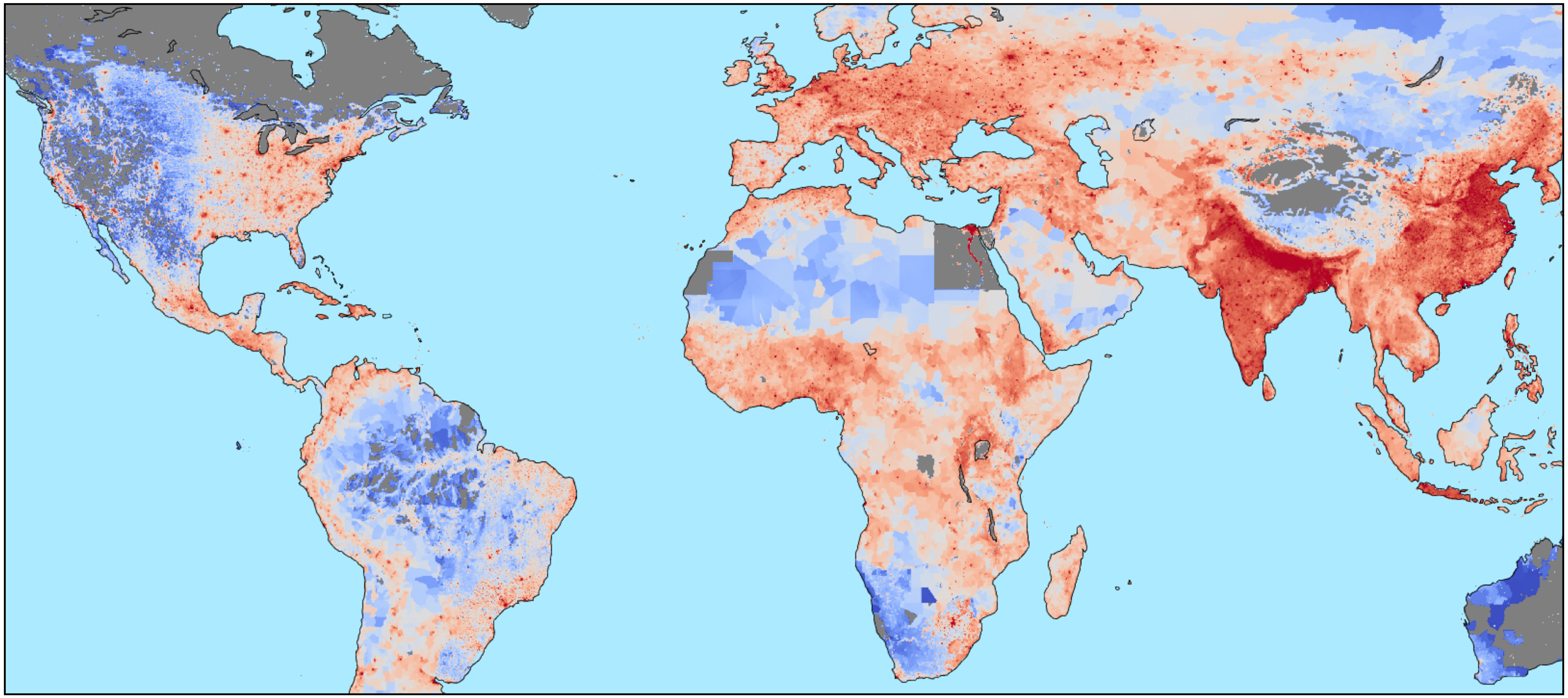
Addressing Global Mortality from $PM_{2.5}$



Joshua Apte, PhD
JSApte@utexas.edu

Assistant Professor, University of Texas at Austin
Department of Civil, Architectural
and Environmental Engineering

Co-authors: Michael Brauer, Aaron Cohen, Majid Ezzati,
Julian Marshall, C Arden Pope III

Goals for lecture

How do we assess the global health impacts of outdoor air pollution?

How do we know what we know?

What is the latest state of knowledge?

