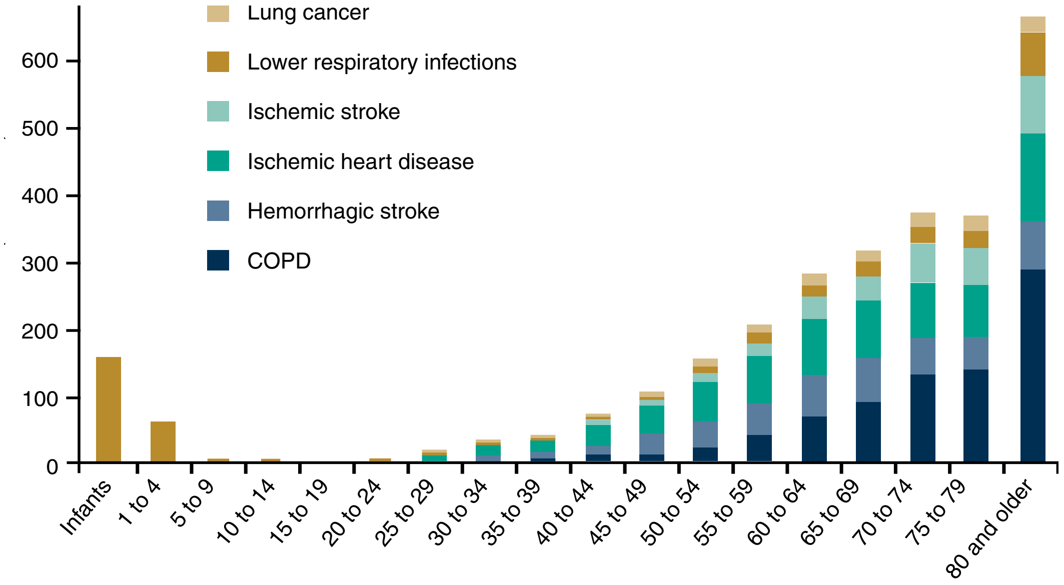
All causes attributable to ambient particulate matter pollution: both sexes, deaths per 100,000



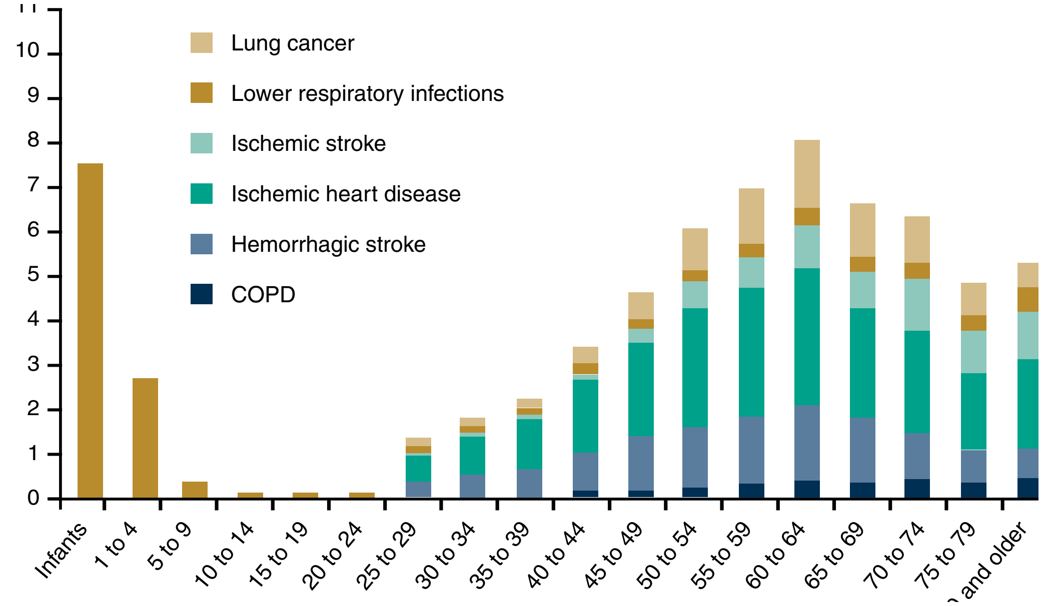
Source: IHME, GBD 2013.

FIGURE 2.9 Total Deaths (a) and Disability-Adjusted Life Years (DALYs) (b) from Ambient $PM_{2.5}$ Pollution by Age Group, 2013

a. Total deaths



b. Total DALYs

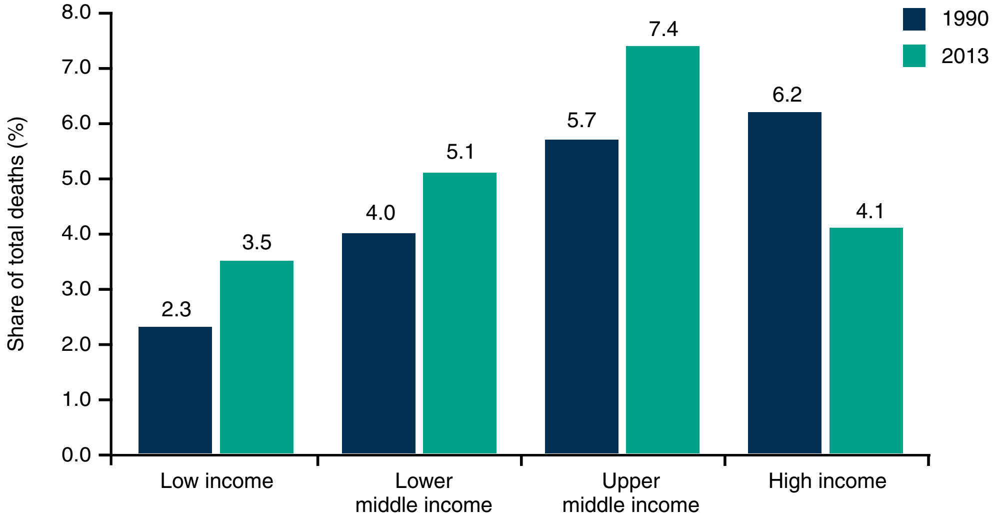


Source: IHME, GBD 2013.

For ambient air pollution, health risks tended to be greater for lower-middle-income countries and lower for countries at higher income levels (figure 2.11).

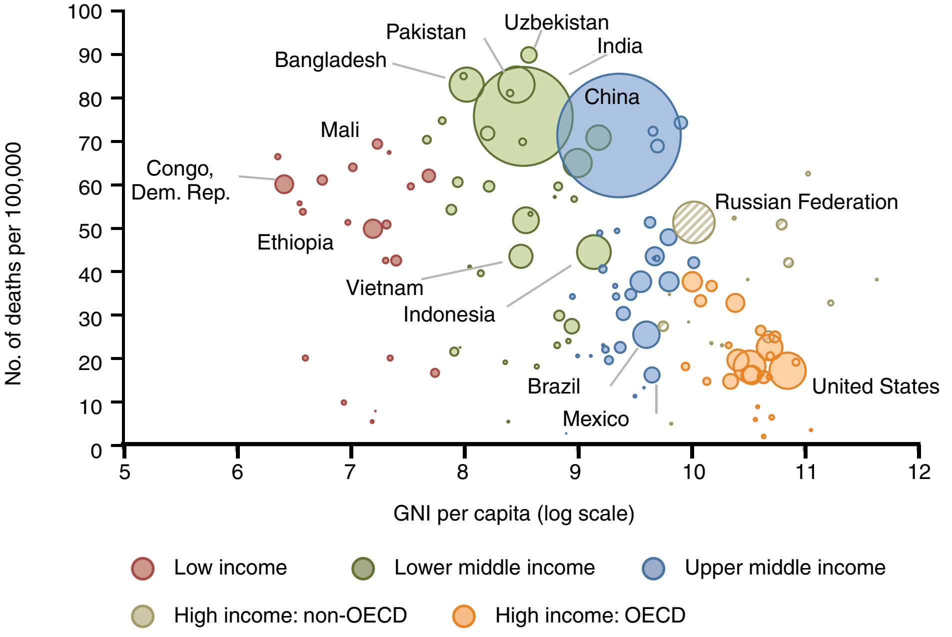
Exposure to ozone contributed to 217,000 premature deaths from COPD in 2013. Although the numbers of deaths from ambient ozone pollution are much smaller than those attributable to ambient $PM_{2.5}$, deaths from ambient ozone increased in all regions globally (figure 2.12). As

FIGURE 2.10 Percentage of Total Deaths from Ambient $PM_{2.5}$ Pollution by Income Group, 1990 and 2013



Sources: World Bank and IHME, using data from IHME, GBD 2013.

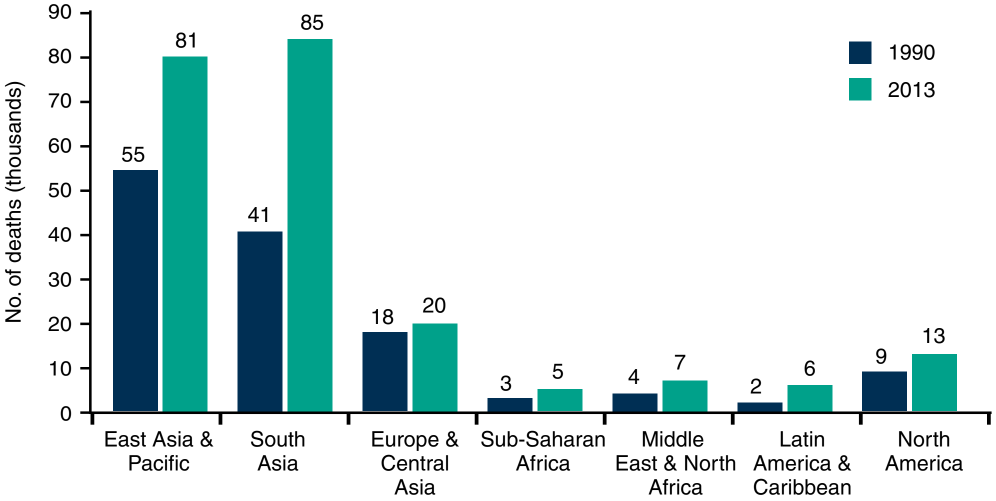
FIGURE 2.11 Ambient $PM_{2.5}$ Death Rate versus Income per Capita, 2013



Sources: World Bank and IHME.

Note: Size of bubble corresponds to total number of deaths. GNI = gross national income; OECD = Organisation for Economic Co-operation and Development.

FIGURE 2.12 **Total Deaths from Ambient Ozone Pollution by Region, 1990 and 2013**



Sources: World Bank and IHME, using data from IHME, GBD 2013.

discussed earlier, deaths from ambient $PM_{2.5}$ decreased in Europe and Central Asia and North America, although they increased in the rest of the regions (figure 2.5). The increase in deaths from ozone exposure reflects both an increase in levels of ozone and increased COPD mortality.

Trends in Household Air Pollution Exposure and Health Impacts

Exposure

Based on estimates only for low- and middle-income countries, 42.2 percent of the world's population was exposed to household air pollution from solid fuels in 2013. The highest average levels of population exposure to HAP worldwide were in Sub-Saharan Africa, ranging from 12 percent in Djibouti to 99.5 percent in Rwanda, and East Asia and the Pacific, ranging from 24.3 percent in the Marshall Islands to 90.9 percent in Myanmar. The lowest country-level exposure (below 0.05 percent) was in the Republic of Korea, Qatar, Lebanon, and the United Arab Emirates. Among low-income countries, the lowest exposures were in Eritrea (61.3 percent) and Zimbabwe (66.2 percent).

Between 1990 and 2013, declines in HAP exposure were evident in most countries, ranging from nearly 100 percent in many higher-income countries to under 10 percent across much of Sub-Saharan Africa. At the country level, Korea (–99.3 percent) and the Arab Republic of Egypt (–94.9 percent) had the largest declines in HAP exposure from 1990 to 2013. Very few countries saw increases in exposure to HAP, apart from Guinea-Bissau, the Marshall Islands, and Sierra Leone, which saw slight total growth in exposure (an additional 2–6 percent of their populations) between 1990 and 2013. Russia also saw a very slight increase, but the total estimated exposure in both time periods was below 1 percent of the population.

Health Impacts

Household air pollution was responsible for 2.9 million deaths in 1990, a number that remained constant over time, with 2.9 million deaths globally in 2013 (see figure 2.13a). In 2013 among males, 1.6 million deaths were attributable to HAP; among females, 1.3 million deaths. This finding is surprising because women are typically exposed to higher concentrations of indoor air pollution as they are primarily responsible for cooking in the household. This result, however, is driven by differences in the distribution of the number of deaths from ischemic heart disease by age of men and women. Age-specific population attributable fractions are lower among men than among women for all of the health outcomes linked to household air pollution, which is to be expected by their differing levels of exposure. In other words, at any specific age, a smaller fraction of premature deaths for men is attributed to exposure to indoor air pollution. However, the highest number of IHD deaths occurs among men at age 60, while the number is greatest among women at 80 and up, and the fraction of premature deaths attributable to IHD is higher at younger ages (figure 2.14). Therefore, although a smaller fraction of premature deaths for men is attributable to household air pollution at any given age, a greater fraction of premature deaths is attributable to HAP for both men and women at a younger age. Because more men die at a younger age, a higher number of deaths is attributable to HAP for males.

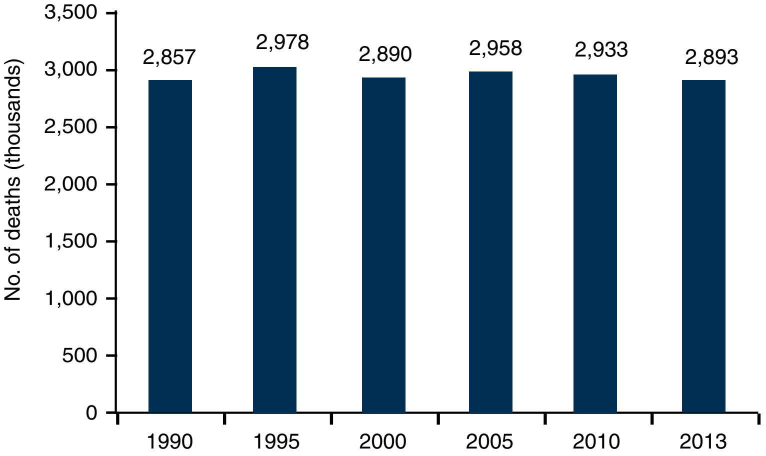
Exposure to household air pollution from solid fuels caused a health loss of 101.6 million DALYs globally in 1990. By 2013 the burden of HAP had decreased by 20.2 percent, to 81.1 million DALYs, accounting for just over 3 percent of global DALYs in 2013.

Exposure to HAP was the eighth-ranked risk associated with death globally in 2013, behind ambient air pollution and ahead of high cholesterol, alcohol use, and childhood undernutrition. More than 5 percent of all deaths in 2013 were attributable to exposure to household air pollution. In 1990 HAP was the fourth-leading risk associated with deaths globally. The main outcomes of HAP exposure are cardiovascular diseases (stroke and IHD), COPD, lower respiratory infections, and lung cancer. In 1990 the most important outcome of HAP risk was cardiovascular disease, with 1.5 million deaths (or 2.7 percent of total deaths). In 2013, 818,000 COPD deaths (1.5 percent of global deaths), 449,000 LRI deaths (0.8 percent of global deaths), and 128,000 cancers (0.23 percent of global deaths) were attributable to HAP. Globally in 2013, HAP was responsible for 12.1 percent of stroke deaths, 8.8 percent of IHD deaths, 27.9 percent of COPD deaths, 16.9 percent of LRI deaths, and 7.8 percent of lung cancer deaths.

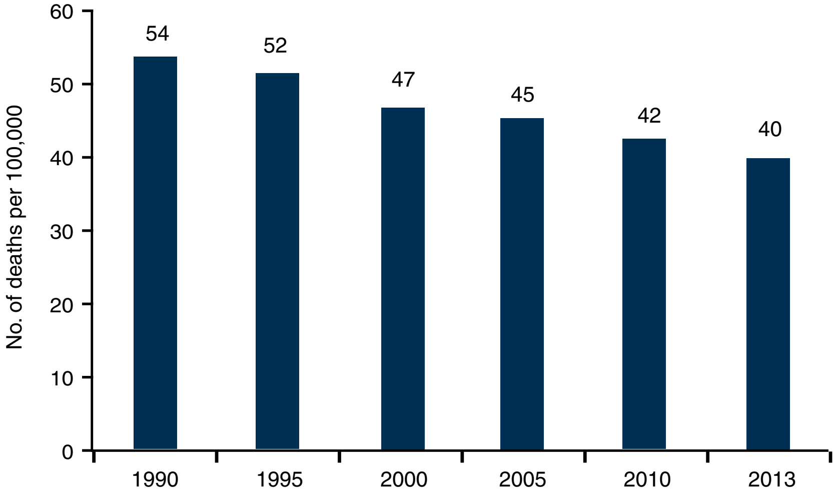
Exposure to household air pollution is also associated with cataracts, a nonfatal outcome. About 21 percent of the burden of cataracts (measured in terms of DALYs) is attributable to exposure to HAP, and it primarily affects older women after prolonged exposure. DALYs associated with cataracts from exposure to HAP increased by 42.5 percent from 1990 to 2013, although the proportion of total cataract DALYs decreased slightly (from 23.3 percent in 1990 to 21 percent in 2013). Disability associated with cataracts from exposure to HAP is concentrated in Asia—India, China, and Indonesia.

FIGURE 2.13 **Total Deaths (a) and Deaths per 100,000 People (b) from Household Air Pollution, 1990–2013**

a. Total deaths



b. Deaths per 100,000 people

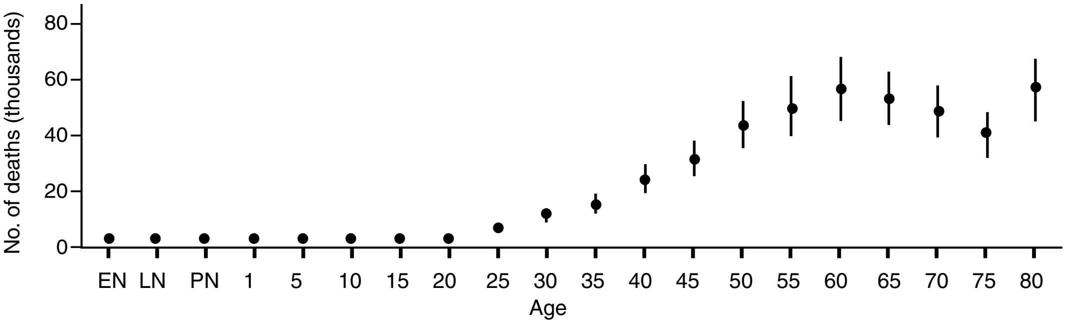


Sources: World Bank and IHME, using data from IHME, GBD 2013.

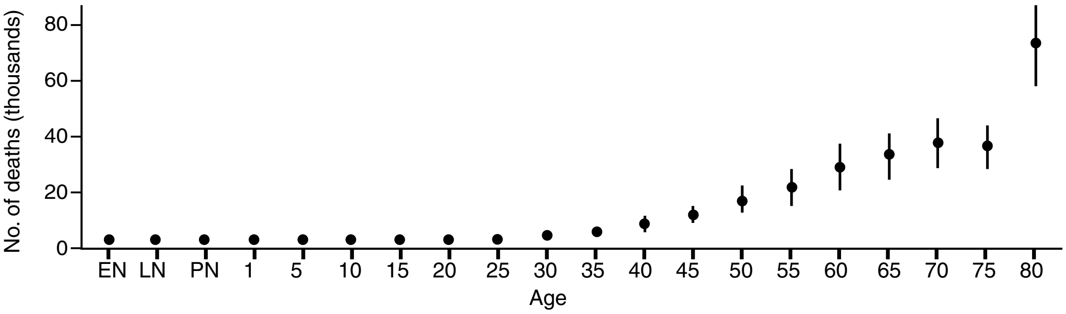
Deaths per 100,000 people for all ages due to HAP exposure decreased steadily from 1990 to 2013, from 54 per 100,000 persons to 40 per 100,000 (figure 2.13b). The age-standardized death rate from HAP tells a similar story, declining steadily from 1990 (75 per 100,000) to 2013 (47 per 100,000), a 37.5 percent drop. However, there are exceptions in some countries in Sub-Saharan Africa. Egypt had the greatest annual percentage decrease from 1990 to 2013 at –17.9 percent, followed by St. Vincent and the Grenadines (–10.7 percent) and the Maldives (–10.1 percent). The largest annualized increases were in the Marshall Islands (1.0 percent), Zambia (0.9 percent), and Lesotho (0.6 percent). The highest age-standardized death rates from HAP were in South Asia (123.3 per 100,000), Sub-Saharan Africa (108.9 per 100,000), and East Asia and the Pacific (53.2 per 100,000). At the country-level, the highest age-standardized death

FIGURE 2.14 Deaths from Ischemic Heart Disease Attributable to Exposure to Household Air Pollution by Age Category for Males and Females, 2013

a. Males



b. Females



Source: IHME, GBD 2013.

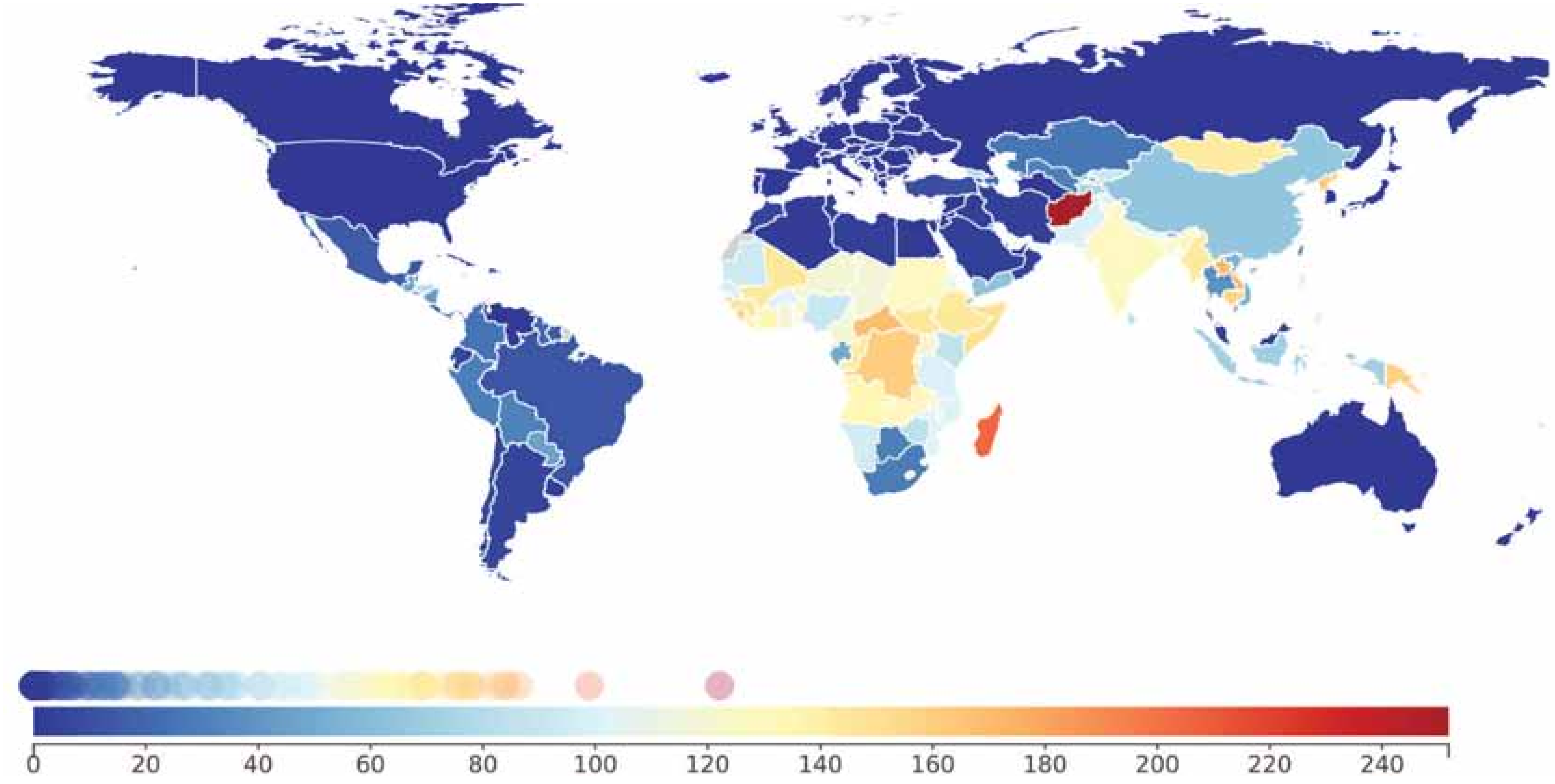
rates were in Afghanistan (251.8 deaths per 100,000), Madagascar (204.0 per 100,000), and Guinea-Bissau (178 per 100,000)—see map 2.4.

The main factors playing a role in the HAP burden trends include population growth, population aging, changes in individual risk, and decreased population exposure. Population growth increases the total burden, as does population aging, because the incidence of outcomes increases with age. Population growth partly explains why the total number of deaths attributable to HAP has remained constant, even as exposure has declined in many places, resulting in declining death rates over the same period. Although the prevalence of diseases affecting older people has been increasing—and this, along with population growth, has kept the absolute numbers steady—the prevalence of lower respiratory infections in young children has been decreasing. The declining burden among young children to some extent counterbalances the increasing burden among older people.

The fraction of outcomes attributable to HAP has improved steadily over the last 23 years. The global population attributable fraction for COPD decreased from 1990 to 2013, revealing a global reduction in household air pollution and improvement in exposure to cooking fuels.

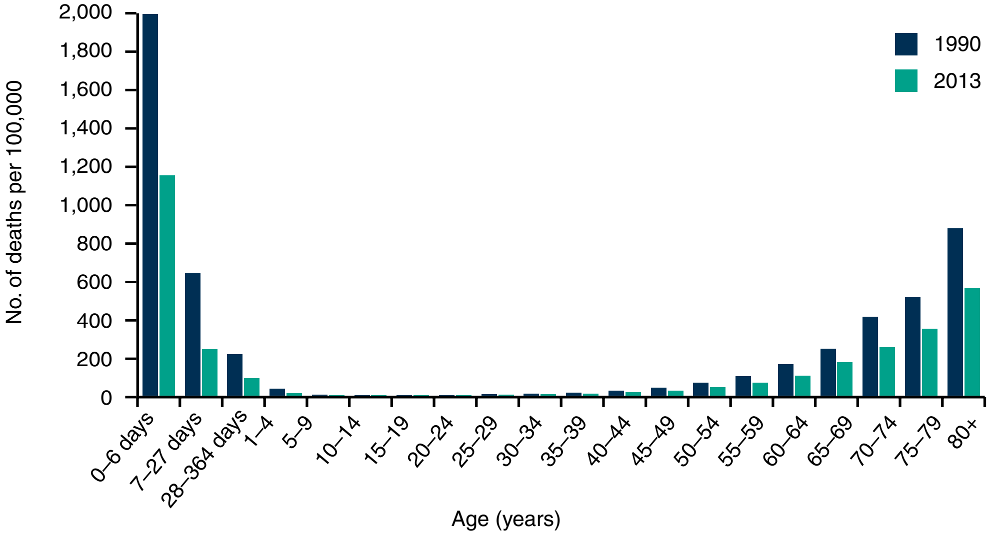
MAP 2.4 Age-Standardized Death Rates from Household Air Pollution, 2013

All causes attributable to number of household air pollution from solid fuels
Both sexes, number of deaths per 100,000



Source: IHME, GBD 2013.

FIGURE 2.15 Deaths per 100,000 People by Age Group, 1990 and 2013



Sources: World Bank and IHME, using data from IHME, GBD 2013.

The decrease is more prominent among females, although the population attributable fraction has declined substantially for both sexes.

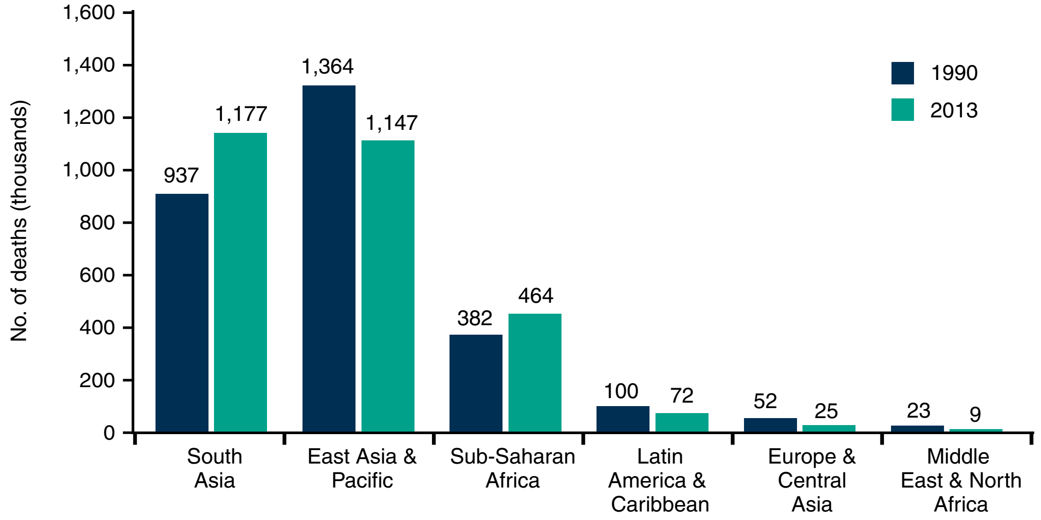
The pattern of declining risk is more nuanced for specific age groups (figure 2.15). Total deaths are down by almost 60 percent among children under 5. The biggest declines in DALYs are in the younger age groups, but even among those 70 and older improvements are visible: DALYs per capita declined 36 percent, from 7,031.4 per 100,000 persons in 1990 to 4,480.6 per 100,000 in 2013. The death rate in 2013 was 33.1 per 100,000 among children under 5 (driven mainly by lower respiratory infections). Among people over age 70 from 1990 to 2013, the death rate from HAP decreased from 557 deaths per 100,00 to 368.6 deaths per 100,000 (the difference in the 2013 under 5 and 70 plus rates is driven in large part by cardiovascular diseases—stroke and IHD).

The constant trend in total number of deaths from indoor air pollution between 1990 and 2013 hides important regional variations. Although the total number of deaths fell in East Asia and the Pacific, Latin America and the Caribbean, Europe and Central Asia, and the Middle East and North Africa, the number of deaths increased substantially in South Asia (26 percent) and Sub-Saharan Africa (21 percent)—see figure 2.16.

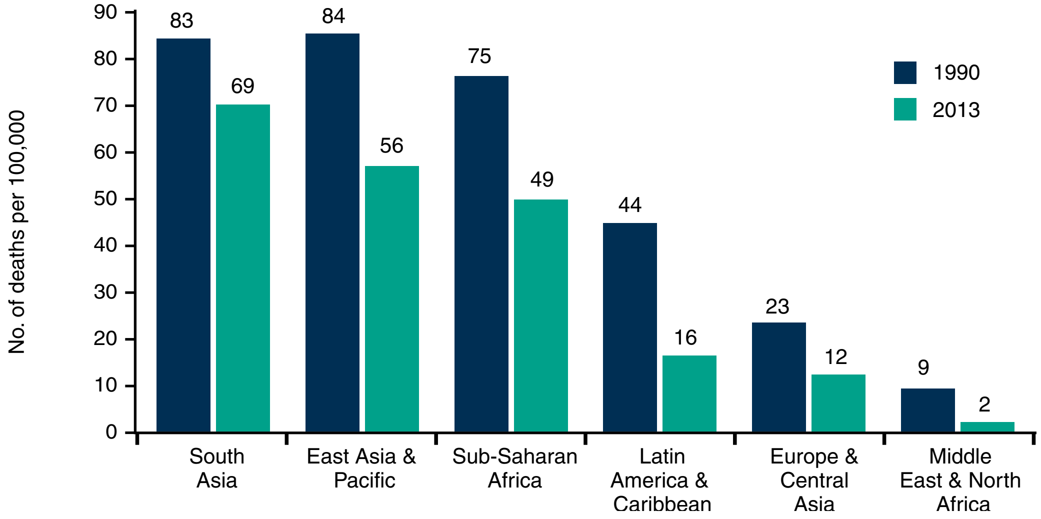
Trends in the health effects of household air pollution also differ across income groups (figure 2.17). In 2013 household air pollution exposure was associated with 5.7 percent of all deaths in upper-middle-income countries, and the percentage of deaths attributable to HAP has been declining there since 1990. In low-income countries, the percentage of total deaths attributable to HAP increased from 6.6 percent of deaths in 1990 to 7.8 percent in 2013. In lower-middle-

FIGURE 2.16 Total Deaths (a) and Deaths per 100,000 People (b) from Household Air Pollution by Region, 1990 and 2013

a. Total deaths



b. Deaths per 100,000 people



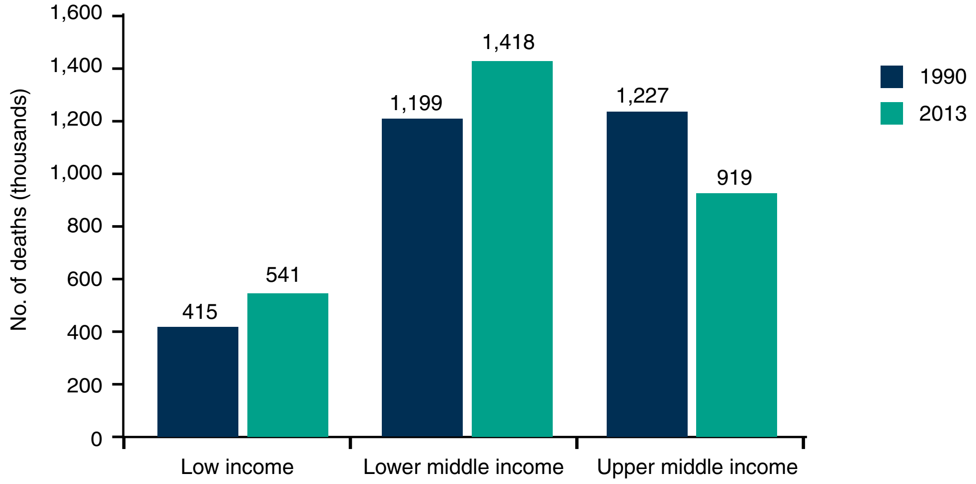
Sources: World Bank and IHME, using data from IHME, GBD 2013.

income countries, the proportion of deaths from HAP hovered at around 7 percent from 1990 to 2013. Two-thirds of HAP deaths occurred in low- and lower-middle-income countries in 2013, a change from 1990 when nearly half of HAP deaths occurred in upper-middle-income countries.

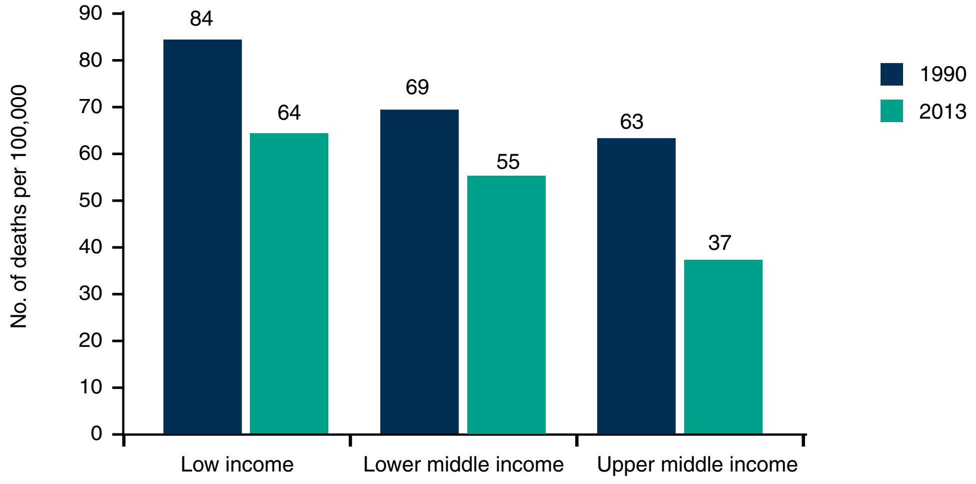
Because access to nonsolid fuels tends to improve for countries with higher incomes, death rates are lower (figure 2.18).

FIGURE 2.17 **Total Deaths (a) and Deaths per 100,000 People (b) from Household Air Pollution by Income Group, 1990 and 2013**

a. Total deaths



b. Deaths per 100,000 people



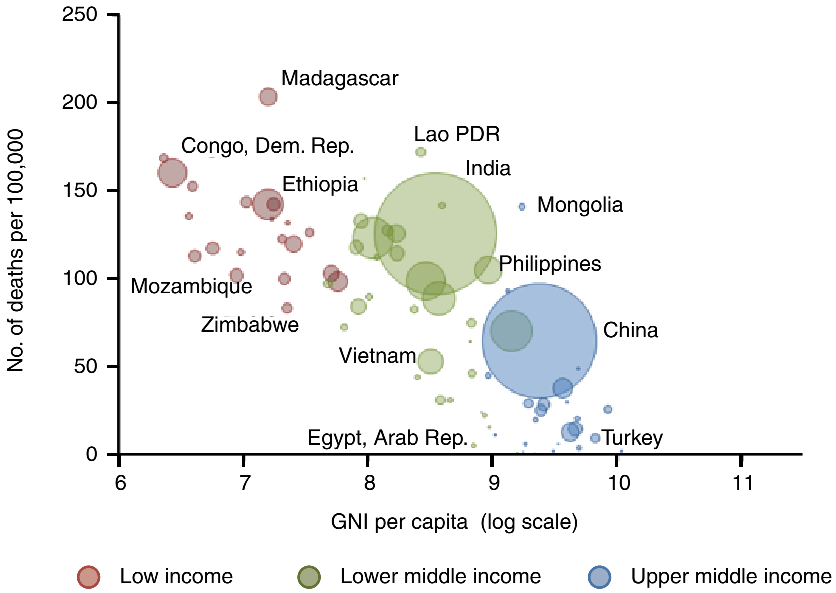
Sources: World Bank and IHME, using data from IHME, GBD 2013.

The Evolution of GBD Estimates

The results of the GBD 2010 study, which estimated air pollution exposure and health outcomes across the globe, both established air pollution as a major risk factor for mortality and significantly advanced the methodology for making such estimates. Because the GBD collaboration is committed to continually updating estimates using improved data and methods, changes were made to the estimation process between GBD 2010 and GBD 2013, which led to some differences in the findings.

For ambient air pollution, improvements since GBD 2010 include expansion of the available ground-level data, which have been augmented by means of a literature review, web scraping, and contact with experts worldwide (Forouzanfar et al. 2015). In addition, the satellite-based

FIGURE 2.18 Household $PM_{2.5}$ Death Rate versus Gross National Income (GNI) per Capita, 2013



Sources: World Bank and IHME.
Note: Size of bubble corresponds with total number of deaths.

estimates were enhanced to more accurately reflect ground concentrations and to characterize trends over time (from 1990 to 2013), and methodological advancements allowed calibration of estimates across the full range of particulate matter concentrations (Brauer et al. 2016). The IERs were updated with the results of new epidemiologic studies and were fit to the data using a Bayesian approach. The GBD 2013 IERs estimate lower relative risks for LRIs, IHD, stroke, and COPD and higher relative risks for lung cancer than the GBD 2010 IERs (Forouzanfar et al. 2015). Pneumonia was added as an outcome of tobacco smoking, and $PM_{2.5}$ was expanded to cover adult lower respiratory infections (Forouzanfar et al. 2015).

For household air pollution, the main improvement in methodology since 2010 was in the exposure modeling step. In GBD 2010, a mixed-effect linear model was used to generate the time series for all country-years included in the analysis, but for GBD 2013 the decision was made to utilize instead the spatiotemporal Gaussian process regression (Forouzanfar et al. 2015). In addition, the mapping of proxy measures of exposure to what is actually experienced (in order to estimate IER relative risks) is now based on 67 studies from eight regions (rather than one study from India), and uncertainty is now propagated from the mapping to the final results. This change has led to a widening of uncertainty and captures regional variation in the level of household $PM_{2.5}$ exposure (Forouzanfar et al. 2015).

GBD 2010 relied on the most directly available data on average $PM_{2.5}$ exposure among households using solid cooking fuels. Average $PM_{2.5}$ exposure for households reporting the use of solid cooking fuel was first derived from measurements in rural households of multiple Indian states and nationally representative Indian data on covariates associated with cooking practices (Balakrishnan et al. 2013). These estimates for India were applied across the globe. For

GBD 2013, the WHO $PM_{2.5}$ database was augmented to include additional studies published between January 2011 and January 2015, expanding the pool of observations included in the latter study.

The GBD 2013 $PM_{2.5}$ air pollution burden estimates also added mortality estimates for pneumonia in adults to the outcomes previously included in GBD 2010. The relative risk of mortality from pneumonia in adults was estimated by adding relative risk estimates for pneumonia mortality from a study of adult tobacco smoking to the previous IER for acute lower respiratory infection (ALRI) mortality, and this updated IER was used to estimate the ALRI and pneumonia burden attributable to $PM_{2.5}$ in both children and adults.

The use of IER curves in estimating the burden of household air pollution has been an important advance in terms of increasing consistency in estimates generated for different sources of particulate matter, including active smoking, second-hand smoke, ambient air pollution, and household air pollution. For example, the IER allows an estimate to be made of the burden of disease from heart disease and stroke attributable to household air pollution in the absence of direct epidemiologic evidence, thereby avoiding the untenable alternative that such high exposures to particulate air pollution pose no risk. That said, the absence of empirical research on exposure to household air pollution and mortality from cardiovascular disease is an important source of uncertainty about the true magnitude of the HAP-attributable burden of disease.

The GBD 2013 exposure estimates used the ground measurements of $PM_{2.5}$ in an advanced regression calibration model, with additional site parameters (whether the $PM_{2.5}$ concentration was directly measured, whether the exact site location was known, and whether the monitoring site classification was known), which were further evaluated by a cross-validation procedure in which 10 percent of the measurement sites were randomly selected for model evaluation. In cross-validation, our estimates explain 64 percent of the variability in measurements. Additional changes were further elaborated by Brauer et al. (2016).

The global number of deaths attributable to household air pollution in 2010, estimated by GBD 2010, was just under 3.5 million. GBD 2013 revised that number down to just over 2.9 million deaths in 2010. Similarly, GBD 2010 estimated about 3.2 million deaths from ambient $PM_{2.5}$ pollution in 2010, which GBD 2013 re-estimated at just under 2.8 million. Likewise, the re-estimated global burden for both AAP and HAP moved both numbers downward. Differences in the estimated burden are a result of improvements in the methodology and availability of data sources, which included the addition of more outcomes, better mapping of household air pollution, and updates to the methods and data used for the integrated exposure response curves.

Note

1. Gridded Population of the World (GPW), v3 "SEDAC," November 16, 2015, http://sedac.ciesin.columbia.edu/data/collection/gpw-v3.

References

Balakrishnan, Kalpana, Santu Ghosh, Bhaswati Ganguli, Sankar Sambandam, Nigel Bruce, Douglas F. Barnes, and Kirk R. Smith. 2013. "State and National Household Concentrations of $PM_{2.5}$ from Solid Cookfuel Use: Results from Measurements and Modeling in India for Estimation of the Global Burden of Disease." *Environmental Health: A Global Access Science Source* 12 (1): 77. doi:10.1186/1476-069X-12-77.

Balakrishnan, Kalpana, Sumi Mehta, Santu Ghosh, Michael Johnson, Michael Brauer, Jim Zhang, Luke Naeher, and Kirk R. Smith. 2014. "WHO Indoor Air Quality Guidelines: Household Fuel Combustion—Review 5: Population Levels of Household Air Pollution and Exposures." World Health Organization, Geneva. http://www.who.int/indoorair/guidelines/hhfc/Review_5.pdf?ua=1.

Bell, M. L., J. K. Levy, and Z. Lin. 2008. "The Effect of Sandstorms and Air Pollution on Cause-Specific Hospital Admissions in Taipei, Taiwan." *Occupational and Environmental Medicine* 65 (2): 104–11. doi:10.1136/oem.2006.031500.

Brauer, Michael, Greg Freedman, Joseph Frostad, Aaron van Donkelaar, Randall V. Martin, Frank Dentener, Rita van Dingenen, et al. 2016. "Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013." *Environmental Science and Technology* 50 (1): 79–88. doi:10.1021/acs.est.5b03709.

Burnett, Richard T., C. Arden Pope III, Majid Ezzati, Casey Olives, Stephen S. Lim, Sumi Mehta, Hwashin H. Shin, et al. 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environmental Health Perspectives* (February). doi:10.1289/ehp.1307049.

Chen, Yong-Shing, Pai-Ching Sheen, Eng-Rin Chen, Yi-Kuen Liu, Trong-Neng Wu, and Chun-Yuh Yang. 2004. "Effects of Asian Dust Storm Events on Daily Mortality in Taipei, Taiwan." *Environmental Research* 95 (2): 151–55. doi:10.1016/j.envres.2003.08.008.

Cohen, Aaron, et al. n.d. "The Global Burden of Disease Attributable to Ambient Air Pollution: Estimates of Current Burden and 23-Year Trends from the GBD 2013 Study." In submission.

Crouse, Dan L., Paul A. Peters, Aaron van Donkelaar, Mark S. Goldberg, Paul J. Villeneuve, Orly Brion, Saeeda Khan, et al. 2012. "Risk of Non-Accidental and Cardiovascular Mortality in Relation to Long-Term Exposure to Low Concentrations of Fine Particulate Matter: A Canadian National-Level Cohort Study." *Environmental Health Perspectives* (February). doi:10.1289/ehp.1104049.

EPA (U.S. Environmental Protection Agency). 2009. "Integrated Science Assessment for Particulate Matter." http://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=216546.

Forouzanfar, Mohammad H., Lily Alexander, H. Ross Anderson, Victoria F. Bachman, Stan Biryukov, Michael Brauer, Richard Burnett, et al. 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." *The Lancet* 386 (10010): 2287–2323. doi:10.1016/S0140-6736(15)00128-2.

GBD 2013 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." *The Lancet* 396 (10010): 2287–2323.

IARC (International Agency for Research on Cancer). 2013. "Air Pollution and Cancer." IARC Scientific Publication No. 161. http://www.iarc.fr/en/publications/books/sp161/.

Jerrett, Michael, Richard T. Burnett, C. Arden Pope, Kazuhiko Ito, George Thurston, Daniel Krewski, Yuanli Shi et al. 2009. "Long-Term Ozone Exposure and Mortality." *New England Journal of Medicine* 360 (11): 1085–95. doi:10.1056/NEJMoa0803894.

Karanasiou, A., N. Moreno, T. Moreno, M. Viana, F. de Leeuw, and X. Querol. 2012. "Health Effects from Sahara Dust Episodes in Europe: Literature Review and Research Gaps." *Environment International* 47 (October): 107–14. doi:10.1016/j.envint.2012.06.012.

Kloog, Itai, Petros Koutrakis, Brent A. Coull, Hyung Joo Lee, and Joel Schwartz. 2011. "Assessing Temporally and Spatially Resolved $PM_{2.5}$ Exposures for Epidemiological Studies Using Satellite Aerosol Optical Depth Measurements." *Atmospheric Environment* 45 (35): 6267–75. doi:10.1016/j.atmosenv.2011.08.066.

Kloog, Itai, Bill Ridgway, Petros Koutrakis, Brent A. Coull, and Joel D. Schwartz. 2013. "Long- and Short-Term Exposure to $PM_{2.5}$ and Mortality: Using Novel Exposure Models." *Epidemiology (Cambridge, Mass.)* 24 (4): 555–61. doi:10.1097/EDE.0b013e318294beaa.

Lee, Hyung Joo, Brent A. Coull, Michelle L. Bell, and Petros Koutrakis. 2012. "Use of Satellite-Based Aerosol Optical Depth and Spatial Clustering to Predict Ambient $PM_{2.5}$ Concentrations." *Environmental Research* 118 (October): 8–15. doi:10.1016/j.envres.2012.06.011.

Mallone, Sandra, Massimo Stafoggia, Annunziata Faustini, Gian Paolo Gobbi, Achille Marconi, and Francesco Forastiere. 2011. "Saharan Dust and Associations between Particulate Matter and Daily Mortality in Rome, Italy." *Environmental Health Perspectives* 119 (10): 1409–14. doi:10.12989/ehp.1003026.

Perez, Laura, Aurelio Tobias, Xavier Querol, Nino Künzli, Jorge Pey, Andrés Alastuey, Mar Viana et al. 2008. "Coarse Particles from Saharan Dust and Daily Mortality." *Epidemiology (Cambridge, Mass.)* 19 (6): 800–807.

Thalib, Lukman, and Abdullah Al-Taiar. 2012. "Dust Storms and the Risk of Asthma Admissions to Hospitals in Kuwait." *Science of the Total Environment* 433 (September): 347–51. doi:10.1016/j.scitotenv.2012.06.082.

van Donkelaar, Aaron, Randall V. Martin, Michael Brauer, and Brian L. Boys. 2015. "Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter." *Environmental Health Perspectives* 123 (2): 135–43. doi:10.1289/ehp.1408646.

Vodonos, Alina, Michael Friger, Itzhak Katra, Lone Avnon, Helena Krasnov, Petros Koutrakis, Joel Schwartz et al. 2014. "The Impact of Desert Dust Exposures on Hospitalizations due to Exacerbation of Chronic Obstructive Pulmonary Disease." *Air Quality, Atmosphere & Health* 7 (4): 433–39. doi:10.1007/s11869-014-0253-z.

Vodonos, Alina, Michael Friger, Itzhak Katra, Helena Krasnov, Doron Zahger, Joel Schwartz, and Victor Novack. 2015. "Individual Effect Modifiers of Dust Exposure Effect on Cardiovascular Morbidity." *PloS One* 10 (9): e0137714. doi:10.1371/journal.pone.0137714.

WHO (World Health Organization). 2014. "Review of Evidence on Health Aspects of Air Pollution—REVIHAAP Project: Final Technical Report." December 2. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report.

3. Economic Impacts of Air Pollution

Introduction

The Global Burden of Disease (GBD) estimates of air pollution exposure and health impacts provide a truly global view of the health toll of air pollution, and they are the basis for assessing the economic costs of pollution for the world's economies. The costs of pollution are myriad. From reducing crop yields to lowering property values to steering talented workers away from polluted places, many of these costs are beyond the scope of this study. Instead, this chapter focuses on what previous studies have found is by far and away the most damaging of economic cost of pollution—the cost of premature mortality.

Methods and Data

Using the GBD data on the health impacts of air pollution, this chapter estimates the costs of premature mortality for more than 180 countries. The technical details of the methodology for valuing these costs are provided in the background paper prepared for this report by Narain and Sall (2016). A brief summary of that methodology follows.

GBD 2013 provides estimates for a range of health metrics associated with air pollution, whereas this report looks specifically at the monetary costs of premature mortality as measured in terms of premature deaths. Nonfatal health outcomes are excluded from the scope of analysis for two reasons. First, morbidity makes up a very small share of the total health impacts of air pollution as estimated for GBD 2013, and regulatory analyses of air pollution control policies in the United States and elsewhere have consistently found that the majority of economic benefits accrued by improving air quality take the form of avoided premature deaths. By focusing on premature mortality, this global assessment aims to account for the largest component of the economic costs arising from the health impacts of pollution. Excluding morbidity costs does not significantly influence the overall magnitude of the cost estimates, although nonfatal outcomes may represent at least another 10 percent of total costs (Hunt et al. 2016). Second, unlike for morbidity costs, a standard framework exists for valuing fatality risks that is supported by a well-developed body of economic theory and empirical studies (Narain and Sall (2016)).

This report takes two approaches to valuing the costs of premature mortality: (1) a welfare-based approach that monetizes the increased fatality risk from air pollution according to individuals' willingness to pay (WTP); and (2) an income-based approach that equates the financial cost of premature mortality with the present value of forgone lifetime earnings. Each of these approaches is given equal weight, although they are tailored to different purposes.