Evidence on $PM_{2.5}$ and health

The New England
Journal of Medicine

Volume 329 DECEMBER 9, 1993 Number 24

Harvard 6 Cities Study

AN ASSOCIATION BETWEEN AIR POLLUTION AND MORTALITY IN SIX U.S. CITIES

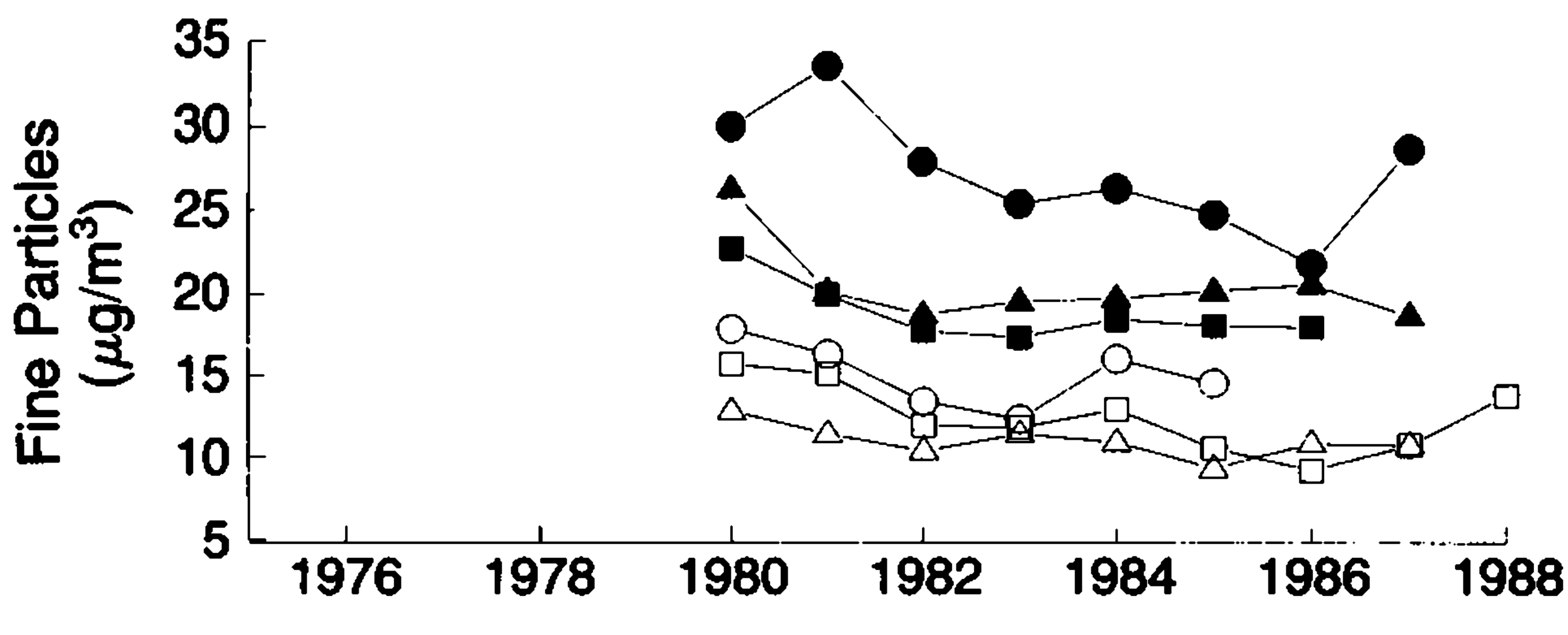
Douglas W. Dockery, Sc.D., C. Arden Pope III, Ph.D., Xiping Xu, M.D., Ph.D.,
John D. Spengler, Ph.D., James H. Ware, Ph.D., Martha E. Fay, M.P.H.,
Benjamin G. Ferris, Jr., M.D., and Frank E. Speizer, M.D.

Abstract *Background.* Recent studies have reported associations between particulate air pollution and daily mortality rates. Population-based, cross-sectional studies of metropolitan areas in the United States have also found associations between particulate air pollution and annual mortality rates, but these studies have been criticized, in part because they did not directly control for cigarette smoking and other health risks.

Methods. In this prospective cohort study, we estimated the effects of air pollution on mortality, while controlling for individual risk factors. Survival analysis, including Cox proportional-hazards regression modeling, was conducted with data from a 14-to-16-year mortality follow-up of 8111 adults in six U.S. cities.

Results. Mortality rates were most strongly associated with cigarette smoking. After adjusting for smoking and other risk factors, we observed statistically significant and robust associations between air pollution and mortality. The adjusted mortality-rate ratio for the most polluted of the cities as compared with the least polluted was 1.26 (95 percent confidence interval, 1.08 to 1.47). Air pollution was positively associated with death from lung cancer and cardiopulmonary disease but not with death from other causes considered together. Mortality was most strongly associated with air pollution with fine particulates, including sulfates.

Conclusions. Although the effects of other, unmeasured risk factors cannot be excluded with certainty, these results suggest that fine-particulate air pollution, or a more complex pollution mixture associated with fine particulate matter, contributes to excess mortality in certain U.S. cities. (N Engl J Med 1993;329:1753-9.)



Evidence on $PM_{2.5}$ and health

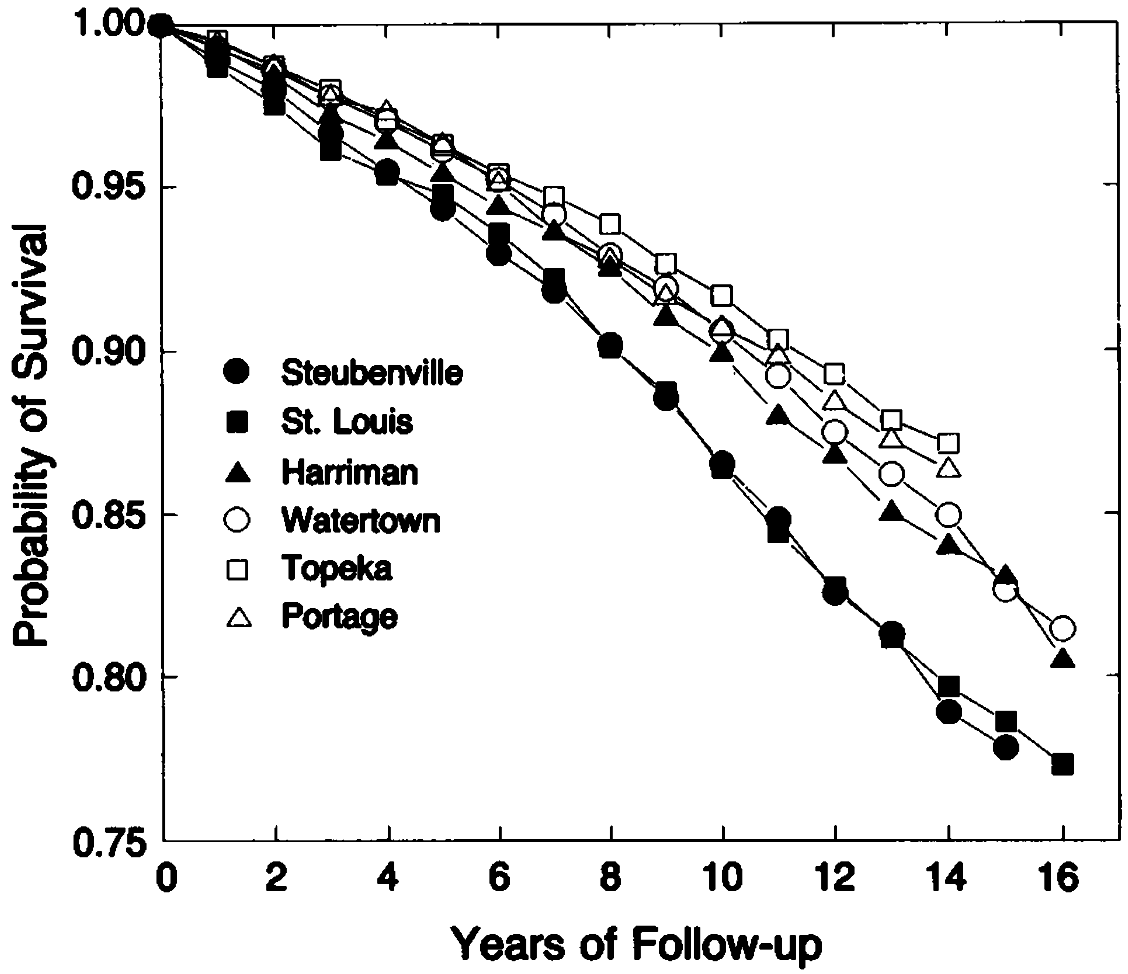
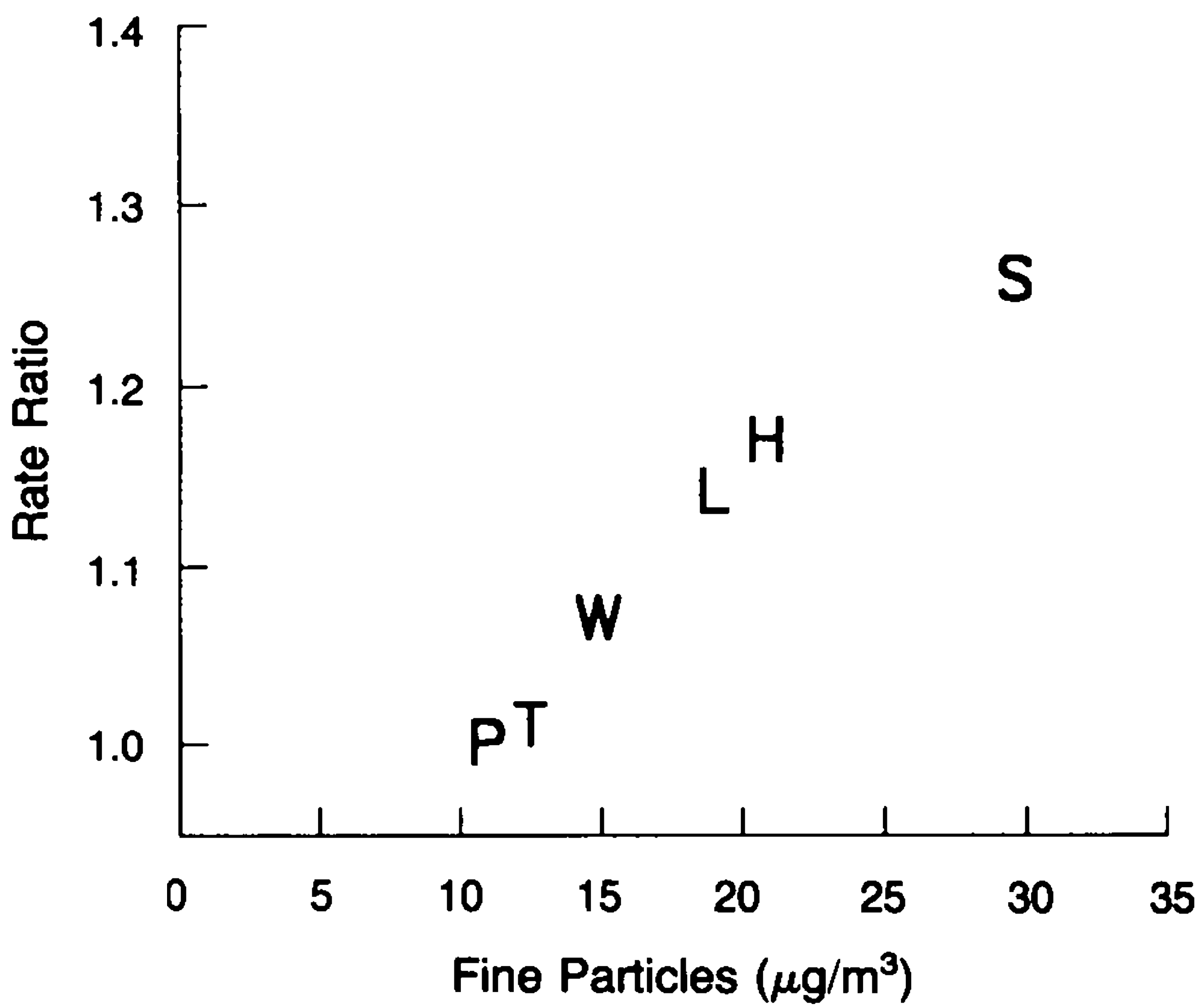


Figure 2. Crude Probability of Survival in the Six Cities, According to Years of Follow-up.

Harvard 6 Cities Study



Agenda: **the contours of the challenge**

Exposure: What populations breathe unhealthy air?

Consequence: How is the burden of disease from air pollution distributed across the global population?

Control: Where do we reduce $PM_{2.5}$? By how much?

Problem: “Air Inequality”

We don’t all breathe the same air.