The income-based approach is more suited to financial analysis and measuring pollution costs within the extended boundaries of the national accounts—for example, as a component of the World Bank's adjusted net savings (ANS) measure. ANS, or "genuine savings," is a measure of the change in the value of a nation's assets, including manufactured capital as well as natural and human capital (see Hamilton and Clemens 1999; World Bank 2005, 2011). Positive savings represents an investment in future well-being as a nation accumulates the assets needed to drive economic growth and at least sustain current levels of consumption. Within the ANS framework, premature mortality due to pollution represents a dis-investment in a nation's human capital stock. As with the degradation of other forms of capital, this dis-investment is valued according to the expected loss of income over the lifetime of the asset. The Ministry of Social Development in Chile, for example, has adopted this approach for valuing premature mortality (Chile MDS 2014). A common criticism of this approach is that it excludes losses suffered by individuals outside the labor force, including retirees. The income-based approach also raises questions about how unpaid work that contributes to the economy, such as subsistence farming and domestic activities, should be valued.

The welfare-based approach is more appropriate for evaluating the full economic costs of premature mortality, which encompass the loss of many other things that individuals value apart from their paychecks, including consumption, leisure, good health, and simply being alive. This value is reflected in the WTP, which captures the marginal trade-offs that individuals are willing to make to reduce their chances of dying. The value of statistical life (VSL) represents the sum of many individuals' WTP for marginal reductions in their mortality risks. It is *not* the value of any single person's life or death, nor does it represent a society's judgment as to what that value should be. The WTP-based approach is best suited for analyses of economic welfare, and it has become the standard approach in high-income countries for valuing mortality risks associated with pollution (see Viscusi 1993; Cropper 2000; OECD 2012).

Because WTP studies are still lacking in many of the world's countries, the only practical way to implement a welfare-based approach in a global cost assessment is to come up with a strategy for adjusting some "base VSL" from the original context in which it was studied (such as the United States) to the context of other countries. The adjustments need to account for characteristics that are likely to influence how individuals under different circumstances value mortality risks. One of the most salient characteristics is income. Both theory and the empirical evidence have consistently shown that the willingness to pay for mortality risk reductions increases for individuals with higher incomes. Because a number of studies have quantified the income elasticity of the VSL (that is, the percent change in the WTP per percent change in income), these studies can provide a basis for adjusting to different circumstances—see Narain and Sall (2016) for a literature review of studies of the VSL.

Country-specific VSLs are determined using a benefit-transfer approach that first assumes a base VSL of $3.83 million.[1] This base VSL estimate represents the mean VSL estimate from a database of quality-screened WTP studies conducted in high-income member countries of the Organisation for Economic Co-operation and Development (OECD).[2] The countries included in this collection of studies have an average gross domestic product (GDP) per capita of about $37,000. The base VSL estimate is then transferred to other countries and years using

$$VSL_{c,n} = VSL_{\mathrm{OECD}} \times \left(\frac{Y_{c,n}}{Y_{\mathrm{OECD}}} \right)^{e} \tag{3.1}$$

where $VSL_{c,n}$ is the VSL for country c in year n; VSL_{OECD} is the average base VSL estimate from the sample of WTP studies in OECD countries (in 2011 U.S. dollars at purchasing power parity, PPP, rates); $Y_{c,n}$ is GDP per capita for country c in year n (adjusted for price inflation and converted to 2011 U.S. dollars at PPP rates); Y_{OECD} is the average GDP per capita for the base sample of OECD countries; and e is the income elasticity of the VSL. For this study, differentiated elasticity values are assumed for low- and middle-income countries versus high-income countries. For low- and middle-income countries, a central value of 1.2 is assumed, with a range from 1.0 to 1.4 for sensitivity analysis. For high-income countries, a central value of 0.8 is assumed, with a range from 0.6 to 1.0 for sensitivity analysis—see Narain and Sall (2016) for detailed discussion on choice of elasticity.

As for the income-based approach, forgone labor output per premature death is obtained by first calculating the present value (PV) of the expected stream of future per capita labor income as

$$PV(I) = \sum_{i=0}^{T} I_0(1+g)^i/(1+r)^i \tag{3.2}$$

where I_0 is average labor income per capita in the present year; T is the expected number of working years for the average person in a particular age group; g is the annual rate of income growth; and r is the social discount rate. In keeping with recent guidance by the World Bank on estimating long-term rates of growth and setting social discount rates for project economic analysis, the discount rate (r) is set at 6 percent for low- and middle-income countries[3] and at 4 percent for high-income countries, and the annual growth rate for real income per capita (g) is set at 3 percent for low- and middle-income countries and at 2 percent for high-income countries.

Ideally, I would be differentiated by age group because people of different ages may have varying levels of education, experience, and other characteristics that affect their earning potential. However, the lack of detailed wage data in many countries does not allow for this level of disaggregation in a global assessment. Instead, average per capita labor income is estimated from the labor share of GDP (s) for each country as

$$I = (GDP \cdot s)/w \tag{3.3}$$

so that average income is equal to the total wage bill divided by the total number of employed workers (w). Data on s are drawn from the Penn World Table (Feenstra, Inklaar, and Timmer 2015), Conference Board Total Economy Database, International Labour Organization (ILO 2014), Lenzen et al. (2012, 2013), OECD aggregate national accounts, and United Nations national accounts.[4] Estimates of w are obtained from the World Bank's World Development Indicators database. Because of the year-on-year volatility in GDP and wages, average labor income per worker is taken as a five-year running average.

Working life expectancy, T, is calculated by weighting life expectancy to maximum working age by the probability that an individual will survive and be active in the labor force. It is expressed as

$$T_j = \sum_{t=j}^{79} s_{j,t} \cdot \ell_t \tag{3.4}$$

where $s_{j,t}$ is the probability that a person of age j will survive to the end of age t, and l is the labor force participation rate.[5] ILO estimates of l are available by five-year age group for ages 15–64 and for the open-ended 65 and up age group.[6] The probability of being economically active in any given year is assumed to be independent of whether an individual was active in previous years, so individuals may move in and out of the workforce freely. Although the ILO estimates of workforce activity do not set a maximum working age for the 65 and up group, for this study we assume that no person above the age of 79 works. The average l for the 65 and up group is applied to the 65–69, 70–74, and 75–79 groups. As for the younger age groups, working life is assumed to begin at age 15, and so the present value of future lifetime earnings among children must be discounted further into the future. Of course, not everyone will enter the workforce upon turning 15, and not everyone will work until the age of 79. Adjusting T for l is one way of capturing when people tend to enter and retire from the workforce in different countries. Because of the likelihood of gender bias in the labor force statistics from which l is derived, the average l for males is applied to both males and females in calculating T.

Finally, survival probabilities, s, are calculated from mean death rates, d, so that $s = 1 - d$. GBD 2013 provides estimates of mean death rates by age group for ages <1 year, 1–4 years, 5–9 years, 10–14 years, and so on up to the open-ended 80 and up age group. Average working life expectancy for 15- and 40-year-olds in different regions and income groups is shown in tables 3.1 and 3.2.

Results: Welfare Losses and Forgone Labor Output

One of the top risks leading to early death worldwide, air pollution is responsible for more than \$5.11 trillion in welfare losses each year (see table 3.3).[7] These losses represent the cost stemming from premature mortality caused by exposure to ambient fine particulate matter ($PM_{2.5}$), household air pollution from cooking with solid fuels, and ambient ozone. The magnitude of losses is greatest in East Asia and the Pacific, where premature mortality costs reached the equivalent of 7.5 percent of GDP in 2013, closely followed by South Asia, where costs were on the order of 7.4 percent of GDP equivalent (figure 3.1).[8] By comparison, in North America welfare losses were 3 percent of GDP equivalent in 2013. Losses were even lower in Latin America and the Caribbean and in the Middle East and North Africa. Although the majority of welfare losses in South Asia and Sub-Saharan Africa were caused by indoor air pollution, in all other regions losses were driven by ambient air pollution, mainly $PM_{2.5}$. Losses from ambient ozone represent the smallest share of the premature mortality costs of air pollution. As a percentage of GDP equivalent, ozone-associated losses in South Asia were roughly equivalent to those in North America.

TABLE 3.1 Working Life Expectancy for 15- and 40-Year-Olds by Region, 2013

number of years

Region	Life expectancy		Working life	
	Age = 15	Age = 40	Age = 15	Age = 40
East Asia and Pacific	61	38	43	24
Europe and Central Asia	63	39	37	20
Latin America and Caribbean	62	39	43	24
Middle East and North Africa	61	38	39	21
North America	65	41	40	22
South Asia	56	33	42	24
Sub-Saharan Africa	53	32	40	24

Sources: World Bank and IHME.

TABLE 3.2 Working Life Expectancy for 15- and 40-Year-Olds by Income Group, 2013

number of years

Income group	Life expectancy		Working life	
	Age = 15	Age = 40	Age = 15	Age = 40
Low income	52	32	43	25
Lower middle income	56	34	42	24
Upper middle income	62	38	41	23
High income	65	41	40	22

Sources: World Bank and IHME.

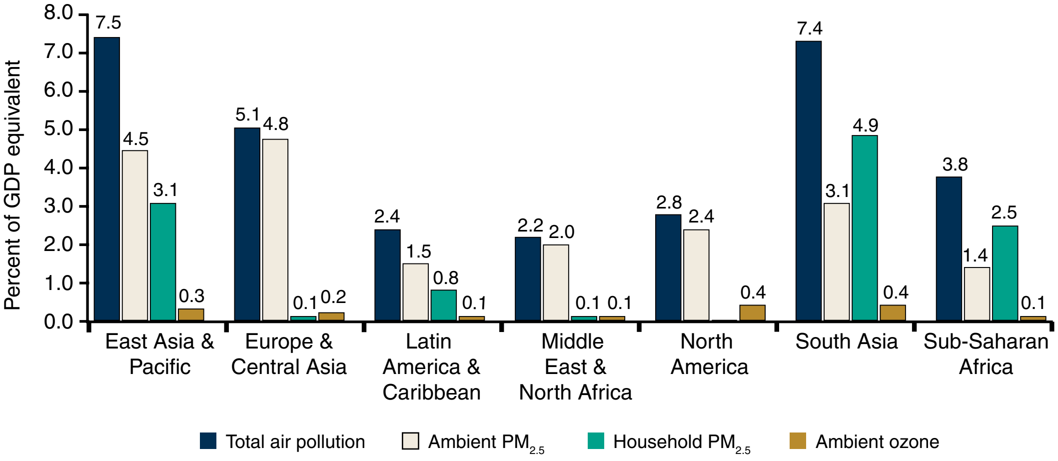
TABLE 3.3 Total Welfare Losses from Air Pollution, by Region: 1990–2013

2011 US$, billions, PPP-adjusted

Region	1990	1995	2000	2005	2010	2013
East Asia and Pacific	439	630	805	1,199	1,822	2,306
Europe and Central Asia	1,308	1,226	1,188	1,301	1,259	1,245
Latin America and Caribbean	105	101	104	127	167	194
Middle East and North Africa	74	82	98	118	144	154
North America	516	544	578	576	514	495
South Asia	135	174	214	303	497	604
Sub-Saharan Africa	61	63	76	90	107	114
Total	2,638	2,821	3,063	3,714	4,510	5,112

Sources: World Bank and IHME.
Note: Totals are for a "balanced" sample of countries for which data are available for all years.

FIGURE 3.1 **Welfare Losses Due to Air Pollution by Region, 2013**

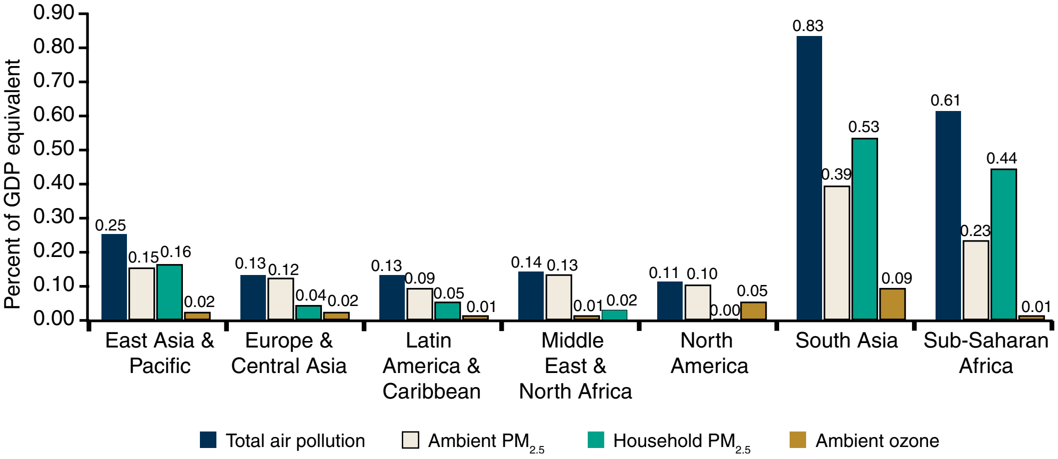


Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product.

Annual labor income losses from premature mortality—$225 billion in 2013 (see table 3.6, which appears later in this chapter)—are lower than total welfare losses, as expected, although still substantial in some regions.[9] Lost income for countries in South Asia from air pollution totaled more than $66 billion in 2013, the equivalent of nearly 1 percent of GDP (figure 3.2). Pollution-related income losses are higher for countries with younger populations. In Sub-Saharan Africa, for example, 30 percent of early deaths from air pollution were suffered by children under 5, and 10 percent of deaths were among the elderly ages 80 and above. By contrast, in Europe and Central Asia less than 1 percent of air pollution deaths were among children under 5, and more than 40 percent were among people over the age of 80 (figure 3.3). Because children have more years remaining in their lifetimes in which they

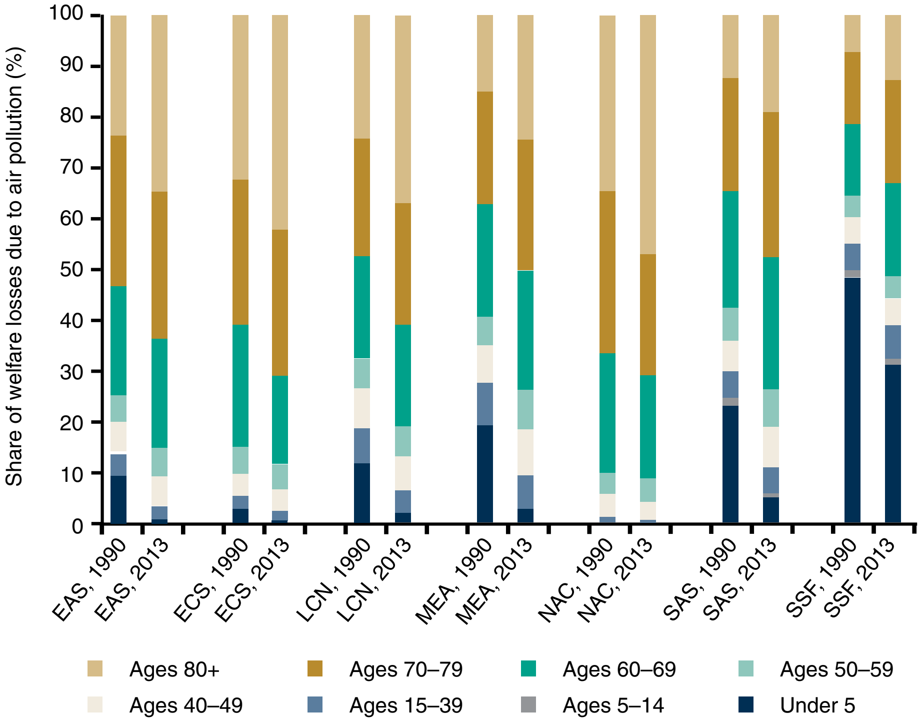
FIGURE 3.2 **Forgone Labor Output Due to Air Pollution by Region, 2013**



Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product.

FIGURE 3.3 Age Profile of Total Deaths and Welfare Losses Due to Air Pollution by Region, 1990 and 2013



Sources: World Bank and IHME.

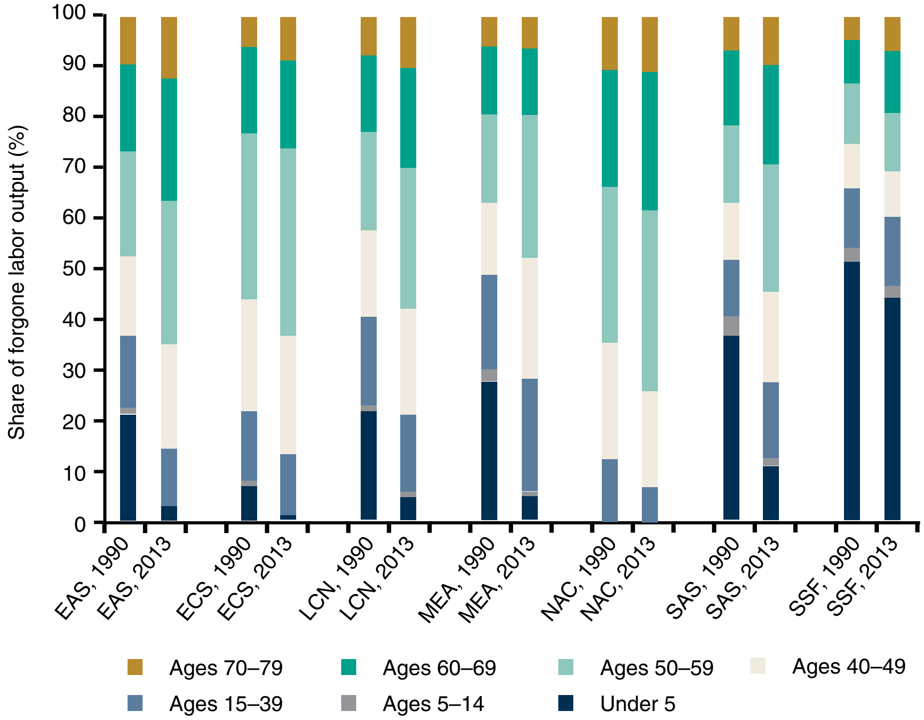
Note: EAS = East Asia and Pacific (all income levels); ECS = Europe and Central Asia (all income levels); LCN = Latin American and Caribbean (all income levels); MEA = Middle East and North Africa (all income levels); NAC = North America; SAS = South Asia; SSF = Sub-Saharan Africa (all income levels).

are likely to work, the expected loss of income per child's death is usually greater,[10] driving up total losses. Consequently, whereas under-5 mortality represented more than 40 percent of forgone income in Sub-Saharan Africa in 2013, in Europe and Central Asia it was about 2 percent (figure 3.4). Outside North America, after Europe and Central Asia, East Asia and the Pacific experienced the highest share (about 30 percent) of mortality—and welfare losses—suffered by people 80 years or older. Thus, although the relative magnitude of welfare losses (which value mortality risks for people of all age groups equally) was similar for South Asia and East Asia and the Pacific, the labor income losses for South Asia were proportionally higher.

As noted in chapter 2, between 1990 and 2013 more of the health burden of pollution shifted from the younger to the older generations. In every region, the share of deaths among children under the age of 5 declined between 1990 and 2013. In most regions, the share of deaths of older children (5–14) and young adults (15–39) also declined. By contrast, the share of deaths of older generations—above the age of 70—increased. And yet in Sub-Saharan African countries the burden on young children is still very high, accounting for over 30 percent of all air pollution–related deaths.

Premature mortality risks and GDP equivalent welfare losses from air pollution are highest for the middle-income countries (lower and upper)—see figure 3.5. Welfare losses

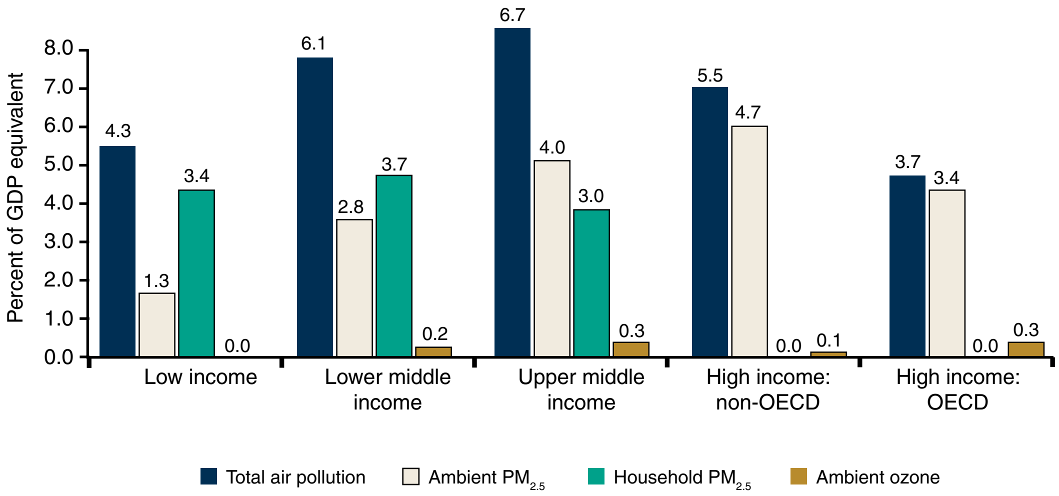
FIGURE 3.4 Age Profile of Total Forgone Labor Output Due to Air Pollution by Region, 1990 and 2013



Sources: World Bank and IHME.

Note: For region abbreviations, see note, figure 3.3.

FIGURE 3.5 Welfare Losses Due to Air Pollution by Income Group, 2013



Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product; OECD = Organisation for Economic Co-operation and Development.

from ambient air pollution are highest in high-income non-OECD countries, followed by upper middle income, while those driven by household air pollution are the highest in lower-middle-income countries followed by low-income countries. In 2013 welfare losses in low- and middle-income countries accounted for 59 percent of the global total. Higher overall exposure, risks, and losses among middle-income countries are driven in large part by trends in India and China.

The economic costs of air pollution have increased significantly over time, a reflection of the growing challenge of pollution. Between 1990 and 2013, total welfare losses due to premature mortality from exposure to air pollution increased by 94 percent (see table 3.3).[11] Damages from exposure to ambient $PM_{2.5}$ air pollution rose by 63 percent between 1990 and 2013, to $3.552 trillion, while damages from household air pollution from cooking with solid fuels rose by 287 percent, to $1.516 trillion (tables 3.4 and 3.5). Welfare losses in East Asia and the Pacific countries more than quintupled between 1990 and 2013, climbing to $2.306 trillion (see table 3.3). Losses in South Asia reached $604 billion, an increase of 347 percent. North America and Europe and Central Asia were the only regions to see declines in welfare losses from

TABLE 3.4 Welfare Losses from Ambient $PM_{2.5}$, by Region: 1990–2013

2011 US$, billions, PPP-adjusted

Region	1990	1995	2000	2005	2010	2013
East Asia and Pacific	273	366	458	668	1,065	1,387
Europe and Central Asia	1,247	1,172	1,129	1,232	1,188	1,170
Latin America and Caribbean	43	47	55	71	100	122
Middle East and North Africa	62	69	86	105	130	141
North America	483	503	527	518	451	431
South Asia	48	63	85	123	203	256
Sub-Saharan Africa	20	20	24	32	39	44
Total	2,176	2,241	2,364	2,751	3,177	3,552

Sources: World Bank and IHME.

Note: Totals are for a “balanced” sample of countries for which data are available for all years.

TABLE 3.5 Welfare Losses from Household Air Pollution, by Region: 1990–2013

2011 US$, billions, PPP-adjusted

Region	1990	1995	2000	2005	2010	2013
East Asia and Pacific	146	250	338	540	780	948
Europe and Central Asia	31	20	18	24	23	23
Latin America and Caribbean	61	52	46	53	64	67
North America	0	0	0	0	0	0
Middle East and North Africa	10	10	7	7	6	5
South Asia	98	125	145	204	335	396
Sub-Saharan Africa	45	47	57	63	73	77
Total	391	503	612	891	1,281	1,516

Sources: World Bank and IHME.

Note: Totals are for a “balanced” sample of countries for which data are available for all years.

air pollution since 1990, although the Middle East and North Africa saw a decline in the welfare losses from household air pollution over this period. The burden of largest loss also shifted between 1990 and 2013, from Europe and Central Asia to the East Asia and the Pacific region.

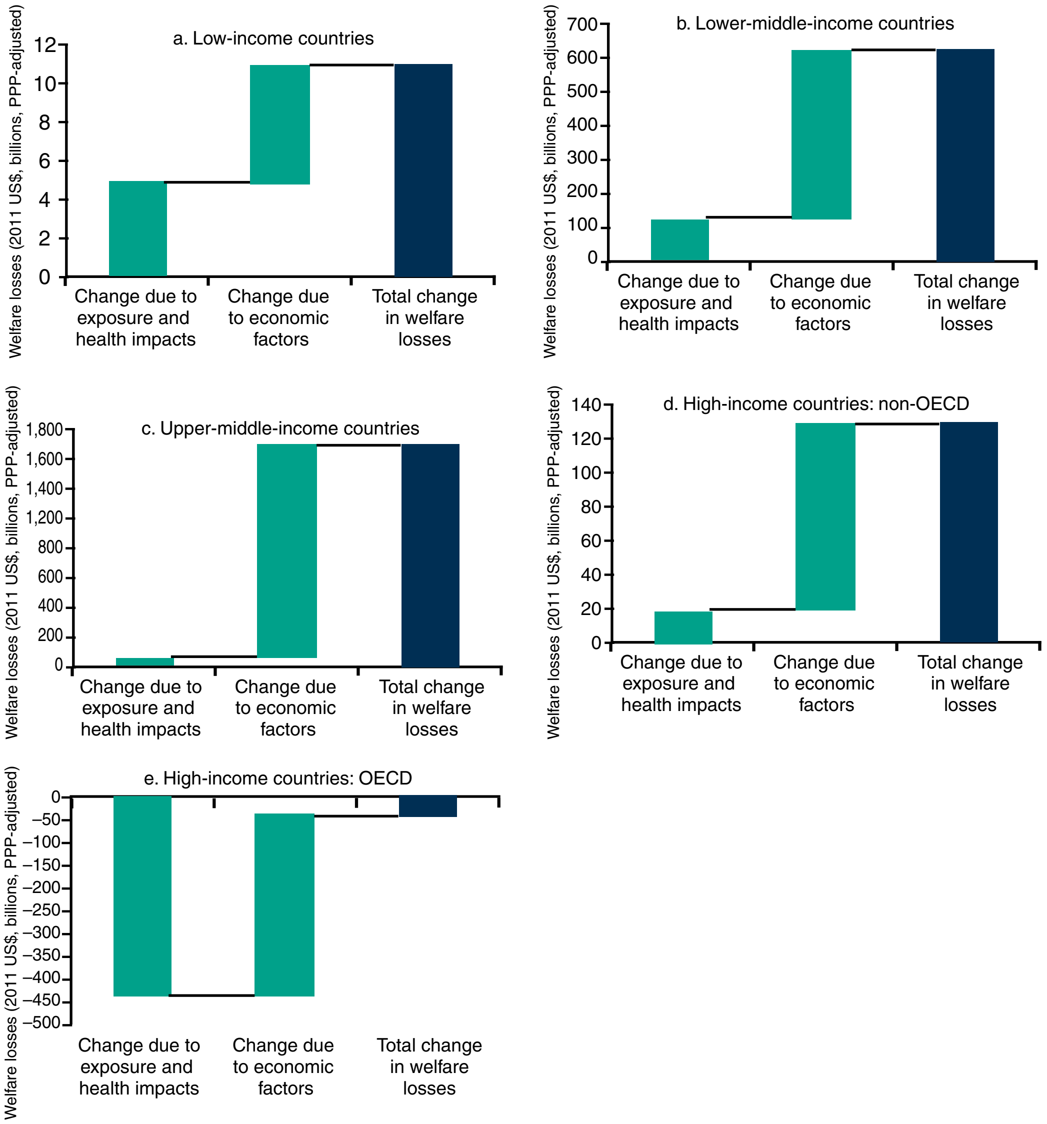
Over time, more of the health burden and costs of air pollution have shifted from the high-income countries to the middle-income countries. From 1990 to 2013, welfare losses increased for countries at all income levels other than the OECD countries, which saw a small decline. These losses increased by 130 percent and 133 percent for lower- and upper-middle-income countries, respectively, excluding India and China, which saw even greater increases. The countries that experienced the greatest increases in welfare losses from ambient air pollution include many of the fastest-growing, fastest-urbanizing ones.