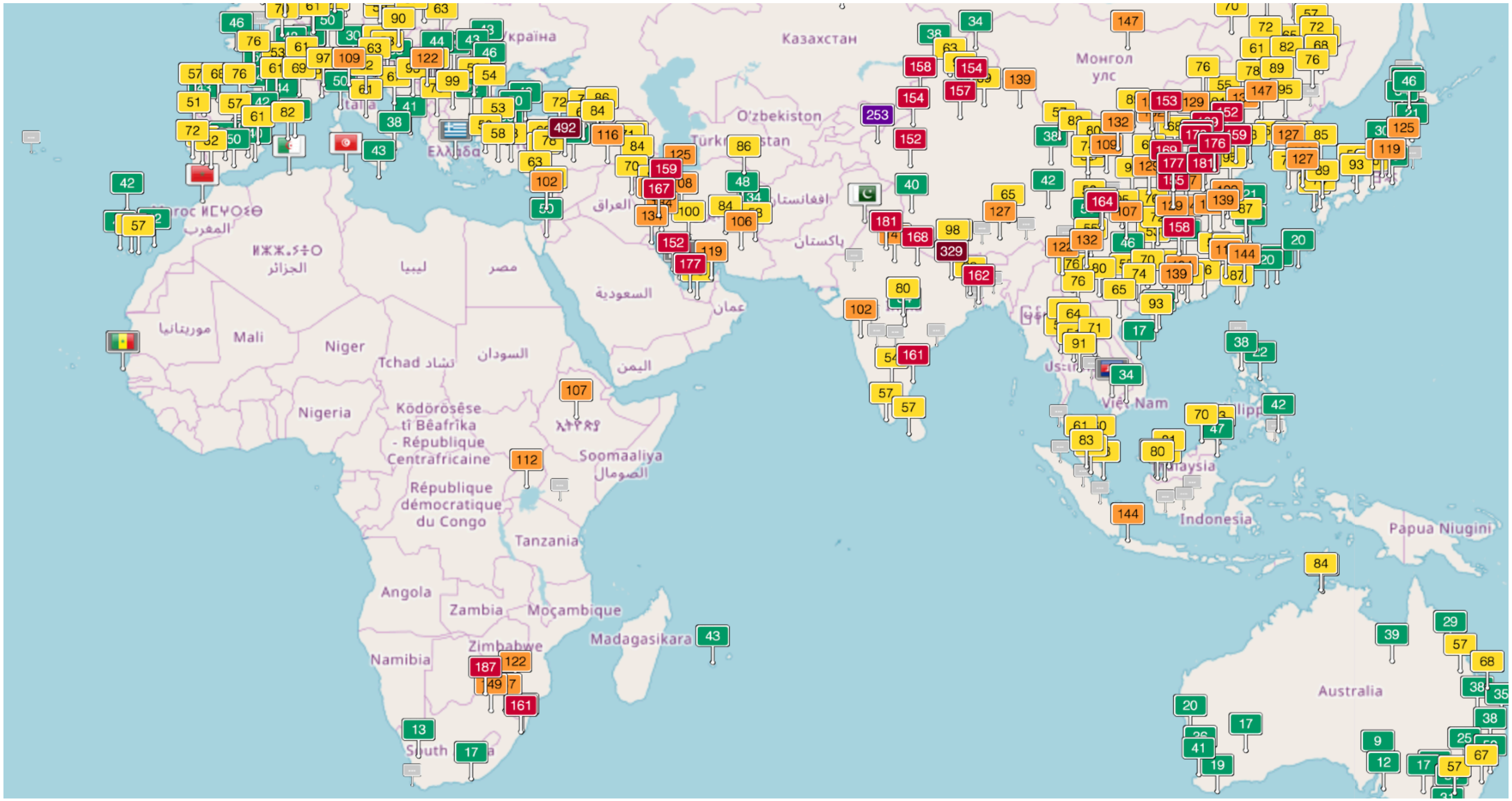
- Some parts of the world much more polluted than others.

- Knowledge base on health effects highly unequal.
  - Thousands of studies in high-income countries.
  - Few long-term studies in lower-income countries.
  - Health data generally incomplete in lower-income countries.

- How do we assess global impacts of air pollution?

Ground based air monitoring is limited

Public continuous $PM_{2.5}$ data in Africa, Asia



All of Africa	**India**	**China**
<< 50 sites	< 200 sites	~3000-5000 sites

Source: AQICN.org global database of web-connected regulatory $PM_{2.5}$ monitors

Two recent papers

Environmental Science & Technology

Article

pubs.acs.org/est

Addressing Global Mortality from Ambient $PM_{2.5}$

Joshua S. Apte,*[,†] Julian D. Marshall,[‡] Aaron J. Cohen,[§] and Michael Brauer[∥]

[†]Department of Civil, Architectural and Environmental Engineering, University of Texas, 301 E. Dean Keeton St., Stop C1700, Austin, Texas 78712, United States

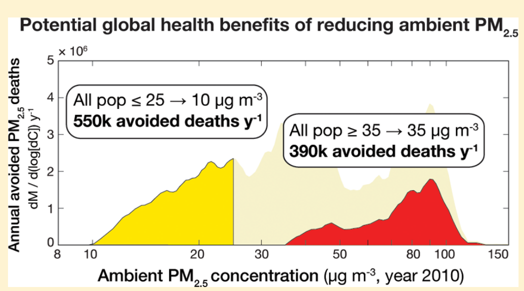
[‡]Department of Civil, Environmental, and Geo- Engineering, University of Minnesota, 500 Pillsbury Drive SE, Minneapolis, Minnesota 55455, United States

[§]Health Effects Institute, Suite 500, 101 Federal Street, Boston, Massachusetts 02110, United States