As shown in figure 3.6, in low-income countries increases in exposure and health impacts and increases in the value that individuals place on reducing their risk of mortality were equally responsible for driving up welfare losses. In the low-income countries, the declines in death rates due to air pollution were more than offset by population growth and greater total exposure to polluted air. In the middle-income countries, total exposure also increased. However, most of the estimated increase in welfare losses for middle-income countries stemmed from economic factors—namely, an increased value placed on reducing fatality risks. Even in high-income countries, the higher value placed on reducing fatality risks substantially countered the improvements in welfare from reduced exposure and health impacts.

There is much variation within income categories, however. Between 1990 and 2013, per capita welfare losses from ambient air pollution increased in about two-thirds of all countries, and one-third of countries saw a decrease (figure 3.7). Improvements in health risks and welfare losses from household air pollution were more widespread. Overall, per capita welfare losses declined for more than half of all countries (figure 3.8). South Asia and East Asia and the Pacific were the only two regions in which average losses from household air pollution increased, stemming mainly from the higher per capita losses in China and India. Some of the greatest reductions in health risks from household air pollution occurred in the low-income countries of Sub-Saharan Africa, as well as the lower-middle-income countries of Central Asia.

Demographic and economic factors have also played an influential role in shaping trends in forgone labor output. Forgone labor income due to air pollution rose from $162 billion in 1990 to $225 billion in 2013 (table 3.6). Labor income losses increased in all regions outside of Europe and Central Asia and Latin America and the Caribbean, although increases in forgone labor income for North America and the Middle East and North Africa were negligible. As with welfare losses, labor income losses in North America were almost entirely from ambient $PM_{2.5}$ (table 3.7), while household air pollution was the dominant cause of income losses for South Asia and Sub-Saharan Africa (table 3.8). To understand the dynamics behind these trends, figure 3.9 dissects the overall change in forgone labor output into the parts attributable to changes in health risks, labor income, and working life expectancy. Since 1990, average wages have increased in real terms in all but the high-income non-OECD countries, causing forgone labor income per death to be higher. Yet across countries in all income groups the age profile of people affected by pollution has shifted, so that a higher proportion of deaths has occurred among people later in their working life (see figure 3.3). This drop in the average remaining working life among people who die from pollution exposure has had a counter-

FIGURE 3.6 Decomposing Changes in Total Welfare Losses Due to Air Pollution, by Income Group: 1990–2013



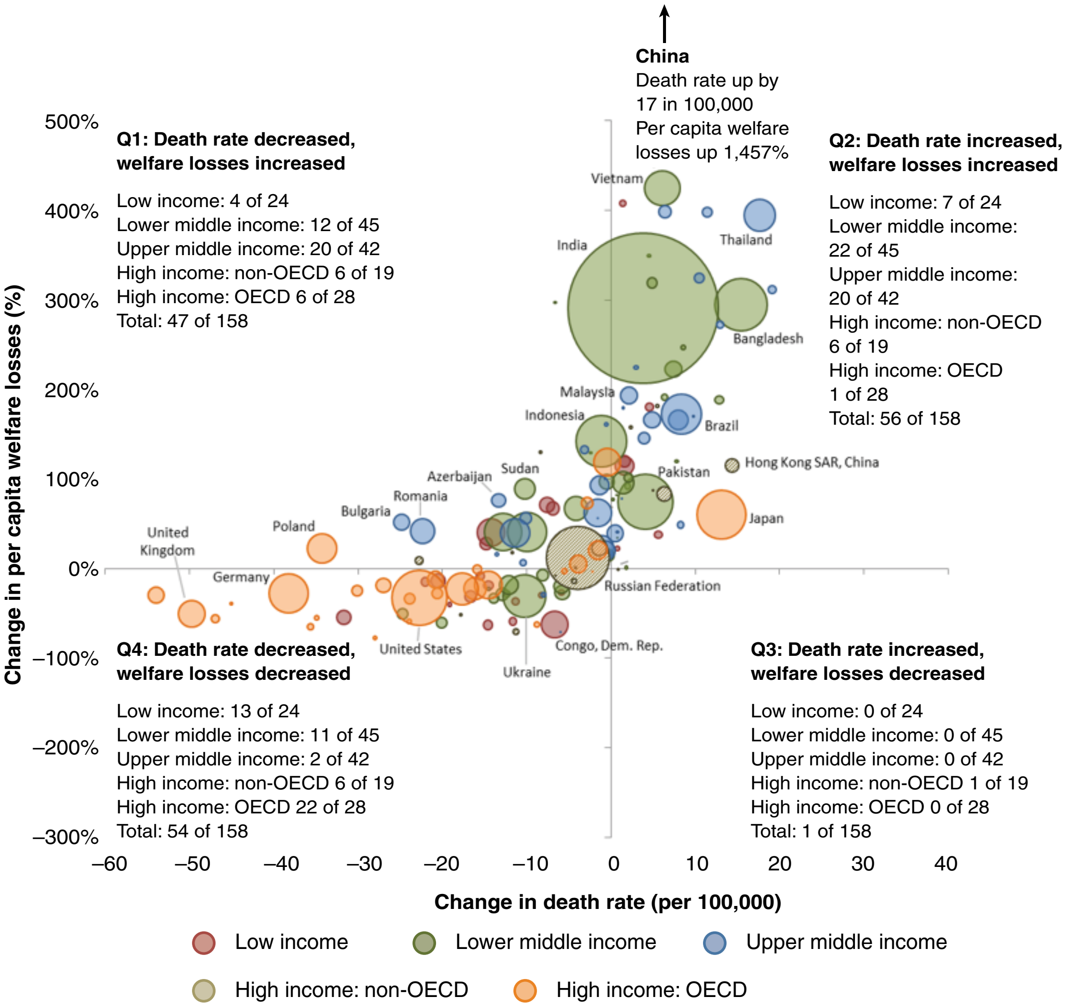
Sources: World Bank and IHME.

Note: Components of the overall change in welfare losses are dissected using the logarithmic mean Divisia index method. OECD = Organisation for Economic Co-operation and Development; PPP = purchasing power parity.

vailing effect on total forgone labor output. The exception is Sub-Saharan Africa, where the persistently large share of children who have died from pollution-related causes has driven up income losses.

Decomposing the changes in losses reveals that even though death rates related to air pollution are gradually declining, incremental improvement is not enough. Marginal decreases in exposure and health risks are counteracted by a growing and aging population in many regions. As incomes continue to rise, the marginal costs of health risks are also rising because of higher levels of labor productivity and the increasing monetary value that individuals attach to

FIGURE 3.7 Changes in Ambient $PM_{2.5}$ Death Rates and Per Capita Welfare Losses by Income Group, 1990–2013



China
Death rate up by
17 in 100,000
Per capita welfare
losses up 1,457%

Q1: Death rate decreased, welfare losses increased

Low income: 4 of 24
Lower middle income: 12 of 45
Upper middle income: 20 of 42
High income: non-OECD 6 of 19
High income: OECD 6 of 28
Total: 47 of 158

Q2: Death rate increased, welfare losses increased

Low income: 7 of 24
Lower middle income: 22 of 45
Upper middle income: 20 of 42
High income: non-OECD 6 of 19
High income: OECD 1 of 28
Total: 56 of 158

Q3: Death rate increased, welfare losses decreased

Low income: 0 of 24
Lower middle income: 0 of 45
Upper middle income: 0 of 42
High income: non-OECD 1 of 19
High income: OECD 0 of 28
Total: 1 of 158

Q4: Death rate decreased, welfare losses decreased

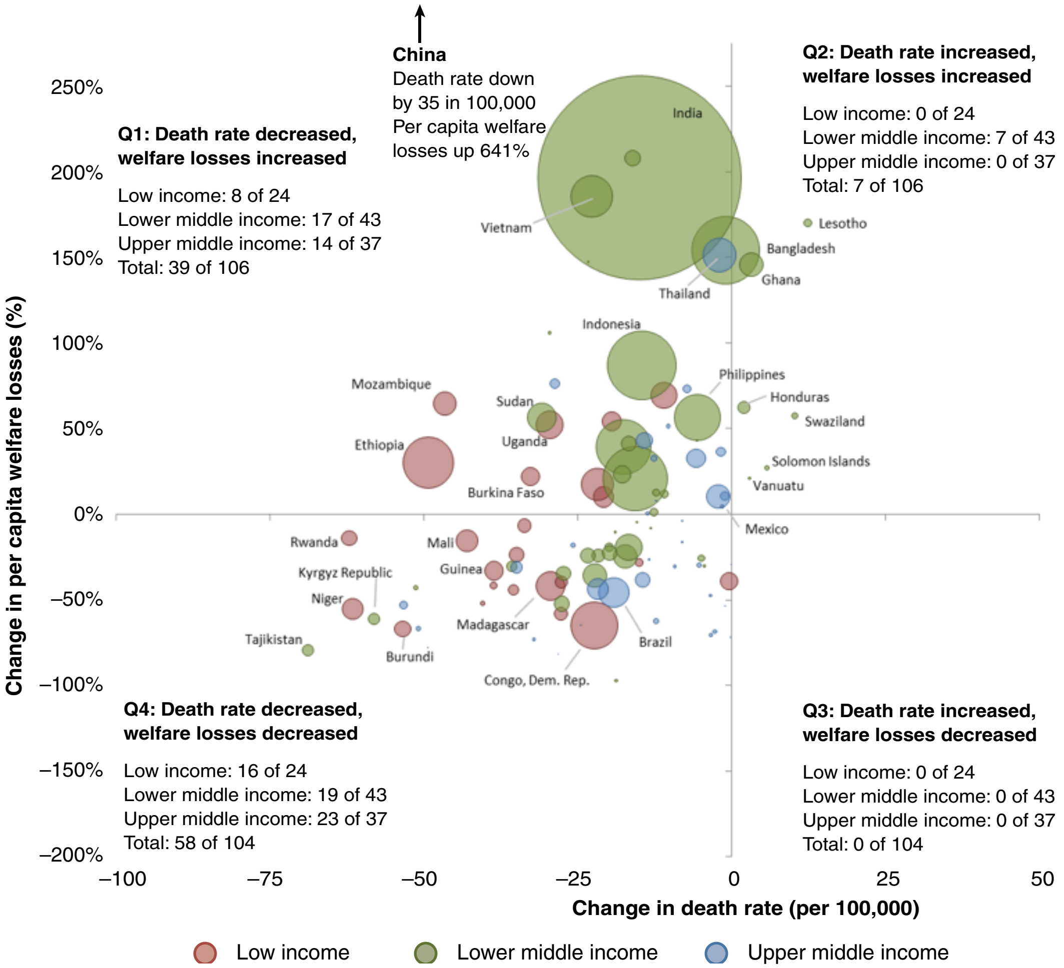
Low income: 13 of 24
Lower middle income: 11 of 45
Upper middle income: 2 of 42
High income: non-OECD 6 of 19
High income: OECD 22 of 28
Total: 54 of 158

Sources: World Bank and IHME.
Note: Only countries for which data are available for 1990 and 2013 are included.

reducing their risk of death. Achieving real reductions in the costs of air pollution thus demands more ambitious action.

Estimates of welfare losses and forgone output for individual countries are presented in appendix B. In dollar terms, welfare losses from air pollution have increased the most on an annual basis in Equatorial Guinea (13.8 percent),[12] China (10.9 percent), Sri Lanka (7.5 percent), Lao People's Democratic Republic (7.2 percent), and India (7.0 percent). Welfare losses have declined the most on an annual basis in western and northern Europe, including in Norway (4.5 percent), Sweden (3.3 percent), Denmark (3.1 percent), Finland (2.6 percent), and the United Kingdom (2.5 percent).

FIGURE 3.8 Changes in Household $PM_{2.5}$ Death Rates and Per Capita Welfare Losses by Income Group, 1990–2013



Sources: World Bank and IHME.

Note: Only countries for which data are available for 1990 and 2013 are included.

TABLE 3.6 Total Forgone Labor Output from Air Pollution, by Region: 1990–2013

2011 $US, billions, PPP-adjusted

Region	1990	1995	2000	2005	2010	2013
East Asia and Pacific	32	38	44	51	62	72
Europe and Central Asia	39	33	29	33	31	30
Latin America and Caribbean	12	10	8	9	10	10
Middle East and North Africa	9	9	9	8	8	9
North America	19	18	20	22	20	19
South Asia	35	37	38	41	56	66
Sub-Saharan Africa	15	15	15	16	17	18
Total	162	159	163	178	204	225

Sources: World Bank and IHME.

Note: Totals are for a "balanced" sample of countries for which data are available for all years.

TABLE 3.7 Forgone Labor Output from Ambient $PM_{2.5}$, by Region: 1990–2013

2011 $US, billions, PPP-adjusted

Region	1990	1995	2000	2005	2010	2013
East Asia & Pacific	17.5	20.2	23.7	27.9	36.3	44.5
Europe & Central Asia	36.3	30.7	27.6	31.0	29.6	28.1
Latin America & Caribbean	4.8	4.6	4.5	4.9	6.1	6.8
Middle East & North Africa	7.9	7.8	7.8	7.2	7.4	8.4
North America	18.0	17.6	18.6	20.6	18.8	17.6
South Asia	14.0	14.8	16.8	18.4	25.5	31.4
Sub-Saharan Africa	4.9	4.9	4.9	5.6	6.1	6.8

Sources: World Bank and IHME.
Note: Totals are for a “balanced” sample of countries for which data are available for all years.

TABLE 3.8 Forgone Labor Output from Household Air Pollution, by Region: 1990–2013

2011 $US, billions, PPP-adjusted

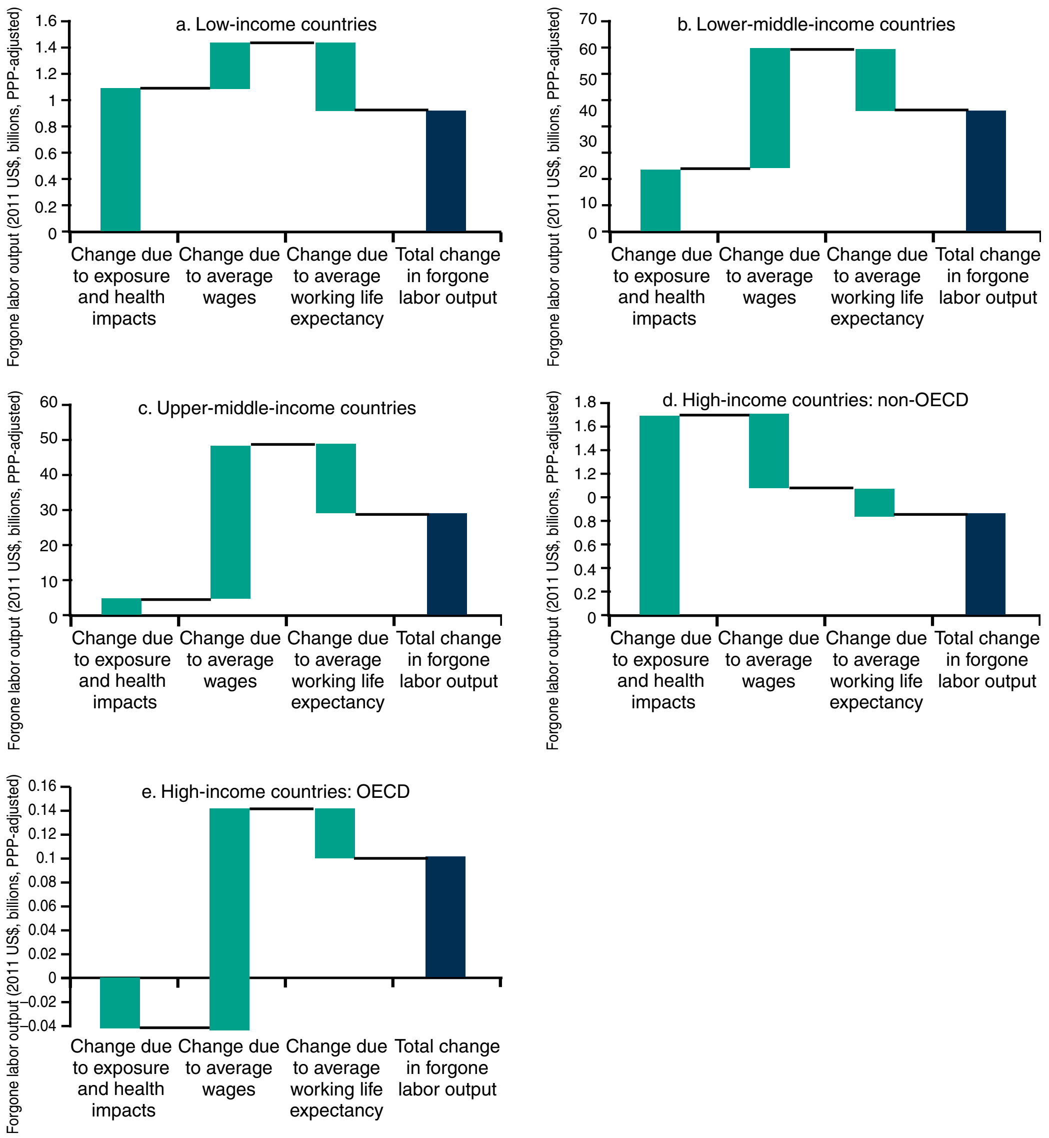
Region	1990	1995	2000	2005	2010	2013
East Asia & Pacific	17.5	20.4	23.9	27.4	31.1	33.8
Europe & Central Asia	3.1	2.3	1.5	1.3	1.1	1.0
Latin America & Caribbean	7.7	5.5	4.1	3.9	3.9	3.6
Middle East & North Africa	1.3	1.1	0.6	0.4	0.3	0.2
South Asia	25.1	25.7	25.1	26.7	36.8	42.6
Sub-Saharan Africa	11.2	11.1	11.6	11.5	12.4	13.1

Sources: World Bank and IHME.
Note: Totals are for a “balanced” sample of countries for which data are available for all years.

Alternative Scenarios and Sensitivity Analysis of Uncertain Parameters

The theoretical literature and body of empirical evidence behind the monetization of fatal health risks is well developed. However, a number of issues remain for which definitive guidance is still lacking, even though choices related to these issues may materially influence the results of the analysis. For welfare losses, key issues include the choice of a base VSL, the valuation of deaths instead of lost life expectancy, and assumptions about the income elasticity of the VSL. For forgone labor output, issues include assumptions about the discount rate, future income growth, and working life expectancy. To gauge the effect of different assumptions on the results, this section compares estimated damages in the base case with alternative scenarios. Sensitivity analysis is then conducted to test the effect of various uncertain parameters in the damage equations. Finally, confidence intervals are estimated that capture the combined uncertainty of different parameters.

FIGURE 3.9 Breakdown of Changes in Total Forgone Labor Output Due to Air Pollution by Income Group, 1990–2013



Sources: World Bank and IHME.

Note: Components of the overall change in welfare losses are dissected using the logarithmic mean Divisia index method.

Alternative Scenarios—Welfare Losses

For the alternative analysis of welfare losses, three scenarios are considered. First, to test the effect of weighting health impacts suffered by the young more heavily than those suffered by the elderly, health impacts are monetized by applying a value per statistical life year (VSLY) rather than valuing all deaths equally using the value of statistical life. The second and third scenarios explore the effect of choosing a different base VSL. In the second scenario, health impacts in middle-income countries are valued using the base VSL from the sample of willingness to pay studies from middle-income countries rather than the base VSL from OECD countries. This scenario is to test whether the use of a base VSL derived from a more similar context significantly influences the results for those middle-income countries. Third, a higher base VSL in line with the value assumed by U.S. agencies for regulatory purposes is tested.

VSLY versus VSL

The choice between using VSL and VSLY depends in part on the metric of health impacts being used. The VSL is used for valuing the number of deaths and the VSLY for years of life lost or reduced life expectancy. Both deaths and years of life lost are common in the medical literature, and the choice between valuing deaths or reduced life expectancy in assessing the burden of disease from air pollution hinges on whether impacts among children or older people should be weighted more heavily. According to the GBD 2013 estimates, in 2013 the over-65 population accounted for 62 percent of deaths attributed to ambient $PM_{2.5}$ and 59 percent of deaths from household air pollution. Meanwhile, children under the age of 15 accounted for only 4 percent of deaths from ambient $PM_{2.5}$ and 8 percent of deaths from household air pollution in 2013. Because remaining life expectancy for the over-65 population is less than that of children, valuing premature mortality using a VSLY instead of the VSL would put greater weight on losses suffered by children.

The empirical basis for estimating the VSLY from willingness to pay for gains in life expectancy is less developed, and there are fewer studies from which to derive a base value for the VSLY than there are for the VSL. Although it is common practice to derive the VSLY from the VSL by dividing the VSL by average remaining life expectancy, this practice is not really consistent with the empirical literature on mortality risks and how adults of different ages value risk reductions.

As for analysis of the welfare losses using the VSLY, only a few studies have been conducted to determine empirically the VSLY from the willingness to pay for gains in life expectancy, and so it is not possible to derive a base VSLY in the same way as the VSL, drawing from a large body of WTP studies conducted across countries and over time. One of the few examples of an empirical VSLY study is the nine-country study conducted in Europe by Desaigues et al. (2007, 2011). The authors of this study recommend a VSLY of $56,384 for the EU-25 countries. By comparison, analyses of the Clean Air for Europe (CAFE) Programme and the EU Clean Air Package have applied a base VSLY of $78,111–$222,316 (Hurley et al. 2005; Holland 2014). The lower and upper values of this range correspond to the median and mean VSLYs from a study of France, Italy, and the United Kingdom by Alberini, Hunt, and Markandya (2004, 2006). In the Alberini et al. study, respondents were asked about their willingness to pay for reduced fatality risks over the next 10 years. The authors imputed the VSLY by dividing respondents' WTP by the implied gain in life expectancy, assuming an annual risk reduction of 5 in 10,000.

To explore the effect of valuing lost life expectancy instead of number of deaths, in this alternative scenario 3 different VSLYs are tested: (1) the base VSLY estimates recommended by the Desaigues et al. study (2007, 2011); (2) the range of VSLY estimates from the Alberini et al.

study (2004, 2006); and (3) a VSLY that is derived indirectly from the base VSL. The VSLY is derived from the VSL by dividing the VSL by discounted remaining life expectancy:[13]

$$VSLY_j = VSL_j / \sum_{j=t}^{T} s_{j,t}(1+r)^{j-t} \tag{3.5}$$

where $VSLY_j$ and VSL_j are the VSLY and VSL for a person of age j; term $s_{j,t}$ is the probability of that person surviving to age t; and r is the discount rate. To derive the VSLY, the average VSL is first estimated for those WTP studies in the OECD's VSL database for which the average age of respondents is reported. The same quality screening criteria used to select studies for the base VSL are applied. The mean VSL for the screened sample of studies is $3.5 million. Associated GDP per capita for the surveys and countries included in the subsample of OECD country studies is $37,350. Respondents in this subsample are 50 years old on average, with a remaining life expectancy of 33 years. Discounting remaining life expectancy by an annual rate of 4 percent would imply that the average VSLY for this subsample of studies is $189,706.

Deriving the VSLY from the VSL in this way suggests that the WTP for reducing mortality risks varies proportionally with age. This suggestion is not supported by empirical evidence. Still, it is common international practice, and a constant VSLY is often used to monetize lost life expectancy or YLLs suffered by people of various ages (Cropper and Khanna 2014). The base VSLY from the OECD subsample is transferred to other countries using the same method as for the VSL and assuming the same income elasticities. In estimating damages using the transferred VSLY, remaining life expectancy is then discounted at 4 percent for high-income countries and 6 percent for low- and middle-income countries.

The spread of welfare losses estimated for 2013 assuming the different base VSLYs and discount rates is shown in tables 3.9 and 3.10. As revealed in the tables, using a VSLY to monetize reduced life expectancy results in significantly lower damages overall. If the VSLY is

TABLE 3.9 Total Welfare Losses from Air Pollution, VSL- versus VSLY-Based Estimates, by Region: 2013

% GDP equivalent

Region	VSL-based	VSLY derived from VSL	Desaigues et al. VSLY	Alberini et al. VSLY (low)	Alberini et al. VSLY (high)
East Asia and Pacific	7.5	3.6	1.2	1.6	4.6
Europe and Central Asia	5.1	2.6	0.8	1.1	3.0
Latin America and Caribbean	2.4	1.2	0.4	0.5	1.5
Middle East and North Africa	2.2	1.2	0.4	0.6	1.7
North America	2.8	1.6	0.6	0.8	2.4
South Asia	7.4	3.7	1.2	1.6	4.6
Sub-Saharan Africa	3.8	2.2	0.7	1.0	2.7

Sources: World Bank and IHME.