[∥]School of Population and Public Health, The University of British Columbia, 2206 East Mall, Vancouver, British Columbia V6T1Z3, Canada

Supporting Information

ABSTRACT: Ambient fine particulate matter ($PM_{2.5}$) has a large and well-documented global burden of disease. Our analysis uses high-resolution (10 km, global-coverage) concentration data and cause-specific integrated exposure-response (IER) functions developed for the Global Burden of Disease 2010 to assess how regional and global improvements in ambient air quality could reduce attributable mortality from $PM_{2.5}$. Overall, an aggressive global program of $PM_{2.5}$ mitigation in line with WHO interim guidelines could avoid 750 000 (23%) of the 3.2 million deaths per year currently (ca. 2010) attributable to ambient $PM_{2.5}$. Modest improvements in $PM_{2.5}$ in relatively clean regions (North America, Europe) would result in surprisingly large avoided mortality, owing to demographic factors and the nonlinear concentration-response relationship that describes the risk of particulate matter in relation to several important causes of death. In contrast, major improvements in air quality would be required to substantially reduce mortality from $PM_{2.5}$ in more polluted regions, such as China and India. Moreover, forecasted demographic and epidemiological transitions in India and China imply that to keep $PM_{2.5}$-attributable mortality rates (deaths per 100 000 people per year) constant, average $PM_{2.5}$ levels would need to decline by ∼20−30% over the next 15 years merely to offset increases in $PM_{2.5}$-attributable mortality from aging populations. An effective program to deliver clean air to the world's most polluted regions could avoid several hundred thousand premature deaths each year.



1. INTRODUCTION

Ambient fine particulate matter air pollution ($PM_{2.5}$) is a major risk factor for ill health and death.[1−6] Epidemiological studies have established robust causal associations between long-term exposure to $PM_{2.5}$ and premature mortality from endpoints such as heart disease, stroke, respiratory diseases, and lung cancer, thereby substantially reducing life expectancy.[1−8] In the Global Burden of Disease 2010 comparative risk assessment (GBD),[9] ∼3.2 million worldwide year-2010 deaths were attributed to ambient air pollution from $PM_{2.5}$, ranking as the sixth largest overall risk factor for global premature mortality. For comparison, the burden of disease from ambient $PM_{2.5}$ is larger than other well-recognized global health threats, such as malaria and HIV-AIDS combined (year-2010 deaths: 1.2 million and 1.5 million, respectively).[9,10]

Here we explore the magnitude of ambient concentration reductions that would be required to substantially decrease mortality from $PM_{2.5}$. By analyzing high-resolution (∼10 km) estimates of mortality attributable to ambient $PM_{2.5}$, we address the following questions that define the overall scale of the $PM_{2.5}$ mitigation challenge: How many people die from $PM_{2.5}$ exposure, where, and under what conditions? How many premature deaths could be avoided by achieving concentration X in region Y? By how much would ambient $PM_{2.5}$ concentrations need to be reduced in order to cut attributable mortality by a given amount? To address these questions, we employ methods and data developed for the GBD study that enable consistent assessment of risks from $PM_{2.5}$ in all regions of the world.

2. MATERIALS AND METHODS

We develop spatially resolved analyses at 0.1° grid resolution (∼10 km at midlatitudes) for (i) premature mortality attributable to ambient $PM_{2.5}$ exposures and (ii) reductions in attributable mortality that could be achieved with reductions in ambient $PM_{2.5}$ concentration. We selected the year 2010 as the most recent period of analysis that was publicly available in the

Received: March 10, 2015
Revised: May 21, 2015
Accepted: May 22, 2015
Published: June 16, 2015

Environmental Science & Technology LETTERS

Letter

Cite This: Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

pubs.acs.org/journal/estlcu

Ambient $PM_{2.5}$ Reduces Global and Regional Life Expectancy

Joshua S. Apte,*[,†] Michael Brauer,[‡] Aaron J. Cohen,[§] Majid Ezzati,[∥] and C. Arden Pope, III[⊥]

[†]Department of Civil, Architectural and Environmental Engineering, The University of Texas, 301 East Dean Keeton Street, Stop C1700, Austin, Texas 78712, United States

[‡]School of Population and Public Health, The University of British Columbia, 2206 East Mall, Vancouver, British Columbia V6T1Z3, Canada

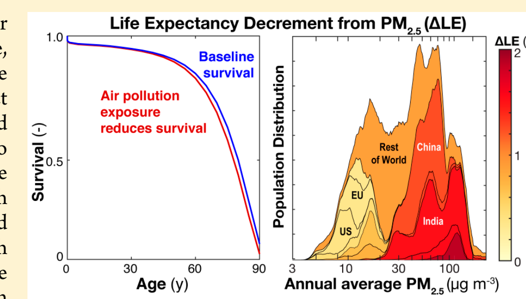
[§]Health Effects Institute, 75 Federal Street, Suite 1400, Boston, Massachusetts 02110, United States

[∥]MRC-PHE Centre for Environment and Health, Imperial College London, London W2 1PG, United Kingdom

[⊥]Department of Economics, Brigham Young University, Provo, Utah 84602, United States

Supporting Information

ABSTRACT: Exposure to ambient fine particulate matter ($PM_{2.5}$) air pollution is a major risk for premature death. Here, we systematically quantify the global impact of $PM_{2.5}$ on life expectancy. Using data from the Global Burden of Disease project and actuarial standard life table methods, we estimate global and national decrements in life expectancy that can be attributed to ambient $PM_{2.5}$ for 185 countries. In 2016, $PM_{2.5}$ exposure reduced average global life expectancy at birth by ∼1 year with reductions of ∼1.2−1.9 years in polluted countries of Asia and Africa. If $PM_{2.5}$ in all countries met the World Health Organization Air Quality Guideline (10 $\mu g\ m^{-3}$), we estimate life expectancy could increase by a population-weighted median of 0.6 year (interquartile range of 0.2−1.0 year), a benefit of a magnitude similar to that of eradicating lung and breast cancer. Because background disease rates modulate the effect of air pollution on life expectancy, high age-specific rates of cardiovascular disease in many polluted low- and middle-income countries amplify the impact of $PM_{2.5}$ on survival. Our analysis adds to prior research by illustrating how mortality from air pollution substantially reduces human longevity.