Note: VSLYs are from Desaigues et al. (2007, 2011) and Alberini et al. (2004, 2006). Estimates from the Desaigues et al. and Alberini et al. studies are adjusted to 2011 U.S. dollars at purchasing power parity (PPP) rates. GDP = gross domestic product; VSL = value of statistical life; VSLY = value per statistical life year.

TABLE 3.10 Total Welfare Losses from Air Pollution, VSL- versus VSLY-Based Estimates, by Income Group: 2013

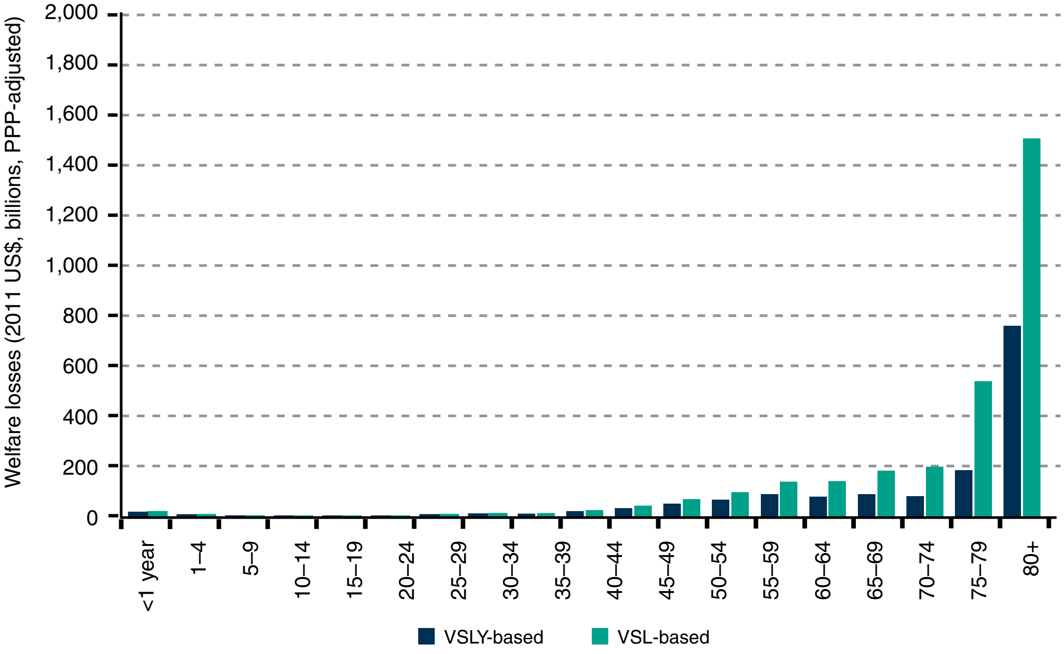
% GDP equivalent

Income group	VSL-based	VSLY derived from VSL	Desaigues et al. VSLY	Alberini et al. VSLY (low)	Alberini et al. VSLY (high)
Low income	4.3	2.4	0.8	1.1	3.0
Lower middle income	6.1	3.1	1.0	1.3	3.8
Upper middle income	6.7	3.2	1.1	1.4	4.0
High income: non-OECD	5.2	2.8	0.8	1.1	3.2
High income: OECD	3.7	1.9	0.7	0.9	2.6

Sources: World Bank and IHME.

Note: VSLYs are from Desaigues et al. (2007, 2011) and Alberini et al. (2004, 2006). Estimates from the Desaigues et al. and Alberini et al. studies are adjusted to 2011 U.S. dollars at purchasing power parity (PPP) rates. OECD = Organisation for Economic Co-operation and Development; VSL = value of statistical life; VSLY = value per statistical life year.

FIGURE 3.10 Age Profile of Welfare Losses from Air Pollution as Estimated Using VSL versus VSLY, 2013



Sources: World Bank and IHME.

Note: The global VSLY-based estimates shown are using the VSLY derived from the VSL. PPP = purchasing power parity; VSL = value of statistical life; VSLY = value per statistical life year.

used, global welfare losses in 2013 are an estimated $2.56 trillion compared with $5.06 trillion using the VSL.[14] The large difference stems from the fact that the use of lost life years shifts the age distribution of costs and puts less weight on premature deaths of the elderly (figure 3.10). Mortality costs among the 65 and over population account for 71 percent of total costs as valued using the VSL. If premature deaths are monetized using the VSLY, mortality costs among the 65 and over population are about 60 percent lower than using the VSL. Most notably, unit damages per excess death among the 80 and over population drop to less than one-quarter in the VSLY scenario versus when the VSL is used. By contrast, mortality costs among the under-45 population are only 16 percent lower when valued using the VSLY instead of the VSL.

VSL from Middle-Income Countries

To compare mortality costs in middle-income countries as estimated using a base VSL from middle-income countries instead of the transferred OECD value, the mean and median VSL estimates from the overall sample of middle-income countries are used: $383,440, with an associated GDP per capita of $7,007, and $481,347, corresponding to a GDP per capita of $6,360. For this analysis, the middle-income VSL is applied only to low- and middle-income countries. The same range of income elasticity values is assumed as in the base case (1.0–1.4, with a central value of 1.2). Although differences in GDP per capita are smaller for this sample of countries than for the overall sample, meta-regression analysis of the middle-income country VSL estimates suggests that the income elasticity is still above 1.

The results in table 3.11 demonstrate that the base case estimates of welfare losses using the OECD base value for the VSL are quite similar to the losses estimated using the median VSL estimate from the sample of middle-income countries as the base value. However, the range of estimates produced by assuming different elasticity values in the base case is much larger than if the VSL is derived from the middle-income country context, especially for regions with lower GDP per capita, including South Asia and Sub-Saharan Africa. This finding reinforces how using a base VSL from a study context that is more similar to the policy context can help reduce the sensitivity of the results to different assumptions about income elasticity.

VSL from U.S. Regulatory Agencies

The final scenario for welfare losses compares the base case with damages estimated using a VSL in line with that now assumed by U.S. regulatory agencies. The base VSL for 2013 for this scenario is $9.0 million, which represents an average of the values recommended by the U.S.

TABLE 3.11 Total Welfare Losses from Air Pollution in Low- and Middle-Income Countries, Base Case VSL Estimates versus Using VSL from Middle-Income Country Studies: 2013

% GDP equivalent

Region	Base case	Using mean VSL from middle-income countries	Using median VSL from middle-income countries
East Asia and Pacific	8.7 (6.9–11.0)	6.3 (5.7–7.0)	9.0 (8.0–10.1)
Europe and Central Asia	5.6 (4.7–6.8)	4.1 (3.6–4.8)	5.8 (5.0–6.9)
Latin America and Caribbean	2.4 (2.0–2.9)	1.7 (1.5–2.0)	2.5 (2.1–2.9)
Middle East and North Africa	2.6 (2.1–3.3)	1.9 (1.7–2.2)	2.7 (2.4–3.1)
South Asia	7.4 (5.0–11.1)	5.4 (5.1–5.8)	7.6 (7.3–8.0)
Sub-Saharan Africa	3.7 (2.5–5.8)	2.7 (2.5–3.0)	3.9 (3.6–4.2)

Sources: World Bank and IHME.

Note: Range in parentheses indicates range of welfare losses estimated by assuming a range of income elasticity values from 1.0 to 1.4 for the transferred VSL; central estimates assume elasticity of 1.2. Only low- and middle-income countries are included. GDP = gross domestic product; VSL = value of statistical life.

TABLE 3.12 Total Welfare Losses from Air Pollution in Base Case Estimates versus Alternate Scenario Using a Base VSL in Line with That Assumed by U.S. Regulatory Agencies, by Income Group: 2013

% GDP equivalent

Income group	Base case	Using U.S. regulatory VSL
Low income	4.3 (2.3–8.0)	6.8 (3.4–13.5)
Lower middle income	6.1 (4.2–8.8)	9.6 (6.2–14.9)
Upper middle income	6.7 (5.4–8.3)	10.6 (8.0–14.0)
High income: non-OECD	5.5 (5.0-–5.9)	9.9 (8.8–11.0)
High income: OECD	3.7 (3.5–3.8)	6.6 (6.3–7.0)

Sources: World Bank and IHME.

Note: Range in parentheses indicates range of welfare losses estimated by assuming different income elasticity values (0.6–1.0 for high-income countries, with a central value of 0.8, and 1.0–1.4 for all other countries, with a central value of 1.2). GDP = gross domestic product; OECD = Organisation for Economic Co-operation and Development; VSL = value of statistical life.

Department of Transportation (DOT 2015), U.S. Department of Health and Human Services (Robinson and Hammitt 2015), and U.S. Environmental Protection Agency (EPA 2016). GDP per capita in the United States in 2013 was about $51,000. The VSL is transferred assuming the same range of income elasticities as for the other scenarios. The resulting damages for this alternate scenario are shown in table 3.12.

As shown in table 3.12, applying the higher VSL that is used for regulatory purposes in the United States leads to much higher estimates of welfare losses. Central estimates of welfare losses in the base case range from the equivalent of 3.7 percent of GDP in the high-income OECD countries to 6.7 percent of GDP in the upper-middle-income countries versus 6.6 percent of GDP in the high-income OECD countries and 10.6 percent of GDP in the upper-middle-income countries in the alternate scenario. Assuming that income elasticity of the VSL is 1 for all countries in the alternate scenario would result in even higher losses, equivalent to 14.0 percent of GDP in the upper-middle-income countries and 7.0 percent of GDP in the high-income OECD countries. Differences between the alternate scenario and base case are most pronounced for the high-income countries. The average VSL for high-income countries in the alternate scenario is $6.1 million for non-OECD countries and $7.4 million for OECD countries, implying a VSL to GDP per capita ratio of 180:1 to 190:1 as opposed to 100:1 in the base case. The average VSLs in the alternate scenario for lower- and upper-middle-income countries is, respectively, $0.6 million and $1.8 million, implying VSL to GDP per capita ratios of 110:1 and 130:1, respectively, versus 70:1 and 90:1 in the base case. The VSLs and VSL to income ratios in the alternate scenario are higher than those suggested by empirical studies in middle-income countries to date (Narain and Sall 2016).

Alternative Scenarios—Forgone Labor Output

The alternative scenarios of forgone labor output look at the effect of specifying working life expectancy in different ways. First, working life expectancy is adjusted for gender-specific labor force participation rates (LFPRs) instead of applying the male rate to both sexes. Second, working life expectancy is weighted only by survival probabilities. In this case, the maximum working age is reduced from 79 to 69. Lowering the maximum working age is important because rates of economic activity decline significantly for people in their late 60s. Without

TABLE 3.13 Total Welfare Losses from Air Pollution in Base Case Estimates versus Alternate Scenario Using a Base VSL in Line with That Assumed by U.S. Regulatory Agencies, by Income Group: 2013

% GDP equivalent

Region	Base case	Working life weighted by gender-specific LFPR	Working life not weighted by LFPR
East Asia and Pacific	0.25	0.21	0.26
Europe and Central Asia	0.13	0.11	0.20
Latin America and Caribbean	0.13	0.10	0.13
Middle East and North Africa	0.14	0.09	0.17
North America	0.11	0.09	0.13
South Asia	0.83	0.59	0.81
Sub-Saharan Africa	0.61	0.55	0.63

Sources: World Bank and IHME.

Note: GDP = gross domestic product; LFPR = labor force participation rate.

discounting for labor force participation, assuming that all people who survive to age 79 will continue to work is unrealistic and would overestimate income losses.

Discounting working life expectancy using gender-specific labor force participation rates greatly reduces the estimates of forgone labor output for those regions where female labor force participation is lowest, South Asia and the Middle East and North Africa (table 3.13). Differences in losses are less pronounced in other regions where labor force participation rates are more equal, particularly Europe and Central Asia, Latin America and the Caribbean, and North America. Removing labor force participation from the calculation of working life expectancy entirely and lowering the maximum working age to 69 yields about the same results as the base case (table 3.13). Differences are greater for regions with lower rates of economic activity among the elderly, especially Europe and Central Asia.

Sensitivity Analysis—Welfare Losses

Next, the sensitivity of the overall results to individual parameters in the calculation of welfare losses is tested. Uncertainty in *each* component of the damage equation is considered, including (1) the GBD estimates of health impacts due to exposure; (2) the base VSL; and (3) the assumed income elasticity of the VSL. Uncertainty in the estimated number of deaths due to air pollution is bounded by the confidence intervals reported in GBD 2013.[15] The range of uncertainty in the base VSL is equal to plus or minus one standard deviation in the lognormal distribution of VSL estimates in the database of candidate studies from the OECD countries ($1.38–$10.64 million). The corresponding range of base values for GDP per capita is $28,944–$46,886. Income elasticities ranging from 1.0 to 1.4 and 0.6 to 1.0 are tested for middle- and high-income countries, respectively.

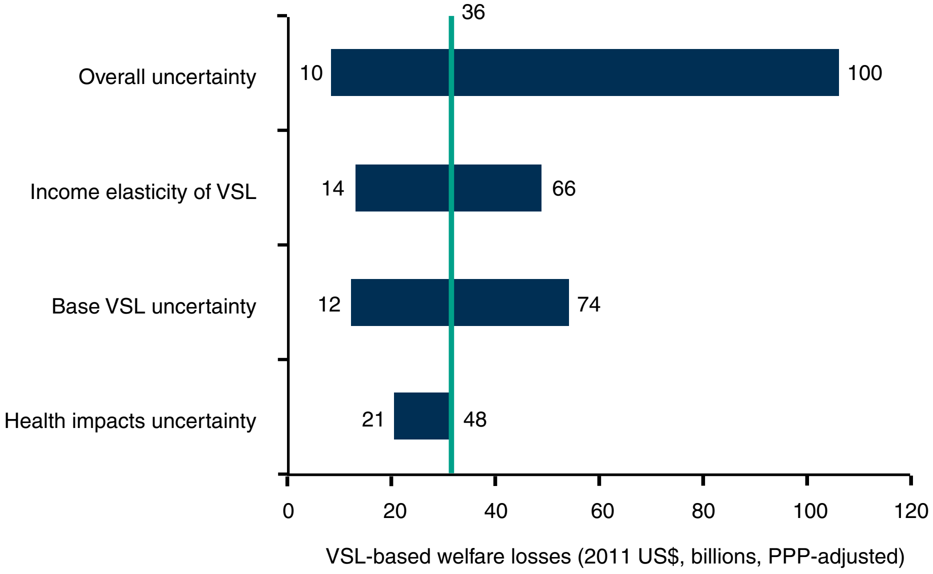
The combined uncertainty of the parameters in the calculation of welfare losses is simulated by Monte Carlo analysis. For each country and year, a 95 percent confidence interval was generated from 5,000 random draws of varying estimates for health impacts, base VSL, and income elasticity. The estimated number of deaths for each country and year was assumed to follow a lognormal distribution, with the lower and upper values reported in GBD 2013 representing the 5th and 95th percentiles of the distribution. Estimates of the base VSL were drawn at random from the database of WTP studies in OECD countries. The income elasticity was assumed to follow a triangular distribution, ranging from 1.0 to 1.4 for low- and middle-income countries, with a median of 1.2, and from 0.6 to 1.0 for high-income countries, with a mode of 0.8.

Figures 3.11 to 3.15 illustrate the overall uncertainty in the estimates of total welfare losses from air pollution as well as the effect of uncertainty on each of the individual parameters. The red line represents the central estimate of welfare losses in the base case. The figures reveal that the base VSL is the most important source of uncertainty in the calculation of losses. Also, the relative importance of the assumed income elasticity varies greatly for countries of different income levels. As noted earlier, the lower a country's per capita income, the more important is the elasticity value. For high-income countries, the assumed income elasticity of the VSL makes little difference in the overall results.

Despite the large uncertainty—and even under highly conservative or extreme assumptions—the results of the analysis show that welfare losses are significant and warrant greater action from the world's governments to reduce air pollution. Under the wide range of assumptions tested, global welfare losses in 2013 were at least $1.448 trillion and as much as $13.210 trillion. The upper end of this range is equally as likely as the lower range. Uncertainty intervals for individual countries are presented in the data table in appendix B.

The uncertainty analysis also reveals that the main sources of uncertainty vary for countries of different income levels. For high-income countries, the choice of the base VSL is far more

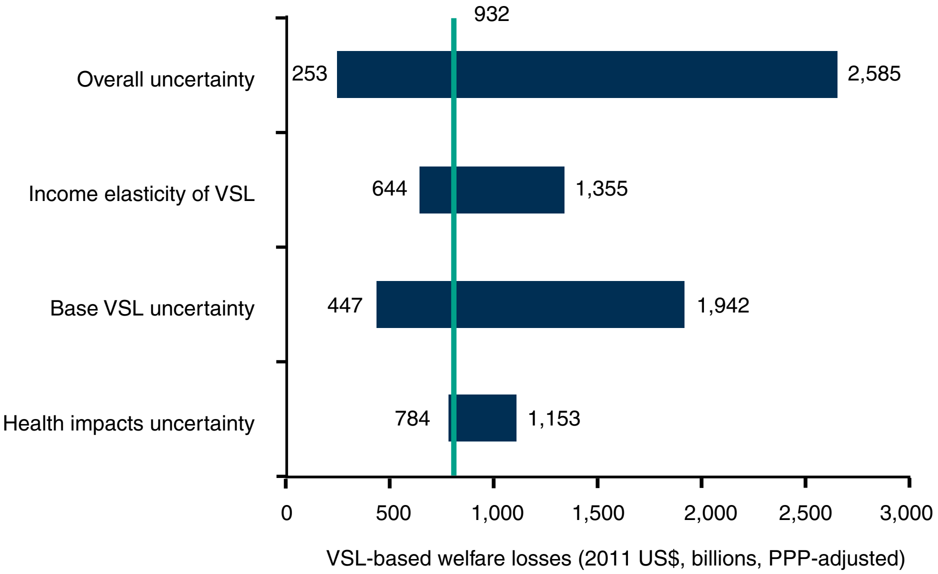
FIGURE 3.11 **Uncertainty in Welfare Loss Parameters: Low-Income Countries, 2013**



Sources: World Bank and IHME.

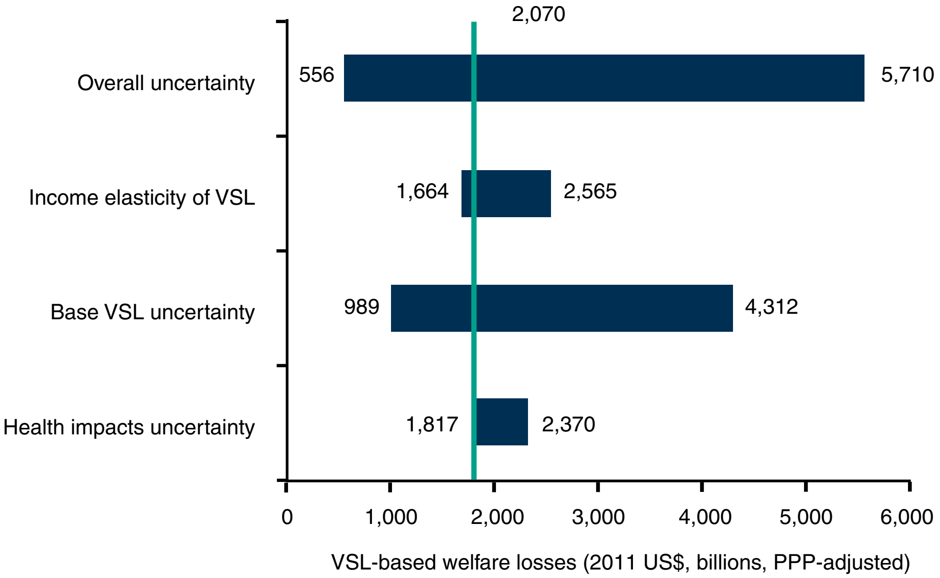
Note: PPP = purchasing power parity; VSL = value of statistical life.

FIGURE 3.12 Uncertainty in Welfare Loss Parameters: Lower-Middle-Income Countries, 2013



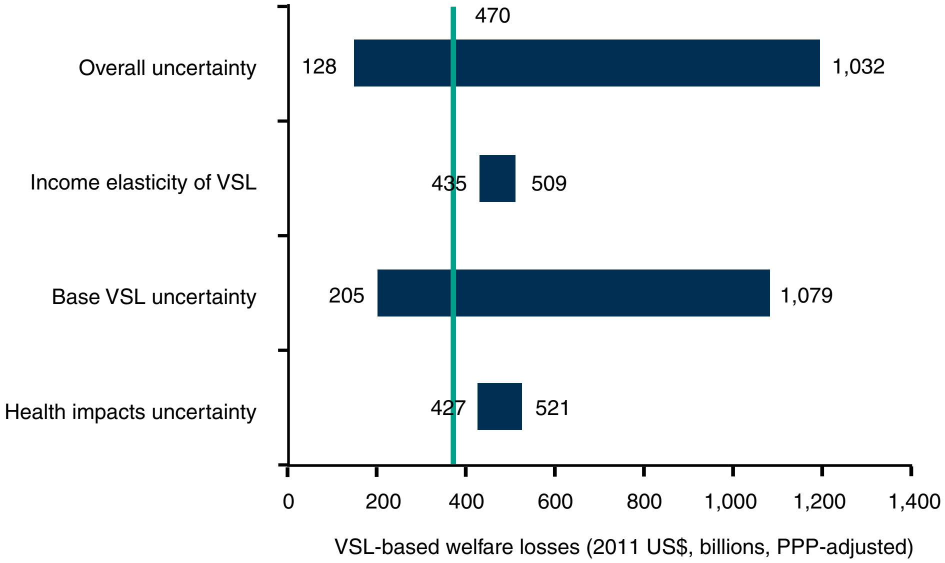
Sources: World Bank and IHME.
Note: PPP = purchasing power parity; VSL = value of statistical life.

FIGURE 3.13 Uncertainty in Welfare Loss Parameters: Upper-Middle-Income Countries, 2013



Sources: World Bank and IHME.
Note: PPP = purchasing power parity; VSL = value of statistical life.

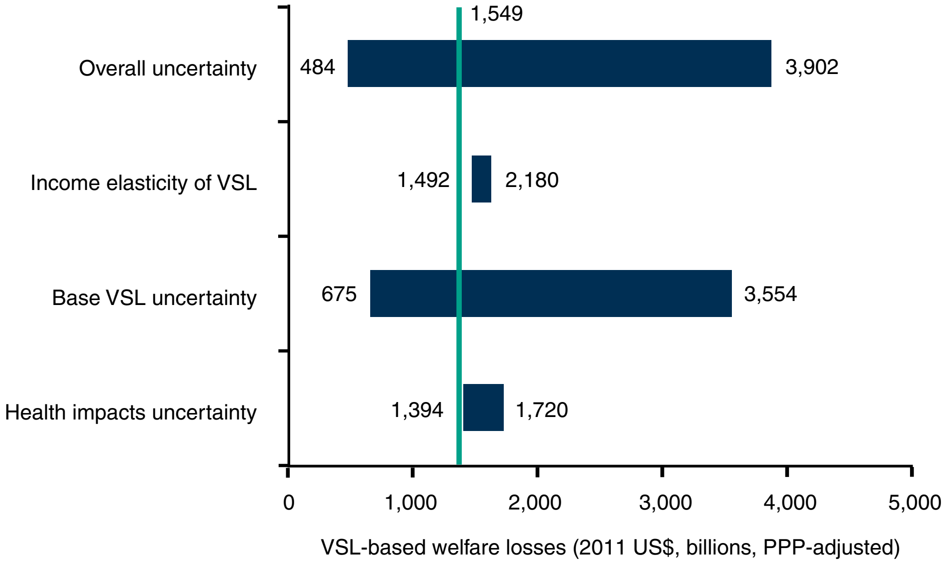
FIGURE 3.14 Uncertainty in Welfare Loss Parameters: High-Income Non-OECD Countries, 2013



Sources: World Bank and IHME.

Note: PPP = purchasing power parity; VSL = value of statistical life.

FIGURE 3.15 Uncertainty in Welfare Loss Parameters: High-Income OECD Countries, 2013



Sources: World Bank and IHME.

Note: PPP = purchasing power parity; VSL = value of statistical life.

influential than assumptions about the income elasticity of the VSL. For low- and middle-income countries, the choice of the base VSL is also the main source of uncertainty, though the income elasticity also plays a significant role. These results speak to the critical need for more empirical studies in low- and middle-income countries of willingness to pay for reduced mortality risks in order to understand the economic costs of pollution in those countries.

Sensitivity Analysis—Forgone Labor Output

In sensitivity tests carried out for the parameters in the estimates of forgone labor output, uncertainty resulting from the estimates of health impacts is compared with the uncertainty associated with the assumed rates of income growth and the social discount rates. As with the welfare loss estimates, the overall spread of uncertainty is then simulated using Monte Carlo analysis.