1. INTRODUCTION

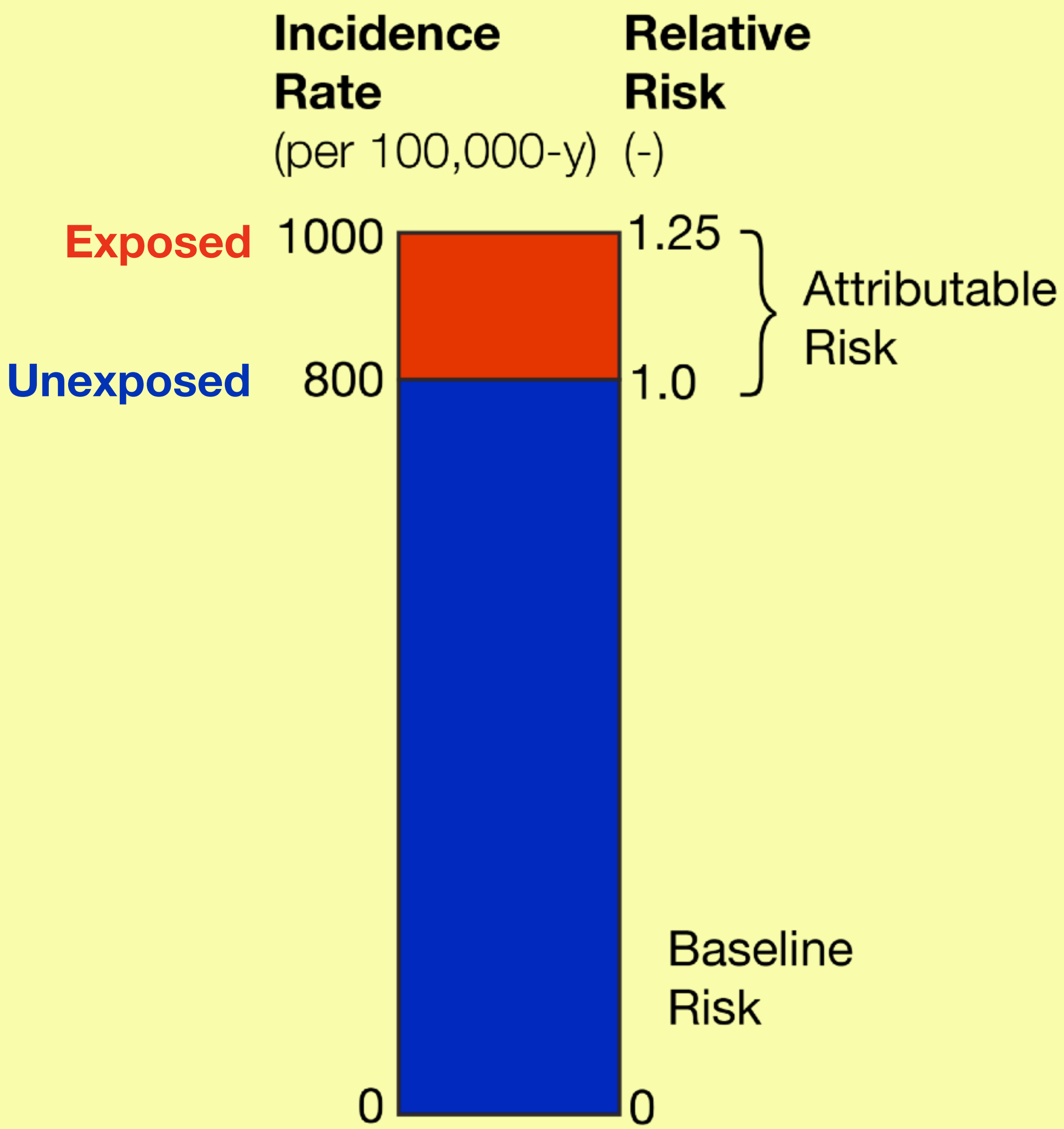
Exposure to ambient fine particulate matter ($PM_{2.5}$) air pollution causes important adverse health outcomes that result in premature death, including ischemic heart disease, strokes, lung cancer, chronic obstructive pulmonary disease, and respiratory infections. Despite the well-documented global burden of disease from $PM_{2.5}$[1−3] (∼4.1 million deaths in 2016),[4] prior research has not systematically explored how global variations in $PM_{2.5}$ exposure affect life expectancy. Here, we use an actuarial modeling approach and data from the Global Burden of Disease (GBD) 2016 study to address the question: "How much does $PM_{2.5}$ air pollution shorten human life expectancy around the world?"

How air pollution affects human longevity has been a topic of continued interest for analysts at the science−policy interface of air pollution over at least the past five decades.[5−13] For the lay public and policymakers alike, health risks that substantially reduce survival time are more compelling than those that merely hasten death by a few days. In the 1980s and 1990s, much research investigated the so-called "harvesting" hypothesis that air pollution might most strongly influence the mortality of those who were already at risk of imminent death.[8−10] By the mid-2000s, the weight of evidence from several large, carefully designed long-term cohort studies suggested a substantial decrement in survival associated with air pollution mortality, because the risks of long-term $PM_{2.5}$ exposure were approximately an order of magnitude greater than risks from day-to-day air quality variation.[9,14] Baccarelli and colleagues demonstrated that the U.S. communities with the most exceptional aging (e.g., populations of >85 or >100) had low ambient air pollution in addition to low rates of smoking, poverty, and obesity, providing suggestive evidence of the benefits of clean air for longevity.[15] Several groups have estimated the relationship between changes in air pollution and changes in life expectancy.[11−13,16,17] For example, Correia et al.[12] used a differences-in-differences approach to model the relationship between $PM_{2.5}$ and life expectancy for 545 U.S. counties and determined that decadal-scale improvements in regional air quality resulted in ∼0.35 year of increased life expectancy at birth per 10 $\mu g\ m^{-3}$ change in $PM_{2.5}$. Similarly, Ebenstein et al. used a regression discontinuity approach to

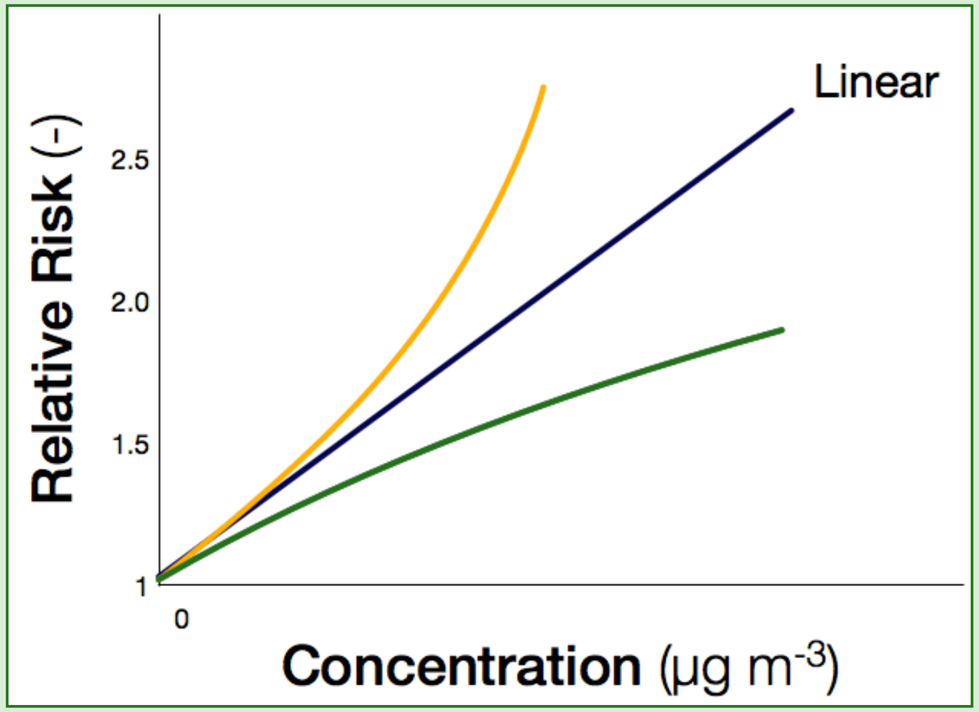
Received: July 13, 2018
Revised: August 10, 2018
Accepted: August 14, 2018

Some terminology

Incidence & Risk



Dose-Response



Other terms
"concentration-response" (CRF)
"exposure-response" (ERF)

Assumption: RR → 1 as exposure → 0

Burden of Disease calculations

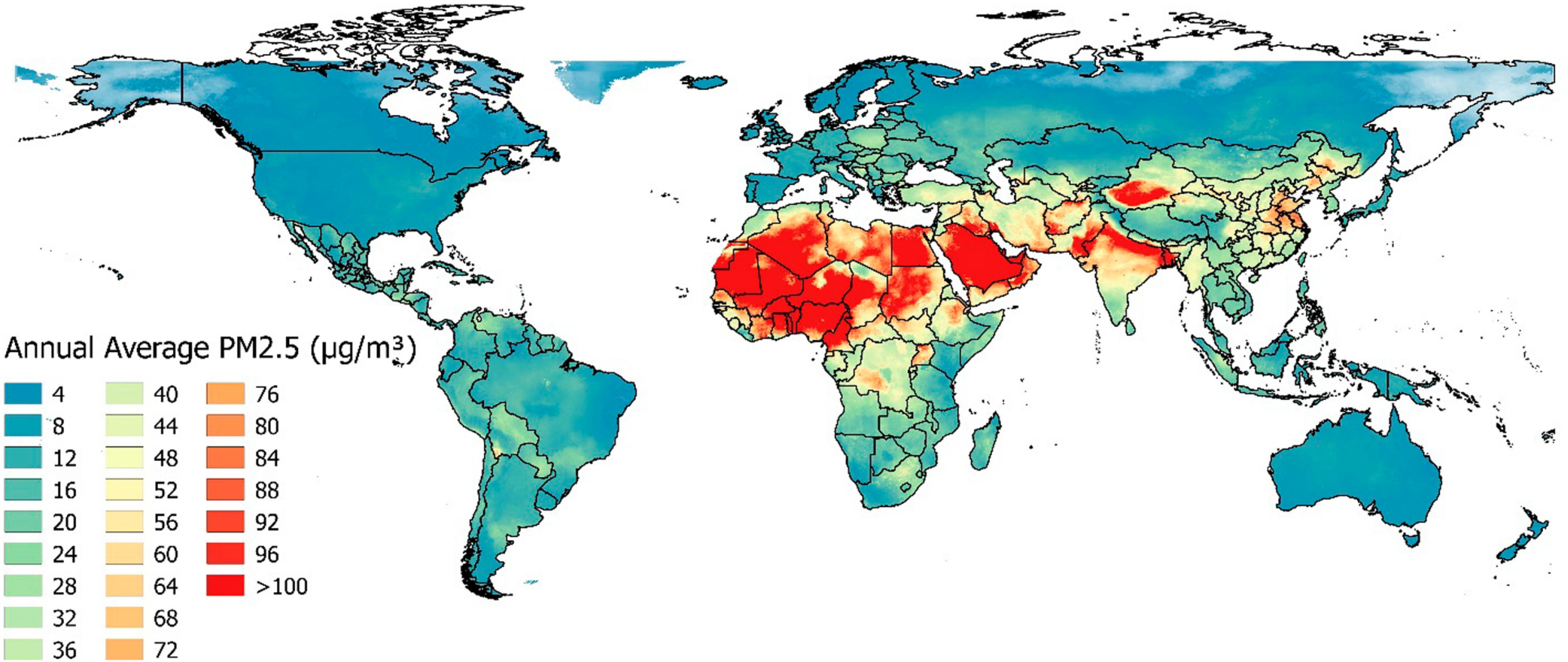
- Population **P**
- Baseline disease rates **I**
- Population attributable fraction **PAF**
- Relative risks at each level of exposure **RR**