To test the uncertainty associated with income growth and social discount rates, the constant rates in the base case are compared with a range of country-specific rates, which are calculated according to observed rates of wage growth and growth in per capita consumption from 1990 to 2010. The social discount rate, r, is specified using Ramsey's formula as

$$r = \delta + \eta \cdot c \tag{3.6}$$

where δ is the pure rate of time preference; η is the (negative) marginal utility of consumption; and c is average annual growth in final consumption expenditure per capita. On ethical grounds, ρ is set at 0 from the perspective that the social planner would value the utility of future generations equally with that of the current generation (see Arrow et al. 2013). Term η is assumed here to be second in line with recent guidance by the World Bank.[16] Country data on real wage growth and final consumption expenditure per capita from 1990 to 2010 are from the World Bank's World Development Indicators database. Based on these data, the effective discount rate is given by the ratio of wage growth, g, to the social discount rate so that

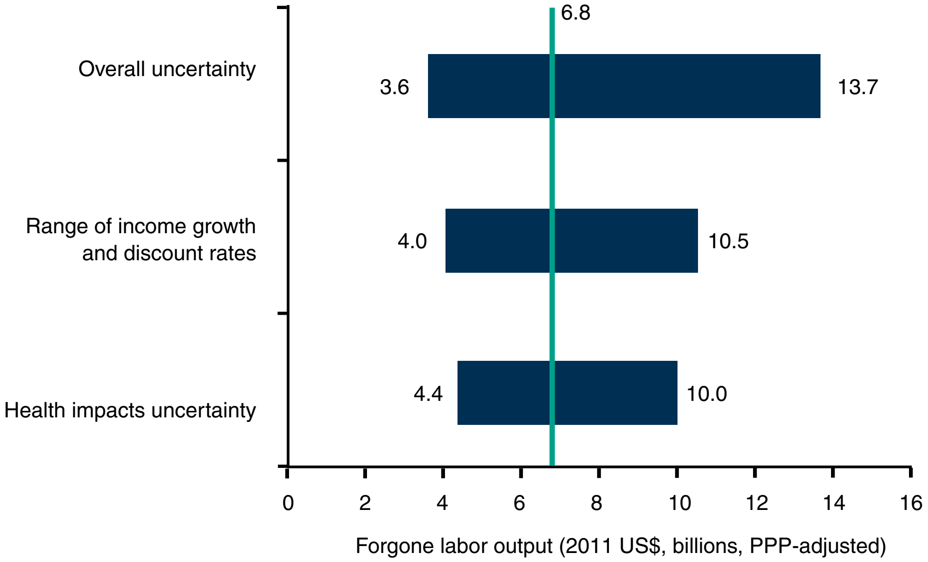
$$R = \frac{1+g}{1+r} \tag{3.7}$$

For the one-way sensitivity tests, uncertainty in the country-specific income growth and discount rates is represented by the 5th and 95th percentiles of R.

The results in figures 3.16 to 3.20 demonstrate that assumptions about future income growth and the discount rate introduce considerable uncertainty into the calculation of forgone output. The magnitude of this uncertainty is about the same as that from the estimates of exposure and health impacts. Relative uncertainty in the parameters is greatest for the low-income countries.

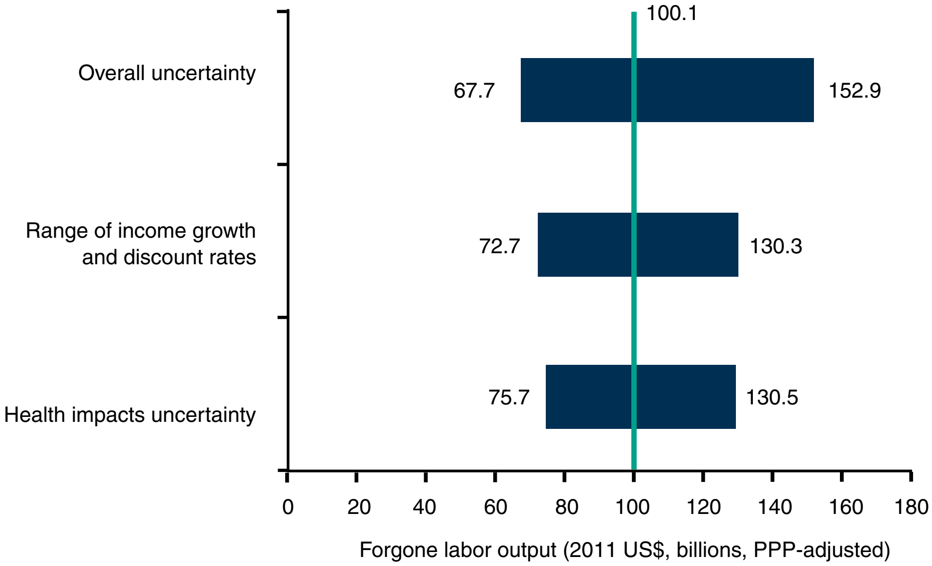
In constructing 95 percent confidence intervals to represent the combined uncertainty in the forgone labor output estimates, 5,000 random draws were obtained from a lognormal distribution of health impact estimates for each country, year, and age group. Five thousand random

FIGURE 3.16 Uncertainty in Forgone Labor Output Parameters: Low-Income Countries, 2013



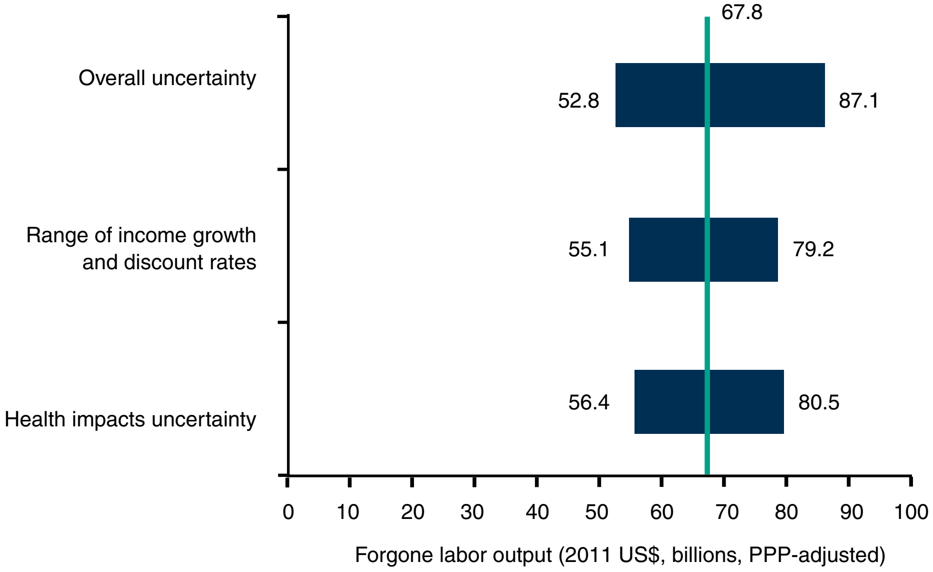
Sources: World Bank and IHME.
Note: PPP = purchasing power parity.

FIGURE 3.17 Uncertainty in Forgone Labor Output Parameters: Lower-Middle-Income Countries, 2013



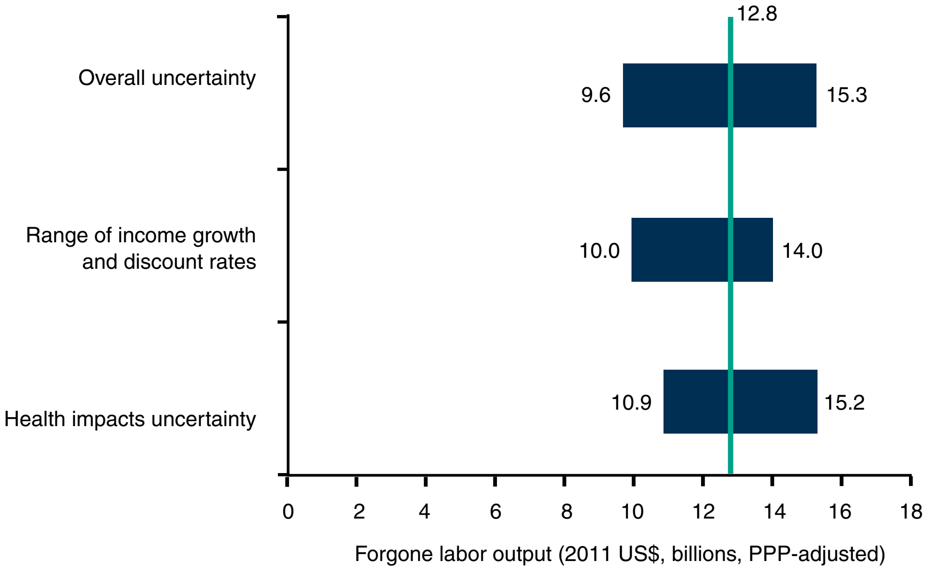
Sources: World Bank and IHME.
Note: PPP = purchasing power parity

FIGURE 3.18 Uncertainty in Forgone Labor Output Parameters: Upper-Middle-Income Countries, 2013



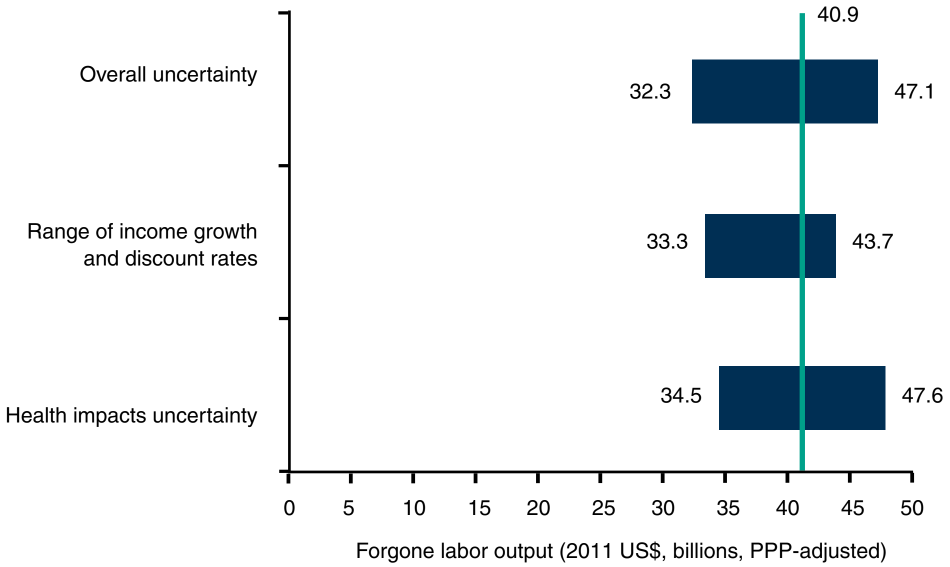
Sources: World Bank and IHME.
Note: PPP = purchasing power parity.

FIGURE 3.19 Uncertainty in Forgone Labor Output Parameters: High-Income Non-OECD Countries, 2013



Sources: World Bank and IHME.
Note: PPP = purchasing power parity.

FIGURE 3.20 Uncertainty in Forgone Labor Output Parameters: High-Income OECD Countries, 2013



Sources: World Bank and IHME.
Note: PPP = purchasing power parity.

draws were then taken from the distribution of the effective discount rate (*R*), obtained from historic rates of growth in wages and per capita consumption. Measurement error in estimates of average wage income derived from the labor share of GDP was represented by a uniform distribution of ±5 percent of the central estimate, and 1,000 random draws were then taken from this distribution. The relative magnitude of uncertainty in the estimates of forgone labor output was much smaller than in the welfare loss estimates.

Compared with welfare losses, the relative magnitude of uncertainty in the estimates of forgone labor output is much smaller. Within the range of varying parameters tested, global labor income losses in 2013 were anywhere from $165 billion to $305 billion. Uncertainty from assumptions about future income growth and the discount rate is about as great as the uncertainty from the range of estimates of health impacts. This finding speaks to the importance of testing a range of discount and growth rates in estimating income losses, especially for the purposes of cost-benefit or project analysis.

Notes

1. All monetary amounts in this report are in terms of constant 2011 U.S. dollars at purchasing power parity (PPP)-adjusted rates.
2. The quality screening criteria are that the WTP studies: (1) report a quantified value for the change in fatality risk; (2) have a main sample larger than 200 observations or a subsample larger than 100 observations; (3) draw from a sample representative of the general population; and (4) pass a scope test for internal or external consistency. In all, the sample includes 167 estimates of VSLs drawn from 16 separate studies in OECD countries.

3. The rate of 6 percent for low- and middle-income countries is keeping with recent World Bank guidance.
4. Conference Board, http://www.conference-board.org/data/economydatabase/, May 2015; Organisation for Economic Co-operation and Development, "Aggregate National Accounts, SNA 2008 (or SNA 1993): Gross Domestic Product," OECD National Accounts Statistics (database), DOI: http://dx.doi.org/10.1787/data-00001-en; United Nations Statistics Division, National Accounts Official Country Data, http://data.un.org/Explorer.aspx.
5. This assumes that life expectancy increases monotonically with age, which is not the case for countries with high rates of infant mortality and where life expectancy at birth is lower than it is for children who survive to age 1.
6. The ILO's definition of the labor force encompasses anyone who is actively working or seeking work. This includes the unemployed as well as the employed. The self-employed, underemployed, and those working informally (such as family workers) are counted as employed. In practice, however, definitions of employment vary among countries, and countries with high levels of informality in the labor market may underreport the size of the economically active population—see ILO (2015).
7. All figures are reported in constant 2011 U.S. dollars, PPP-adjusted.
8. Here, welfare losses are expressed as a percentage equivalent of GDP only to provide a convenient sense of relative scale and not to suggest that welfare is a share of GDP or that the two are a measure of the same thing.
9. The discrepancy in magnitude between welfare losses and forgone labor output is not surprising—after all, future earnings from labor are just part of the value that individuals attach to being alive, and an increase in the risk of death cannot be measured by reduced earnings potential alone. As noted, the VSL is a welfare-based measure of fatality risk, whereas forgone labor output is an income-based measure more in line with national accounting boundaries.
10. Though expected lifetime earnings are discounted more heavily farther into the future.
11. Total losses are reported here for a balanced data set only for countries for which damage estimates are available for each year from 1990 to 2013.
12. The increases noted for Equatorial Guinea result almost entirely from changes in GDP per capita and wages, not exposure or health impacts.
13. Note that the VSLY is used here to value remaining life expectancy and not years of life lost (YLLs). YLLs are calculated against a reference life table, which assumes the same life expectancy for all people in a given age cohort regardless of what country they are living in and how life expectancy varies between countries.
14. Global welfare losses from air pollution reported here for the base case are slightly lower than reported elsewhere in this chapter because they exclude damages for Hong Kong SAR, China; Macao SAR, China; and the Republic of Yemen—the three administrative units for which life expectancy data are unavailable and thus YSLY-based damages cannot be calculated or compared.
15. Sources of uncertainty in the estimates of health impacts and specification of confidence intervals are described in chapter 2 of this report and in Cohen et al. (n.d.).
16. The marginal utility of consumption (or coefficient of relative risk aversion) is often assumed to be between 1 and 2. Dasgupta (2008) argues that $\delta = 0$ assuming implies that η should be from 1.5 to 3, considering saving/output ratios.

References

Alberini, Anna, Alistair Hunt, and Anil Markandya. 2004. "Willingness to Pay to Reduce Mortality Risks: Evidence from a Three-Country Contingent Valuation Study." Paper 111.2004, Fondazione Eni Enrico Mattei Note di Lavoro Series, September.

———. 2006. "Willingness to Pay to Reduce Mortality Risks: Evidence from a Three-Country Contingent Valuation Study." *Environmental and Resource Economics* 33: 251–64.

Arrow, Kenneth, Maureen Cropper, Christian Gollier, Ben Groom, Geoffrey Heal, Richard Newell, William Nordhaus et al. 2013. "How Should Benefits and Costs Be Discounted in an Intergenerational

Context? The Views of an Expert Panel." Discussion Paper 12-53, Resources for the Future, Washington, DC.

Chile MDS (Ministerio de Desarrollo Social, Chile). 2014. "Estimación del valor de los costos sociales por fallecimiento prematuro en chile (Estimation of the Social Costs of Premature Mortality in Chile)." Report by the Division of Social Evaluation of Investments, Sub-Secretary of Social Evaluation, Ministry of Social Development, Government of Chile, March.

Cohen, Aaron et al. n.d. "The Global Burden of Disease Attributable to Ambient Air Pollution: Estimates of Current Burden and 23-Year Trends from the GBD 2013 Study." In submission.

Cropper, Maureen. 2000. "Has Economic Research Answered the Needs of Environmental Policy?" *Journal of Environmental Economics and Management* 39 (3): 328–50.

Cropper, M., and S. Khanna. 2014. "How Should the World Bank Estimate Air Pollution Damages?" Discussion Paper No. 14-30, Resources for the Future, Washington, DC, September.

Dasgupta, Partha. 2008. "Discounting Climate Change." *Journal of Risk and Uncertainty* 37: 141–69.

Desaigues, Brigitte, Ari Rabl, Sue Chilton, Hugh Metcalf, Alistair Hunt, Ramon Ortiz, Stale Navrud et al. 2007. "Final Report on the Monetary Valuation of Mortality and Morbidity Risks from Air Pollution." Delivery no. 6.7—RS 1b, New Energy Externalities Developments for Sustainability (NEEDS) project, 6th Framework Programme, Paris, February.

Desaigues, B., D. Ami, M. Braun-Kohlova, S. Chilton, M. Czajkowski, V. Farreras, A. Hunt et al. 2011. "Air Pollution Mortality: A 9-Country Contingent Valuation Survey of a Value of a Life Year (VOLY)." *Ecological Indicators* 11: 902–10.

DOT (U.S. Department of Transportation). 2015. "Guidance on the Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2015 Adjustment." https://www.transportation.gov/office-policy/transportation-policy/guidance-treatment-economic-value-statistical-life.

EPA (U.S. Environmental Protection Agency). 2016. "Valuing Mortality Risk Reductions for Policy: A Meta-Analytic Approach." White paper prepared by U.S. EPA Office of Policy, National Center for Environmental Economics, for review by the EPA's Science Advisory Board, Environmental Economics Advisory Committee, February.

Feenstra, Robert C., Robert Inklaar, and Marcel P. Timmer. 2015. "The Next Generation of the Penn World Table." *American Economic Review.* Available for download at http://www.ggdc.net/pwt.

Hamilton, Kirk, and Michael Clemens. 1999. "Genuine Savings Rates in Developing Countries." *World Bank Economic Review* 13 (2): 333–56.

Holland, Mike. 2014. "Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package, Version 2, Corresponding to IIASA TSAP Report #11, Version 2a." Report for European Commission DG-Environment, October.

Hunt, Alistair, Julia Ferguson, Fintan Hurley, and Alison Searl. 2016. "Social Costs of Morbidity Impacts of Air Pollution." Environment Working Paper No. 99, Organisation for Economic Co-operation and Development, Paris. http://dx.doi.org/10.1787/5jm55j7cq0lv-en.

Hurley, Fintan, Hilary Cowie, Brian Miller, and Paul Watkiss. 2005. "Methodology for the Cost-Benefit Analysis for CAFE, Volume 2: Health Impact Assessment." Report to the European Commission DG-Environment, Didcot, U.K., February.

ILO (International Labour Organization). 2014. "Global Wage Report 2014/2015." http://www.ilo.org/global/research/global-reports/global-wage-report/2014/lang--en/index.htm.

______. 2015. *Key Indicators of the Labor Market*. 9th ed. http://www.ilo.org/global/statistics-and-databases/research-and-databases/kilm/lang--en/index.htm.

Lenzen, Manfred, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke. 2012. "Mapping the Structure of the World Economy." *Environmental Science and Technology* 46 (15): 8374–81.

Lenzen, Manfred, Daniel Moran, Keiichiro Kanemoto, and Arne Geschke. 2013. "Building Eora: A Global Multi-Region Input-Output Database at High Country and Sector Resolution." *Economic Systems Research* 25 (1): 20–49.

Narain, Urvashi, and Chris Sall. 2016. "Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions." Draft working paper, World Bank, Washington, DC, March.

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

Robinson, Lisa A., and James K. Hammitt. 2015. "Research Synthesis and the Value per Statistical Life." *Risk Analysis* 35 (6): 1086–1100.

Viscusi, W. Kip. 1993. "The Value of Risks to Life and Health." *Journal of Economic Literature* 31: 1912–46.

World Bank. 2005. *Where Is the Wealth of Nations? Measuring Capital for the 21st Century*. Washington, DC: World Bank.

______. 2011. *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium.* Washington, DC: World Bank.

4. A Synthesis and the Way Forward

Air Pollution: A Costly and Persistent Challenge

Air pollution is a major health risk and an economic burden, especially on low- and middle-income countries. It has been the fourth most important health risk in terms of attributable deaths and premature mortality since 1990, despite the fact that nearly all countries have reduced the number of deaths per 100,000 persons caused by air pollution through many developments, including improvements in health services. In 2013 air pollution was associated with 5.5 million deaths—that is, 1 in 10 deaths globally, an increase from 4.8 million in 1990.

Low- and middle-income countries bear a bigger share of the burden. Air pollution is the third most important health risk leading to early death in low- and lower-middle-income countries. The proportion of deaths attributable to air pollution has increased in both income groups since 1990, although this share is highest in upper-middle-income countries.

The very young and older adults are particularly vulnerable: in 2013 about 5 percent of deaths of children under 5 was attributed to air pollution, compared with less than 1 percent among older children and young adults and more than 10 percent for older adults in every age group above 50. This age pattern of mortality has remained unchanged since 1990. Among all ages and over time, a larger share of men than women have died prematurely from air pollution–based illnesses.

These health impacts have put a real drag on development. In 2013 exposure to ambient and household air pollution cost the world's economy some $5.11 trillion in welfare losses, amounting to as much as 7.5 percent and 7.4 percent of gross domestic product (GDP) equivalent in East Asia and the Pacific and South Asia, respectively, and, at the lowest end, 2.2 percent in the Middle East and North Africa. Indoor air pollution was the biggest cause of losses in South Asia and Sub-Saharan Africa. In all other regions, losses were largely caused by ambient air pollution from fine particulate matter ($PM_{2.5}$). Losses were highest for middle-income countries, and low- and middle-income countries together accounted for 59 percent of the total global losses.

Labor income losses, while expectedly lower than welfare losses, were nonetheless substantial in regions with younger populations. Lost income for countries in South Asia totaled more than $66 billion in 2013, the equivalent of nearly 1 percent of GDP. Globally, the labor income losses totaled $225 billion in 2013.

Moreover, air pollution costs have grown since 1990. From 1990 to 2013, welfare losses nearly doubled and labor income losses increased by 40 percent, despite countries having made great gains in economic development and health outcomes. In low-income countries, declines in death rates were more than offset by population growth and greater total exposure to polluted air. In middle-income countries, total exposure also increased. However, most of the estimated increase in welfare losses stemmed from people placing a greater value on reducing fatality risks. Similarly, from 1990 to 2013 average wages increased in real terms in all but the high-income countries that are not members of the Organisation for Economic Co-operation and Development (OECD), causing forgone labor income losses per premature death to be higher. Across countries in all income groups, the age profile of people affected by pollution shifted, so that a higher proportion of deaths occurred among people later in their working life, having a countervailing, but not equal or greater, effect on income losses. These effects suggest that incremental progress to improve air quality will not be sufficient and that achieving real reductions in the cost of pollution will require more ambitious action.

Ambient Air Pollution: A Growing Challenge

As noted, in 2013 about 87 percent of the world's population lived in areas that exceeded the Air Quality Guideline of the World Health Organization (WHO), which is an annual average of 10 micrograms per cubic meter (μg/m^3) $PM_{2.5}$. Thirty-five percent of the global population resided in areas with concentrations above the WHO Interim Target 1 of an annual average of 35 μg/m^3 $PM_{2.5}$, with nearly all of the most extreme (>65 μg/m^3) concentrations experienced by populations in China and India. Since the 1990s, exposure to ambient air pollution has grown in most countries (other than high-income countries), with some of the greatest increases in the heavily populated, fastest-growing regions, including South Asia and East Asia and the Pacific.

Exposure to ambient air pollution was the seventh most important risk factor leading to early death in 2013, resulting in 2.9 million deaths in 2013—1.7 million among men and 1.2 million among women. Of these deaths, 75 percent occurred in middle-income countries. Children and the elderly faced higher risks, particularly in low-income countries. Death rates for lower respiratory infections attributable to $PM_{2.5}$ among children under 5 were more than 60 times higher in low-income countries (31.9 per 100,000 persons) than in high-income countries (0.5 per 100,000).

Although the age-standardized death rate due to ambient $PM_{2.5}$ exposure has decreased in most countries since 1990 because of overall improvements of health, population growth and increased exposure have nonetheless increased the number of premature deaths. From 1990 to 2013, premature mortality attributable to ambient pollution increased by 30 percent, from 2.2 million to 2.9 million. In 1990 the outcome was largely attributable to pneumonia, whereas in 2013 the cause shifted to cardiovascular disease and lung cancer. All regions other than Europe and Central Asia and North America saw an increase in the number of deaths. With the exception of high-income countries, the percentage of total deaths attributable to ambient air pollution also increased.

The development burden has also increased over time. Welfare losses from ambient air pollution increased by nearly 300 percent between 1990 and 2013, growing from \$2.18 trillion to \$3.55 trillion. Welfare losses increased in about two-thirds of all countries. Europe and Central Asia and North America were the only regions in which losses from ambient air pollution steadily and consistently declined.

Indoor Air Pollution: A Remaining Challenge Despite Some Gains

Although two-fifths of the world's population was exposed to household air pollution (HAP) from solid fuels in 2013, between 1990 and 2013 declines in HAP exposure, ranging from nearly 100 percent in many higher-income countries to under 10 percent across much of Sub-Saharan Africa, were evident in most countries.

The age-standardized death rate from household air pollution declined steadily from 1990 (75.3 per 100,000 persons) to 2013 (47.1 per 100,000), a 37.5 percent drop. Total deaths were down by almost 60 percent among children under 5, but even among adults 70 and older improvements were visible.

And yet despite the reductions in exposure to household air pollution and declines in death rates, the number of deaths associated with indoor air pollution has mostly remained constant. Approximately 2.9 million deaths were attributed to indoor air pollution in 1990 and also in 2013, with increases in South Asia and Sub-Saharan Africa but decreases in other regions. Two-thirds of HAP deaths occurred in low- and lower-middle-income countries.

Meanwhile, welfare losses grew 63 percent between 1990 and 2013. Declines in the share of households that rely on solid fuels for cooking have not kept pace with factors such as population growth, aging, and rising incomes, which have led to more deaths and higher costs.

The Way Forward

Supporting Policy

This report has presented evidence on the health impacts of exposure to ambient and indoor air pollution and estimated the cost of these impacts on the global economy. It has highlighted the severity of the issues to make the case that countries should take action to reduce air pollution. The fact that global welfare losses from fatal illness attributable to air pollution are in the trillions of dollars—even under the most conservative assumptions—is a call to action. The additional costs of pollution not captured by this report make reducing exposure all the more urgent for achieving the goals of shared, inclusive, and sustainable prosperity. At the very least, these numbers give policy makers an appreciation of the magnitude of the benefits that air pollution management will bring to their economies and a credible basis against which to compare the costs of such policies.

Meanwhile, by placing air pollution–related health risks in the context of other health risks that, unlike air pollution, are typically within the purview of health agencies, the Global Burden of Disease (GBD) approach has also emphasized the need for health agencies to consider this important health burden and called for ministries of environment and health to work together to deal with this challenge.

The methodology and the data presented in this report also support other policy discussions such as those in energy and transport project–related cost-benefit analysis (see box 4.1). Such projects can be a source of ambient air pollution. But by encouraging a modal shift toward cleaner transport or promoting cleaner sources of energy, such projects can also help reduce pollution. In either case, air pollution–related economic impacts, especially health impacts, need to be incorporated into project cost-benefit analysis. Although the methodology to estimate exposure to project-related emissions differs from the approach used in the Global Burden of Disease Study, the same methodologies can be applied to estimate the economic costs and benefits of project-related health impacts.

BOX 4.1 Transport: Valuing the Health Impacts of Air Pollution in Transport Project Cost-Benefit Analyses

Emissions from transport can be an important source of ambient air pollution, and health impacts related to transport emissions can be substantial. Hill et al. (2009) have estimated that the health costs of gasoline produced and consumed in the United States are on the order of $0.36 per gallon ($.09 per liter)—more than twice the cost associated with greenhouse gas emissions per gallon.[1]

Transport projects change demand for transport services and their modal composition, mainly through changes in the monetary costs of travel, travel times, and comfort of one or more modes. New road infrastructure, for example, shortens distances or relieves congestion, thereby reducing travel times. Road rehabilitation has the same effect by improving road quality. Both have effects on fuel use and emissions, depending on the density of traffic:

- Lower transport costs generate more traffic, leading to more fuel use and emissions.
- If initial speeds are low, an increase in infrastructure capacity can increase speeds and reduce fuel consumption per vehicle-km traveled, thereby reducing emissions. If initial speeds are already high, more road capacity will increase fuel use and emissions, instead.
- Improving traffic flows in congested parts of the road network can reduce emissions.

Public transport projects reduce modal travel times, increase comfort, and make it more attractive to switch from other modes. Such changes in general reduce fuel use and emissions.

The health impacts of transport emissions must therefore be incorporated into project cost-benefit analyses. Although methodologies to estimate exposure at the project level differ from those used to estimate exposure at the country level in GBD 2013, the same methodologies are applied to estimating health impacts and economic costs.

The health cost savings from reducing emissions depends on exposure—that is, how emissions disperse and how many people are affected. Because of the low height of emissions, a high share of the intake fraction occurs at short distances from the emissions source. More than 50 percent of the health impacts is incurred within a distance of 5 kilometers from the sources of the emissions, whether a road, a bus terminal, or an airport.

Dose-response parameters (health cases per $\mu g/m^3$ additional pollutants) determine how the changes in pollutants (mainly particulate matter, nitrogen oxides, and sulfates) change the frequency of premature death, chronic bronchitis, hospital admissions, or work day losses as the most important costs of health impacts.

The changes in the frequency in health incidence is valued using the value of statistical life (VSL), which is the willingness to pay (WTP) for a small reduction in the risk of mortality. If local, context-relevant WTP studies are unavailable, a base VSL may be transferred to the study context in the same way as in this report.

Source: Andreas Kopp (World Bank).

As the report shows, satellite-based observations combined with data from ground-level monitors are necessary for global assessments of air pollution burden. This methodology can also potentially be used for country-level assessments and air quality planning, especially when ground-level monitor-based and satellite-based estimates are well aligned. Ground-level monitors are a critical component of any air pollution management approach, particularly at the city level, and countries need to enhance ground-level monitoring networks to fight the challenge of air pollution. Moreover, satellite-based observations must be calibrated and validated using data from ground-level monitoring networks. At the same time, however, satellite-based observations can provide spatial coverage that is often hard to achieve with ground-level monitors alone. As is the practice in the U.S. Environmental Protection Agency's AirNow program, where satellite-based observations are consistent with ground-level observations, satellite-based observations can be used to enhance the spatial and temporal coverage of air quality data (see box 4.2).

Improving Estimates

It would be remiss to end this report without discussing how measurement of the disease burden and the economic costs associated with air pollution can be improved and made more useful for policy applications. Efforts are already under way to link exposure and health impacts to pollution sources to support policy actions (see box 4.3) and to provide subnational estimates to help prioritize areas within countries (see box 4.4). Further work is needed in both of these areas.

Measurement of the disease burden of pollution will continue to evolve as the state of the art evolves in the science of epidemiology. Estimates for the Global Burden of Disease Study, led by the Institute for Health Metrics and Evaluation (IHME), are updated yearly with new data and improved methods for integrating different data sources. The next iteration of the GBD will benefit from improvements in merging satellite-based estimates with ground measurements, which will lead to improved accuracy and representation of spatial patterns in ambient air pollution. Few studies currently allow estimation of the quantitative contribution of household air pollution to ambient air pollution, or vice versa. Improved global exposure estimates, and more studies allowing for this kind of estimation, will improve GBD estimates for both the combined burden of air pollution as well as the individual risk factors. There is growing evidence that other diseases may be affected by air pollution, including diabetes, preterm birth complications, low birth weight, and incident asthma. In addition, GBD air pollution estimates do not capture near-roadway pollution impacts, which are characterized by other pollutants such as nitrogen dioxide (NO_2) and are likely to be at least partially independent of the effects that are characterized by the IERs used for the GBD 2013. More research is also needed on the health impacts of natural dust versus other components of particulate matter and how to accurately measure concentrations in dusty places, especially for populations in environments where a large share of pollution is from windblown dust, such as North Africa.

BOX 4.2 Morocco: Using Ground-Level and Satellite Data to Estimate the Cost of Air Pollution

In 2000 the World Bank estimated for the first time the cost of environmental degradation (COED) in Morocco (World Bank 2003). It showed that environmental degradation cost society 3.7 percent of GDP, of which air pollution was the second most important component. These results raised awareness about the monetary damage that can result from environmental degradation. Most important, they positively influenced policies, investments, and strategies to achieve more sustainable and greener development in Morocco. In 2014 the government of Morocco asked the World Bank to update the original COED study.

As part of the update (World Bank, 2016), the study looked at the impact of ambient air pollution on people's health. It relied on PM_{10} concentrations measured by a well-developed network of air quality monitoring stations in Morocco, consisting of 29 fixed stations and three mobile stations located in major cities. The authors converted PM_{10} into $PM_{2.5}$ concentrations using the latest available information on PM composition in Morocco. Of the 13 cities equipped with air quality stations, eight had estimated annual $PM_{2.5}$ concentrations above 10 μg/m^3 (WHO Guideline value)—see table B4.2.1. The population exposed to pollution monitored at each station was assessed using a geographic information system (GIS). Based on population exposure and correlations between exposure and health impacts (Apte et al. 2015), the number of premature deaths for these eight cities was estimated at 2,200.

By contrast, using satellite-based exposure estimates, the present study estimated that exposure to ambient air pollution resulted in 6,014 premature deaths in Morocco as a whole in 2013, thereby raising the question as to whether the two estimates—one from ground-level monitoring data for eight cities and the other from satellite observations for the whole country—are consistent.

TABLE B4.2.1 Comparison of Ambient $PM_{2.5}$ Concentrations from Ground-Level Monitors and Satellite Observations at the City Level

City (no. of stations)	Range of annual $PM_{2.5}$ concentrations estimated from ground-level monitors (μg/m^3)	GBD 2013 satellite-based $PM_{2.5}$ concentration (μg/m^3)
Tanger (1)	22	11
Marrakesh (3)	17–24	18
Casablanca (11)	9–27	18
Mohammedia (2)	10–25	17
Settat (1)	17	21
Fes (1)	16	12
Benslimane (1)	13	13
Khouribga (1)	12	12

Sources: World Bank (2016) and IHME.
Note: GBD = Global Burden of Disease.

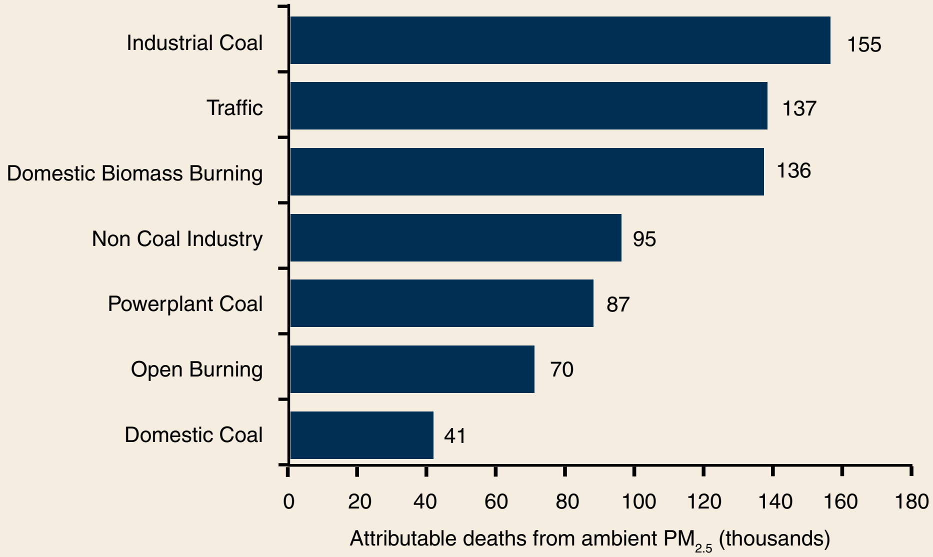
A city-by-city comparison of $PM_{2.5}$ concentration estimates from ground-level monitored and satellite-based observations shows that the concentration estimates are well aligned for all eight cities, with the exception of Tanger (see table B4.2.1). Furthermore, these eight cities, the largest in the country, account for about 23 percent or one-fifth of Morocco's total population. A comparison with the national estimates suggests that these cities account for one-third of total premature deaths. Because cities are likely to bear the highest health burden from ambient air pollution, the burden of disease estimates from the two approaches appear to be consistent. Even though a more detailed analysis is needed to determine conclusively the consistency between the estimates from the two approaches, the analysis presented here points in that direction.

BOX 4.3 China: Estimating the Impact of Pollution Sources on Disease Burden

Although cause-attributable burden estimates are important to help governments prioritize actions across risk factors, policy makers need information on sources of pollution to implement actions to reduce air pollution. Detailed information needed for policy action on sources of pollution can only be obtained from city-level and regional source apportionment studies, but the GBD framework is suited to indicating the sources of pollution as well. GBD MAPS (Global Burden of Disease from Major Air Pollution Sources) has been established to estimate the disease burden attributable to ambient air pollution from major $PM_{2.5}$ sources in China, India, and eastern Europe. Specifically, the fractional contributions to ambient $PM_{2.5}$ from major sources of ambient air pollution are estimated using the GEOS-Chem chemical transport model for 2013. When combined with exposure and health impacts, this allows disease burdens to be attributed to different sources of pollution.

A recently completed study—"Burden of Disease Attributable to Coal-Burning and Other Major Sources in China"—provides such estimates for China (see figure B4.3.1). (GBD MAPS Working Group 2016).

FIGURE B4.3.1 Deaths Attributable to Ambient $PM_{2.5}$ Pollution in China, by Source of Emissions, 2013



Source: GBD MAPS Working Group (2016).

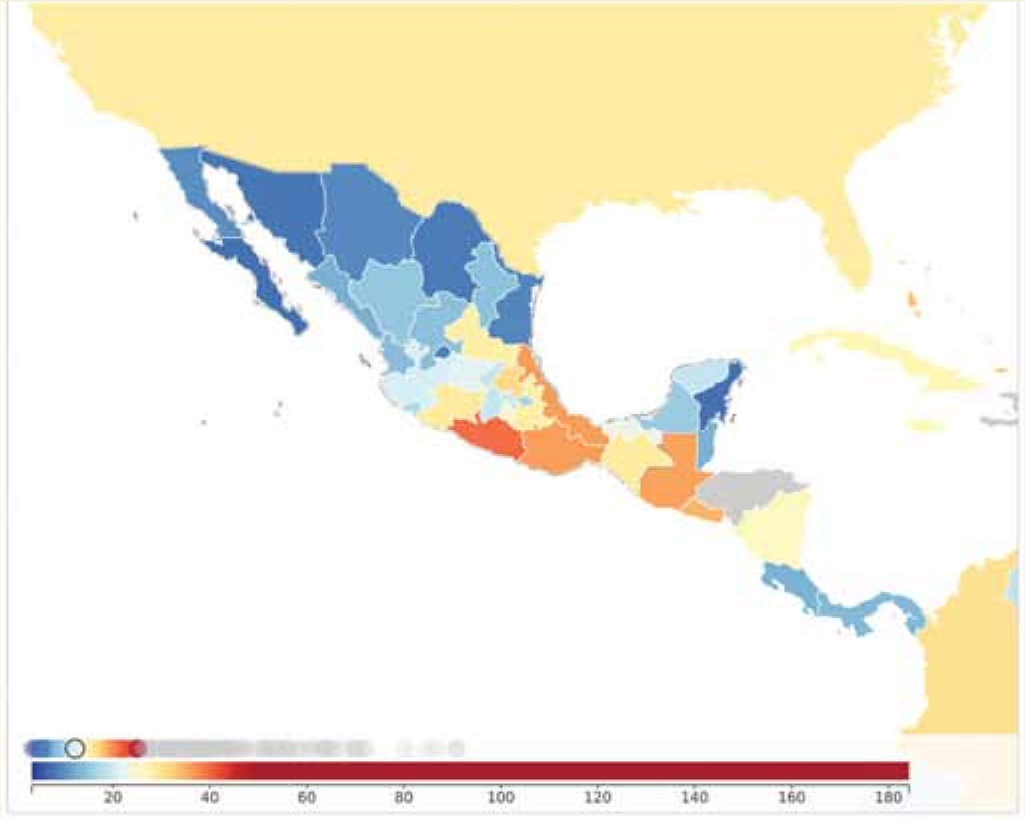
BOX 4.4 Mexico: Subnational Estimates Matter

GBD 2013, like GBD 2010, provides ambient exposure estimates at 0.1° × 0.1° resolution. Beginning with GBD 2013, health burdens attributable to $PM_{2.5}$ exposure are now available at the subnational level for China, the United Kingdom, and Mexico. GBD 2010 only provided health impacts at the national level, but health impacts can vary widely within countries. Although the attributable rates per 100,000 persons varied twofold in the United Kingdom, they varied 24-fold in China and 74-fold in Mexico. Rates were highest in the Districto Federal, which includes Mexico City—22.9 deaths per 100,000 persons—and the lowest in Yucatan—0.3 deaths per 100,000 (Cohen et al. n.d.).

Map B4.4.1 shows the variation in all deaths attributable to air pollution across Mexico. When household air pollution and ozone-related risks are added, the highest rates were found in Guerrero at 39.6 deaths per 100,000 persons and the lowest in Quintana Roo and Baja California Sur at 7.5 deaths per 100,000.

MAP B4.4.1 Deaths per 100,000 Persons Attributable to Air Pollution at the Provincial Level: Mexico, 2013

All causes attributable to air pollution:
both sexes, all ages, deaths per 100,000



Source: IHME, GBD 2013.

On the economics side, one of the principal sources of uncertainty in the estimates of lost welfare from air pollution is the value of statistical life. According to the analysis in this report, the uncertainty associated with the VSL far outweighs the uncertainty in the estimates of health impacts. Thus the lack of data on willingness to pay for reduced mortality risks in many countries, particularly in low- and middle-income ones, represents a critical knowledge gap in understanding the costs of pollution. On-the-ground empirical studies are the best way to fill this gap and will require facilitating greater comparability in measuring willingness to pay across diverse country settings.

One area that has continued to lag behind in the economics of environmental health is the monetary valuation of nonfatal outcomes—that is, morbidity. As already noted, the decision to exclude morbidity from the cost estimates in this report stemmed in large part from the lack of a standard, agreed-on framework for valuing these costs. Morbidity costs are more complicated to value and involve a plurality of health endpoints (lost work days, hospital admissions, expenditures for long-term medical treatment, etc.) suffered by a plurality of agents (the patient as well as the patient's friends, family, coworkers, etc.). These complications raise the possibility of double counting or inconsistency in cost estimation methods for different outcomes. Data may be missing on health expenditures and medical treatment costs for a wide array of countries. Differences among countries in health care systems—and how health care costs are allocated to patients, care providers, and the public treasury—are also a problem. Finally, there are fewer studies of willingness to pay to avoid different kinds of illnesses and other medical conditions associated with pollution exposure than there are of willingness to pay to avoid mortality risk, and so measuring disutility costs is more difficult. Recent work by the OECD attempting to establish a common set of endpoints and unit costs for morbidity is a welcome improvement (Hunt et al. 2016), but more work is still needed.

Greater action on air pollution will also require greater uptake by decision makers of the scientific and economic findings on the impacts of pollution. Part of improving uptake is communicating policy-relevant findings in a clear, effective, and credible way. This includes

- Being clear about exactly which costs are included, which are excluded, and why
- Following the existing guidance in countries, if any, about monetizing the costs of health impacts, including VSLs used by public agencies for previous analyses
- Making greater use of context- or country-specific research on the willingness to pay to reduce mortality risks among the population most affected, if available
- Being up-front about the sources and magnitude of uncertainty and showing how the range of cost estimates depends on methodological choices. Providing a single, deterministic cost value based on a core set of assumptions without testing the robustness of this result for alternate scenarios and assumptions is misleading and should be avoided.

Finally, although they are significant, the damages from air pollution estimated in this report represent only a partial accounting of the full costs of air pollution to the global economy. Beyond the costs of fatal illness, air pollution hurts the economy in many other ways that can have lasting effects on future productivity by, for example, degrading natural ecosystems. Further work is needed to value the full cost of air pollution.

Note

1. This assumes a social cost of $50 per ton of carbon (C). In the original study by Hill et al., the authors assume a higher cost of $125 per ton C emitted, in line with the carbon capture and storage (CCS) costs for an integrated gasification combined-cycle (IGCC) electricity generation plant. By comparison, the mean social cost of carbon in the literature reviewed by Hill et al. was $45 per ton C. As with elsewhere in this report, all monetary amounts have been converted into year 2011 U.S. dollars.

References

Apte, J. S., J. D. Marshall, A. J. Cohen, and M. Brauer. 2015. "Addressing Global Mortality from $PM_{2.5}$." *Environmental Science and Technology* 49: 8057–66.

Cohen, Aaron et al. n.d. "The Global Burden of Disease Attributable to Ambient Air Pollution: Estimates of Current Burden and 23-Year Trends from the GBD 2013 Study." In submission.

GBD MAPS Working Group. 2016. "Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China." Special Report 20, Health Effects Institute, Boston, MA, http://pubs.healtheffects.org/view.php?id=455.

Hill, Jason, Stephen Polasky, Erik Nelson, David Tilman, Hong Huo, Lindsay Ludwig, James Neumann, Haochi Zheng, and Diego Bonta. 2009. "Climate Change and Health Costs of Air Emissions from Biofuels and Gasoline." *Proceedings of the National Academy of Sciences* 106(6): 2077–82.

Hunt, Alistair, Julia Ferguson, Fintan Hurley, and Alison Searl. 2016. "Social Costs of Morbidity Impacts of Air Pollution." Environment Working Paper No. 99, Organisation for Economic Co-operation and Development, Paris. http://dx.doi.org/10.1787/5jm55j7cq0lv-en.

World Bank. 2003. "Kingdom of Morocco: Cost of Environmental Degradation." Sector Note No. 25992-MOR. Washington, D.C.

World Bank. 2016. "Royaume du Maroc: Evaluation du Cout de la Dégradation de l'Environnement." Rapport N° 105633-MA, Washington, D.C.

Appendix A Supplementary Materials on Health Impacts

Supplementary Tables and Figures for Global Burden of Disease 2013 (GBD 2013) Estimates of Exposure to Ambient and Household Air Pollution

TABLE A.1 Regions Included in GBD 2013 Ambient Air Pollution $PM_{2.5}$ Mapping Database

Region	No. of $PM_{2.5}$ measurements	No. estimated from $PM_{2.5}/PM_{10}$ ratio	% $PM_{2.5}$ vs. PM_{10}
Andean Latin America	4	12	25
Western Sub-Saharan Africa	5	0	100
Central Asia	6	10	38
North Africa and Middle East	8	110	7
High-income Asia Pacific	11	57	16
Central Latin America	13	23	36
Eastern Europe	14	5	74
Southern Sub-Saharan Africa	14	16	47
South Asia	18	185	9
Tropical Latin America	19	50	28
Southern Latin America	29	22	57
Australasia	44	26	63
Southeast Asia	62	55	53
East Asia	99	304	25
Central Europe	166	345	32
Western Europe	548	773	41
High-income North America	793	231	77

Source: IHME.

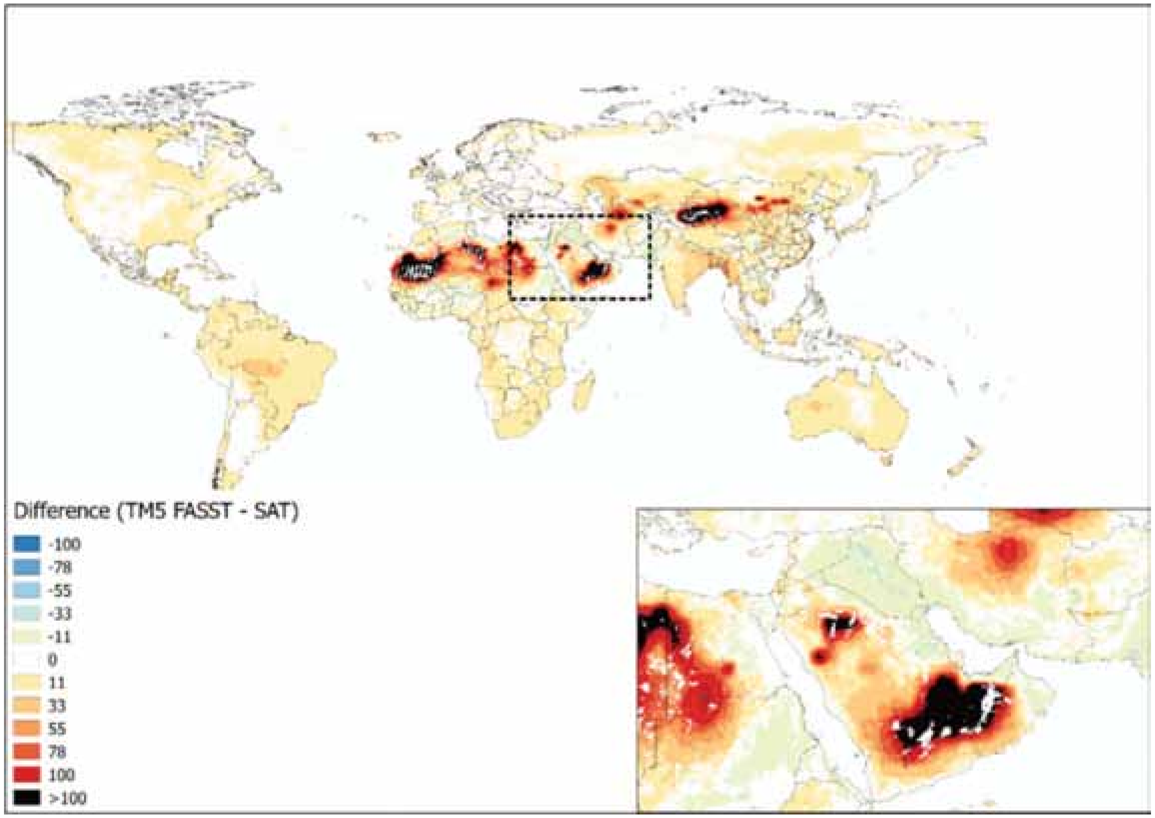
Note: Regions with no measurements are not included in the table: Caribbean, Central Sub-Saharan Africa, Eastern Sub-Saharan Africa, and Oceania.

TABLE A.2 Countries and Regions Included in GBD 2013 Household Air Pollution $PM_{2.5}$ Mapping Database

Region	Country
Andean Latin America	Peru
East Asia	China
Eastern Sub-Saharan Africa	Ethiopia
Central Latin America	Costa Rica, Guatemala, Honduras, Mexico, Nicaragua
South Asia	Bangladesh, India, Nepal, Pakistan
Southeast Asia	Indonesia
Southern Latin America	Chile
Western Sub-Saharan Africa	The Gambia, Ghana

Source: IHME.

MAP A.1 Differences in Grid-Cell Estimates of (2011) Annual Average $PM_{2.5}$ Concentrations from TM5-FASST and from Satellite-Based Estimates



Source: IHME.

Note: TM5-FASST-SAT = FAst Scenario Screening Tool.

Note: This map shows the differences in grid cell estimates of (2011) annual average $PM_{2.5}$ concentrations taken from TM5-FASST estimates and from satellite-based estimates. The inset figure zooms in on the Middle East. For most of the earth, differences were less than an absolute value of 11 µg/m^3, with TM5-FASST generally estimating higher concentrations. Larger differences were evident in areas with high contributions from windblown mineral dust. There, the TM5-FASST estimates were typically much higher than the satellite-based estimates.

Method for Estimating the Combined Effects of Exposure to Ambient and Household Air Pollution

Solid fuel is a major source of ambient air pollution (AAP) in many regions, including Sub-Saharan Africa, South Asia, and parts of Latin America (Chafe et al. 2014). There is a concern that the burden of exposure to AAP is already included in the burden of the other risk, household air pollution (HAP), and so the total risk might overestimate the total burden, or the burdens should be adjusted. Although AAP can penetrate a house and be a risk, in settings with indoor use of solid fuels AAP exposure is much lower compared with exposure from indoor emissions from solid fuel use. If exposure to AAP causes a relative risk (RR) of RR_{AP} and HAP a relative risk of RR_{HP}, assuming time-exclusive exposure, the assumptions of no interaction between risks and also no overhaul effect of the integrated exposure-response (IER) curve (where the IER curve flattens with increasing particulate matter ($PM_{2.5}$), indicating a smaller increase in RR in higher levels of $PM_{2.5}$) are plausible. Standard approaches can then be applied to calculate the population attributable fraction (PAF) of both risks:

$$RR_{total} = RR_{AP} * RR_{HP}, \tag{A.1}$$

$$1/RR_{total} = 1/RR_{AP} * RR_{HP} = 1/RR_{AP} * 1/RR_{HP}, \tag{A.2}$$

$$1 - PAF_{total} = (1 - PAF_{AP}) * (1 - PAF_{HP}), \tag{A.3}$$

$$PAF_{total} = 1 - (1 - PAF_{AP}) * (1 - PAF_{HP}). \tag{A.4}$$

The total PAF in the GBD was calculated for combinations of risks in this way.

The second concern of exposure to both risks is a shared outcome between risks, so the outcome should not be counted twice during aggregation. This issue is also handled by the formulas shown in (A.1)–(A.4).

For an individual with exposure to both risks, the PAF is the probability of an outcome caused by the risk, so the total probability of an outcome caused by either of the risks (assuming no interaction at the individual level) is expressed as

$$PAF_{total} = PAF_{AP} \cup PAF_{HP} = PAF_{AP} + PAF_{HP} - PAF_{AP} * PAF_{HP}, \tag{A.5}$$

$$PAF_{total} = 1 - (1 - PAF_{AP}) + PAF_{HP} - PAF_{AP} * PAF_{HP}, \tag{A.6}$$

$$PAF_{total} = 1 - (1 - PAF_{AP}) + PAF_{HP} * (1 - PAF_{AP}) * PAF_{HP}, \tag{A.7}$$

$$PAF_{total} = 1 - (1 - PAF_{AP}) * (1 - PAF_{HP}). \tag{A.8}$$

In this way, the multiplicative method of aggregating PAF for multiple risks can address the two concerns, taking into account the assumptions such as lack of interaction of the risks.

The total burden of AAP, HAP, and ozone for a common outcome was calculated by expanding equation (A.8) for n risks as

$$PAF_{total\ n\ risks} = 1 - \prod_{i=1}^{n} (1 - PAF_i). \tag{A.9}$$

For risks with distinct outcomes, the total burden is the sum of the burden from each risk because the outcomes were estimated independently and no overlap is assumed for causes in the GBD study (a categorical attribution approach in which each outcome, such as death, is attributed to only one cause, such as ischemic heart disease).

Reference

Chafe, Zoë A., Michael Brauer, Zbigniew Klimont, Rita Van Dingenen, Sumi Mehta, Shilpa Rao, Keywan Riahi et al. 2014. “Household Cooking with Solid Fuels Contributes to Ambient $PM_{2.5}$ Air Pollution and the Burden of Disease.” *Environmental Health Perspectives* 122 (12): 1314–20. doi:10.1289/ehp.1206340.

Appendix B Country Data

TABLE B.1 Mean Annual $PM_{2.5}$, Total Deaths from Pollution, Total Welfare Losses, and Total Forgone Labor Output, by Country

	Mean annual ambient $PM_{2.5}$				*Total welfare losses*		*Total forgone labor output*	
	(μg/m³)		*Total deaths from air pollution*		*(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)*		*(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)*	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Algeria	20.68	19.26	5,726	7,845	4,750 (1.78%)	8,855 (1.74%)	472 (0.18%)	331 (0.07%)
Armenia	20.52	17.75	3,926	2,401	965 (7.29%)	1,357 (6.07%)	156 (1.18%)	114 (0.51%)
Australia	7.68	5.93	2,067	777	6,466 (1.33%)	3,361 (0.34%)	179 (0.04%)	76 (0.01%)
Austria	25.78	14.85	5,523	3,573	18,492 (7.74%)	15,797 (4.23%)	313 (0.13%)	243 (0.07%)
Azerbaijan	26.42	20.80	8,699	5,994	5,748 (9.43%)	8,823 (5.65%)	756 (1.24%)	203 (0.13%)
Bahrain	39.54	43.63	173	188	643 (3.66%)	798 (1.41%)	59 (0.33%)	38 (0.07%)
Bangladesh	29.92	48.36	92,880	154,898	6,379 (4.66%)	27,452 (6.14%)	1,195 (0.87%)	2,579 (0.58%)
Belarus	25.23	13.60	9,890	9,816	6,142 (7.46%)	14,963 (9.25%)	239 (0.29%)	470 (0.29%)
Belgium	28.62	18.53	7,844	5,858	25,788 (8.51%)	24,190 (5.35%)	461 (0.15%)	404 (0.09%)
Benin	26.23	26.71	5,325	6,350	423 (5.80%)	679 (3.52%)	166 (2.28%)	168 (0.87%)
Bolivia	5.32	10.89	2,600	2,667	634 (2.49%)	1,179 (1.86%)	.. ..	.. ..

	Mean annual ambient $PM_{2.5}$				Total welfare losses		Total forgone labor output	
	(μg/m³)		Total deaths from air pollution		(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Bosnia and Herzegovina	21.59	13.63	2,211	1,882	.. ..	1,401 (3.90%)	.. ..	73 (0.20%)
Brazil	9.68	16.50	59,606	62,246	49,389 (3.19%)	82,612 (2.66%)	6,029 (0.39%)	4,927 (0.16%)
Brunei Darussalam	7.91	9.47	14	42	96 (0.49%)	274 (0.94%)	8 (0.04%)	14 (0.05%)
Bulgaria	28.25	15.93	10,523	7,297	7,716 (9.53%)	10,299 (8.85%)	252 (0.31%)	219 (0.19%)
Burkina Faso	29.26	29.23	9,125	10,410	364 (5.04%)	877 (3.36%)	151 (2.09%)	252 (0.96%)
Burundi	14.69	17.10	7,459	7,317	400 (6.79%)	252 (3.32%)	135 (2.30%)	71 (0.93%)
Cambodia	10.18	19.74	9,935	19,595	.. ..	3,637 (8.16%)	.. ..	294 (0.66%)
Cameroon	22.78	21.34	11,432	16,392	1,962 (5.87%)	2,785 (4.57%)	590 (1.77%)	573 (0.94%)
Canada	11.48	12.14	7,839	9,466	26,280 (3.03%)	40,460 (2.73%)	764 (0.09%)	1,016 (0.07%)
Central African Republic	19.82	19.33	4,270	5,161	199 (7.25%)	134 (4.96%)	22 (0.79%)	15 (0.56%)
Chad	30.06	30.71	6,432	11,067	369 (5.58%)	1,290 (4.89%)	143 (2.17%)	534 (2.03%)
Chile	17.23	18.38	4,756	4,309	6,031 (4.96%)	10,855 (2.83%)	248 (0.20%)	369 (0.10%)
China	39.30	54.36	1,518,942	1,625,164	126,592 (7.35%)	1,589,767 (9.92%)	12,558 (0.73%)	44,567 (0.28%)

table continues next page

Economy	Mean annual ambient $PM_{2.5}$ (µg/m³) 1990	Mean annual ambient $PM_{2.5}$ (µg/m³) 2013	Total deaths from air pollution 1990	Total deaths from air pollution 2013	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013
Colombia	9.15	12.63	10,635	14,636	6,068 (2.35%)	15,046 (2.58%)	961 (0.37%)	916 (0.16%)
Congo, Dem. Rep.	17.03	18.08	39,416	62,412	2,650 (5.98%)	1,964 (4.02%)	678 (1.53%)	509 (1.04%)
Congo, Rep.	16.76	13.81	2,874	3,393	1,065 (8.49%)	1,400 (5.54%)	130 (1.04%)	153 (0.60%)
Costa Rica	8.08	9.31	593	629	325 (1.44%)	748 (1.14%)	35 (0.16%)	43 (0.07%)
Côte d'Ivoire	19.50	20.30	12,265	16,264	2,524 (6.44%)	2,994 (4.72%)	848 (2.16%)	650 (1.02%)
Croatia	24.89	13.93	3,943	2,716	.. ..	6,392 (7.50%)	.. ..	125 (0.15%)
Cuba	9.49	10.97	3,838	3,052	4,486 (3.10%)	5,603 (2.47%)	178 (0.12%)	124 (0.05%)
Cyprus	20.24	16.46	312	303	843 (6.11%)	988 (3.81%)	21 (0.15%)	20 (0.08%)
Czech Republic	32.83	16.55	12,074	6,640	28,206 (13.76%)	20,521 (6.93%)	600 (0.29%)	339 (0.11%)
Denmark	18.30	11.41	3,880	1,632	13,702 (8.01%)	7,011 (2.94%)	339 (0.20%)	149 (0.06%)
Dominican Republic	11.62	12.49	2,310	3,828	869 (2.27%)	3,792 (3.09%)	169 (0.44%)	232 (0.19%)
Ecuador	8.01	13.91	2,206	3,156	1,246 (1.63%)	2,721 (1.64%)	100 (0.13%)	113 (0.07%)
Egypt, Arab Rep.	35.92	36.41	40,881	39,118	17,802 (5.25%)	31,545 (3.58%)	2,810 (0.83%)	2,367 (0.27%)
El Salvador	10.73	12.92	2,115	2,182	656 (2.76%)	1,306 (2.74%)	89 (0.37%)	85 (0.18%)

	Mean annual ambient $PM_{2.5}$ (μg/m³)		Total deaths from air pollution		Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Estonia	14.03	9.09	1,219	504	.. ..	1,451 (4.27%)	.. ..	33 (0.10%)
Ethiopia	15.99	17.60	64,137	71,018	1,943 (6.20%)	5,059 (4.02%)	547 (1.74%)	793 (0.63%)
Finland	9.56	7.03	1,798	653	5,628 (3.95%)	2,612 (1.24%)	133 (0.09%)	50 (0.02%)
France	22.76	14.02	27,464	21,138	87,942 (5.11%)	81,840 (3.33%)	1,750 (0.10%)	1,530 (0.06%)
Georgia	20.43	15.51	10,191	7,995	6,267 (16.28%)	4,127 (13.27%)	660 (1.72%)	222 (0.71%)
Germany	29.75	15.35	71,136	41,485	240,370 (9.62%)	180,099 (5.19%)	5,358 (0.21%)	3,178 (0.09%)
Ghana	22.53	26.54	8,454	17,524	935 (3.33%)	4,446 (4.43%)	207 (0.74%)	542 (0.54%)
Greece	23.04	15.37	7,742	8,320	19,040 (8.86%)	22,681 (8.55%)	460 (0.21%)	378 (0.14%)
Guatemala	11.35	12.40	5,355	5,546	1,940 (4.11%)	2,879 (2.64%)	445 (0.94%)	323 (0.30%)
Guinea	26.62	27.02	8,139	10,147	474 (6.98%)	634 (4.45%)	122 (1.79%)	132 (0.93%)
Haiti	12.03	13.35	7,129	7,878	.. ..	716 (4.21%)	.. ..	113 (0.66%)
Honduras	8.60	8.67	2,295	4,013	470 (2.99%)	1,269 (3.51%)	120 (0.76%)	171 (0.47%)
Hong Kong SAR, China	..	..	7,069	9,235	21,116 (13.72%)	46,387 (12.49%)	.. ..	.. ..

table continues next page

	Mean annual ambient $PM_{2.5}$				Total welfare losses		Total forgone labor output	
	(µg/m³)		Total deaths from air pollution		(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		(Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Hungary	34.09	15.76	12,163	7,435	.. ..	19,428 (8.60%)	.. ..	407 (0.18%)
Iceland	7.07	7.18	22	21	69 (0.95%)	89 (0.67%)	3 (0.04%)	3 (0.02%)
India	30.25	46.68	1,043,182	1,403,136	104,906 (6.80%)	505,103 (7.69%)	28,742 (1.86%)	55,390 (0.84%)
Indonesia	21.02	14.77	140,373	162,410	42,900 (5.28%)	125,119 (5.15%)	7,715 (0.95%)	11,899 (0.49%)
Iran, Islamic Rep.	28.64	31.89	17,035	21,680	13,940 (2.44%)	30,599 (2.48%)	2,533 (0.44%)	1,471 (0.12%)
Iraq	29.13	32.57	6,541	10,372	6,211 (3.09%)	13,658 (2.67%)	378 (0.19%)	1,135 (0.22%)
Ireland	12.12	7.93	1,665	558	4,116 (5.50%)	2,562 (1.21%)	122 (0.16%)	65 (0.03%)
Israel	27.17	25.78	2,030	2,201	4,255 (5.27%)	7,405 (2.94%)	191 (0.24%)	234 (0.09%)
Italy	30.61	18.34	37,544	29,482	124,524 (7.14%)	105,464 (5.18%)	3,256 (0.19%)	1,584 (0.08%)
Japan	19.42	16.03	44,843	64,428	144,083 (3.95%)	240,353 (5.30%)	5,406 (0.15%)	4,414 (0.10%)
Jordan	26.47	25.64	870	1,055	459 (2.05%)	990 (1.34%)	88 (0.39%)	93 (0.13%)
Kazakhstan	16.43	14.22	17,130	12,317	18,342 (8.81%)	26,084 (6.81%)	1,107 (0.53%)	886 (0.23%)
Kenya	10.09	11.43	13,690	18,237	1,956 (3.51%)	3,102 (2.58%)	746 (1.34%)	901 (0.75%)
Korea, Rep.	35.59	29.08	17,198	20,370	27,028 (5.22%)	70,948 (4.32%)	1,870 (0.36%)	2,482 (0.15%)

Economy	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 1990	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 2013	Total deaths from air pollution 1990	Total deaths from air pollution 2013	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013
Kuwait	36.50	49.13	329	547	.. ..	3,671 (1.38%)	.. ..	149 (0.06%)
Kyrgyz Republic	19.55	18.34	6,712	4,952	1,513 (9.92%)	981 (5.50%)	218 (1.43%)	83 (0.47%)
Lao PDR	14.64	27.48	5,211	7,251	471 (6.83%)	2,409 (7.63%)	87 (1.26%)	235 (0.74%)
Latvia	19.78	12.02	2,605	1,407	.. ..	3,482 (8.11%)	.. ..	76 (0.18%)
Lebanon	24.39	23.56	1,160	1,816	683 (3.27%)	2,660 (3.58%)	82 (0.39%)	148 (0.20%)
Liberia	14.20	22.72	2,291	2,985	98 (5.36%)	118 (3.38%)	32 (1.76%)	25 (0.72%)
Libya	30.25	27.82	1,178	1,956	.. ..	3,506 (2.86%)	.. ..	314 (0.26%)
Lithuania	23.26	13.75	3,187	2,270	.. ..	6,343 (8.64%)	.. ..	113 (0.15%)
Luxembourg	27.18	14.80	305	188	1,646 (7.64%)	1,468 (3.01%)	41 (0.19%)	27 (0.06%)
Macao SAR, China	..	..	369	359	1,420 (10.68%)	3,915 (5.06%)	.. ..	.. ..
Macedonia, FYR	25.70	17.00	1,073	1,294	822 (4.28%)	1,272 (5.18%)	96 (0.50%)	57 (0.23%)
Madagascar	5.81	6.20	12,764	18,718	1,187 (6.19%)	1,377 (4.40%)	224 (1.17%)	228 (0.73%)
Malawi	7.20	9.13	7,576	10,184	184 (3.60%)	373 (3.02%)	56 (1.10%)	87 (0.70%)

table continues next page

	Mean annual ambient $PM_{2.5}$ (μg/m³)		Total deaths from air pollution		Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Malaysia	18.49	14.40	4,452	7,612	3,763 (1.98%)	16,940 (2.45%)	436 (0.23%)	1,263 (0.18%)
Mali	33.65	35.93	12,028	14,057	679 (7.30%)	1,125 (4.63%)	215 (2.31%)	319 (1.31%)
Malta	21.96	14.09	175	159	355 (6.03%)	501 (4.10%)	9 (0.15%)	9 (0.08%)
Mauritania	76.51	70.13	1,592	2,559	277 (4.89%)	601 (4.32%)	144 (2.53%)	153 (1.10%)
Mexico	14.51	11.93	20,502	26,484	21,559 (2.01%)	37,709 (1.89%)	2,520 (0.23%)	1,815 (0.09%)
Moldova	32.11	17.06	4,026	2,908	1,903 (8.00%)	904 (5.59%)	112 (0.47%)	47 (0.29%)
Mongolia	11.14	8.33	2,690	2,424	966 (8.64%)	2,121 (6.90%)	125 (1.12%)	144 (0.47%)
Morocco	18.25	17.36	6,398	7,034	1,673 (1.69%)	3,723 (1.55%)	418 (0.42%)	435 (0.18%)
Mozambique	5.66	7.33	12,421	12,525	194 (3.86%)	659 (2.41%)	72 (1.44%)	131 (0.48%)
Nepal	29.68	46.09	16,436	22,038	1,033 (4.60%)	2,833 (4.68%)	195 (0.87%)	287 (0.47%)
Netherlands	28.15	16.84	9,581	7,428	33,067 (6.84%)	33,632 (4.41%)	792 (0.16%)	781 (0.10%)
New Zealand	8.49	8.64	730	728	1,988 (2.49%)	2,576 (1.74%)	48 (0.06%)	68 (0.05%)
Nicaragua	6.93	6.98	1,527	1,578	291 (2.32%)	490 (1.82%)	57 (0.45%)	32 (0.12%)
Niger	36.60	38.12	12,446	13,609	559 (7.80%)	583 (3.65%)	301 (4.20%)	220 (1.37%)

Economy	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 1990	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 2013	Total deaths from air pollution 1990	Total deaths from air pollution 2013	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013
Nigeria	30.97	29.51	77,585	97,248	14,844 (5.12%)	37,609 (3.99%)	3,400 (1.17%)	7,338 (0.78%)
Norway	9.41	6.04	1,456	337	6,349 (3.46%)	1,990 (0.62%)	159 (0.09%)	37 (0.01%)
Oman	27.25	30.35	418	655	1,541 (2.43%)	2,619 (1.73%)	138 (0.22%)	106 (0.07%)
Pakistan	36.55	46.18	103,111	156,191	19,935 (6.06%)	47,713 (5.88%)	4,713 (1.43%)	6,582 (0.81%)
Panama	6.18	6.81	535	524	304 (1.64%)	912 (1.26%)	28 (0.15%)	32 (0.04%)
Papua New Guinea	6.56	5.90	3,753	5,256	335 (5.02%)	822 (4.39%)	30 (0.45%)	51 (0.27%)
Paraguay	8.61	14.13	1,526	3,010	667 (2.62%)	1,909 (3.59%)	92 (0.36%)	168 (0.31%)
Peru	7.84	12.90	8,362	9,374	3,105 (2.70%)	8,723 (2.52%)	537 (0.47%)	329 (0.10%)
Philippines	9.09	8.60	38,676	57,403	10,356 (4.17%)	26,758 (4.31%)	2,171 (0.87%)	2,774 (0.45%)
Poland	30.93	16.98	36,290	23,295	49,555 (12.82%)	61,626 (6.99%)	2,158 (0.56%)	1,362 (0.15%)
Portugal	14.79	9.90	5,492	3,282	13,058 (6.45%)	9,459 (3.51%)	439 (0.22%)	240 (0.09%)
Qatar	34.46	38.36	62	110	.. ..	1,178 (0.42%)	.. ..	44 (0.02%)
Romania	31.15	16.82	24,080	15,880	22,069 (8.51%)	26,658 (7.21%)	1,184 (0.46%)	792 (0.21%)

table continues next page

	Mean annual ambient $PM_{2.5}$ (μg/m³)		Total deaths from air pollution		Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
Economy	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Russian Federation	19.66	14.23	113,744	104,379	260,457 (9.08%)	279,801 (8.28%)	6,808 (0.24%)	8,604 (0.25%)
Rwanda	17.32	17.02	9,734	6,410	405 (6.57%)	534 (3.18%)	138 (2.24%)	117 (0.69%)
Saudi Arabia	49.71	54.12	3,945	6,285	14,625 (2.53%)	30,246 (2.05%)	1,390 (0.24%)	1,792 (0.12%)
Senegal	40.92	41.21	5,941	7,747	634 (4.53%)	1,005 (3.22%)	127 (0.91%)	120 (0.39%)
Serbia	26.46	15.78	5,535	4,627	.. ..	5,029 (5.45%)	.. ..	234 (0.25%)
Sierra Leone	23.69	23.92	5,129	5,284	380 (7.03%)	553 (4.88%)	143 (2.65%)	139 (1.23%)
Singapore	49.80	16.68	1,634	1,601	5,918 (5.66%)	11,153 (2.66%)	186 (0.18%)	298 (0.07%)
Slovak Republic	31.38	15.94	5,173	3,383	.. ..	9,764 (6.98%)	.. ..	173 (0.12%)
Slovenia	25.45	13.62	1,221	847	.. ..	2,557 (4.54%)	.. ..	44 (0.08%)
South Africa	11.68	14.33	20,398	19,802	17,067 (4.68%)	20,656 (3.12%)	3,072 (0.84%)	1,349 (0.20%)
South Sudan	14.96	16.33	7,369	9,966	.. ..	1,115 (5.02%)	.. ..	.. ..
Spain	17.82	11.65	18,484	14,689	50,472 (5.39%)	49,331 (3.39%)	1,550 (0.17%)	1,051 (0.07%)
Sri Lanka	11.45	17.15	11,239	19,693	2,714 (4.34%)	16,336 (7.75%)	567 (0.91%)	1,480 (0.70%)
Sudan	24.43	26.59	21,196	26,785	2,103 (4.65%)	6,824 (4.61%)	879 (1.95%)	690 (0.47%)
Sweden	11.66	7.32	4,220	1,329	14,052 (5.31%)	5,809 (1.39%)	256 (0.10%)	98 (0.02%)

Economy	Mean annual ambient $PM_{2.5}$ (μg/m³)		Total deaths from air pollution		Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)		Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent)	
	1990	**2013**	**1990**	**2013**	**1990**	**2013**	**1990**	**2013**
Switzerland	22.92	17.60	3,927	3,016	18,165 (5.80%)	15,910 (3.58%)	606 (0.19%)	357 (0.08%)
Taiwan, China	18.95	19.53	12,915	16,739	24,980 (7.88%)	71,685 (7.26%)	.. ..	.. ..
Tajikistan	20.85	19.62	7,683	5,230	1,829 (9.50%)	779 (3.90%)	212 (1.10%)	64 (0.32%)
Tanzania	7.35	9.16	18,097	25,370	1,456 (4.00%)	3,552 (3.12%)	395 (1.08%)	483 (0.42%)
Thailand	17.24	22.36	31,173	48,819	15,317 (4.07%)	63,369 (6.29%)	1,155 (0.31%)	2,361 (0.23%)
Togo	25.39	25.40	3,597	4,123	261 (5.10%)	292 (3.18%)	133 (2.60%)	111 (1.21%)
Tunisia	19.96	16.35	2,690	3,792	1,093 (2.36%)	3,308 (2.83%)	205 (0.44%)	206 (0.18%)
Turkey	19.88	17.21	33,264	28,881	28,823 (5.00%)	48,625 (3.49%)	3,110 (0.54%)	2,011 (0.14%)
Turkmenistan	44.24	41.68	3,008	3,730	1,943 (6.34%)	4,307 (6.06%)	301 (0.98%)	330 (0.46%)
Uganda	15.09	17.63	15,789	20,658	587 (4.36%)	1,927 (3.16%)	141 (1.05%)	382 (0.63%)
Ukraine	29.24	15.09	62,160	49,078	52,774 (9.69%)	31,631 (8.34%)	1,805 (0.33%)	1,328 (0.35%)
United Arab Emirates	35.68	40.95	394	900	3,741 (1.80%)	5,233 (0.93%)	515 (0.25%)	528 (0.09%)
United Kingdom	19.74	10.81	45,453	19,803	131,836 (8.86%)	76,694 (3.21%)	3,035 (0.20%)	1,569 (0.07%)

table continues next page

Economy	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 1990	Mean annual ambient $PM_{2.5}$ ($\mu g/m^3$) 2013	Total deaths from air pollution 1990	Total deaths from air pollution 2013	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total welfare losses (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 1990	Total forgone labor output (Million 2011 U.S. dollars, PPP-adjusted; % GDP equivalent) 2013
United States	16.42	10.75	127,240	91,045	490,053 (5.30%)	454,675 (2.80%)	17,942 (0.19%)	18,127 (0.11%)
Uruguay	6.06	6.68	310	358	414 (1.35%)	818 (1.24%)	13 (0.04%)	17 (0.03%)
Uzbekistan	27.27	25.53	17,975	19,085	3,440 (5.53%)	6,662 (4.40%)	534 (0.86%)	562 (0.37%)
Venezuela, RB	10.16	13.43	2,517	5,738	4,563 (1.59%)	12,229 (2.28%)	381 (0.13%)	555 (0.10%)
Vietnam	19.09	25.47	57,774	66,314	4,758 (4.80%)	23,832 (5.18%)	442 (0.45%)	1,557 (0.34%)
West Bank and Gaza	26.64	26.36	577	1,006	.. ..	309 (1.65%)	.. ..	.. ..
Yemen, Rep.	32.50	36.19	10,490	13,442	2,298 (5.66%)	3,229 (3.45%)	.. ..	.. ..
Zambia	9.38	11.78	5,843	8,549	811 (4.29%)	2,027 (3.67%)	205 (1.09%)	315 (0.57%)
Zimbabwe	7.36	9.07	4,776	7,391	734 (2.77%)	699 (2.78%)	196 (0.74%)	138 (0.55%)

Sources: World Bank and IHME.

Note: Estimates of mean annual exposure to ambient $PM_{2.5}$ are generated by combining data from atmospheric chemistry transport models, satellite observations of aerosols in the atmosphere, and ground-level monitoring of particles. Uncertainty in the data on exposure to ambient air pollution is greatest for areas with high concentrations of windblown mineral dust, emissions sources that are highly variable or at too small of scale to be captured by the satellite observations and models, high levels of pollution during wintertime and nighttime when satellite retrievals are limited, or rugged local topography. Total deaths from air pollution represent the combined health impacts of ambient $PM_{2.5}$, household air pollution, and ambient ozone pollution. Given exposure, uncertainty in the estimates of health impacts may arise from the integrated exposure-response functions (IERs) used to describe the health risks associated with exposure to different levels of pollution. The IERs draw from studies of the relative risks of ambient air pollution, second-hard smoking, active smoking, and household air pollution. Total welfare losses are estimated using a value of statistical life (VSL), which is an aggregate measure of people's willingness to pay (WTP) to reduce fatality risks. Country-specific VSLs are derived from empirical studies done in high-income countries, which are then adjusted to account for cross-country differences in per capita income. The absence of WTP studies in many low- and middle-income countries contributes to the uncertainty of the VSL-based estimates of welfare losses, as does a lack of consensus about the elasticity of the VSL with respect to income. Forgone labor output is a measure of lost labor earnings due to premature mortality. The principal sources of uncertainty in the estimates of forgone labor output include assumptions about future rates of income growth and the discount rate; ".." = data not available.

WORLD BANK GROUP