$$AB = P \times I \times PAF$$

$$PAF = \frac{RR - 1}{RR}$$

Satellite remote sensing: ambient $PM_{2.5}$

Gridded estimates of ground-based $PM_{2.5}$ at ~10×10 km scale

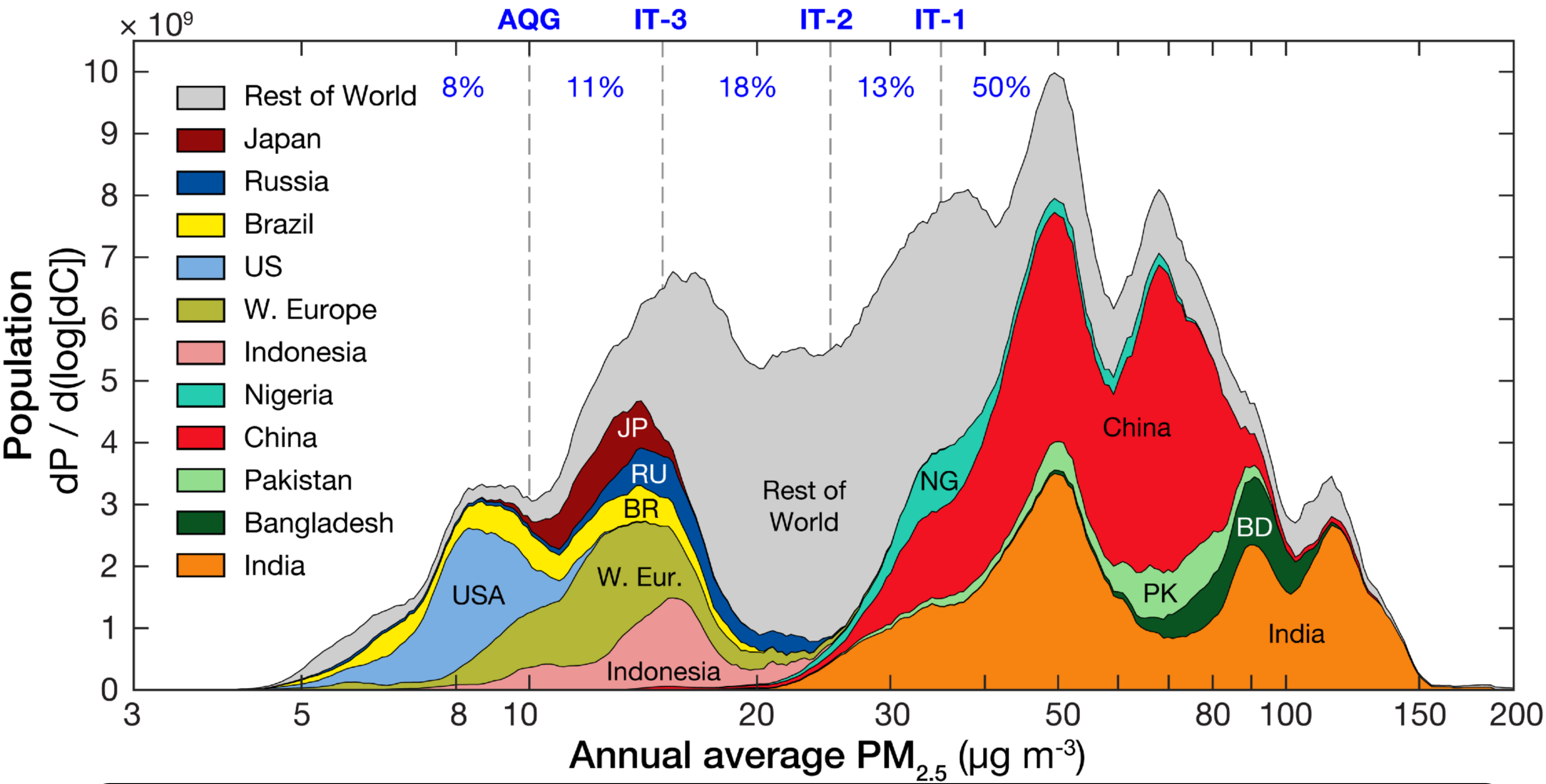


Issues:

- estimating ground-level concentrations
- optical-to-mass relationship
- subgrid variation

Graphic: Shaddick et al., *Environ. Sci. Technol.* 2018, 52, 9069–9078

Population-concentration distribution

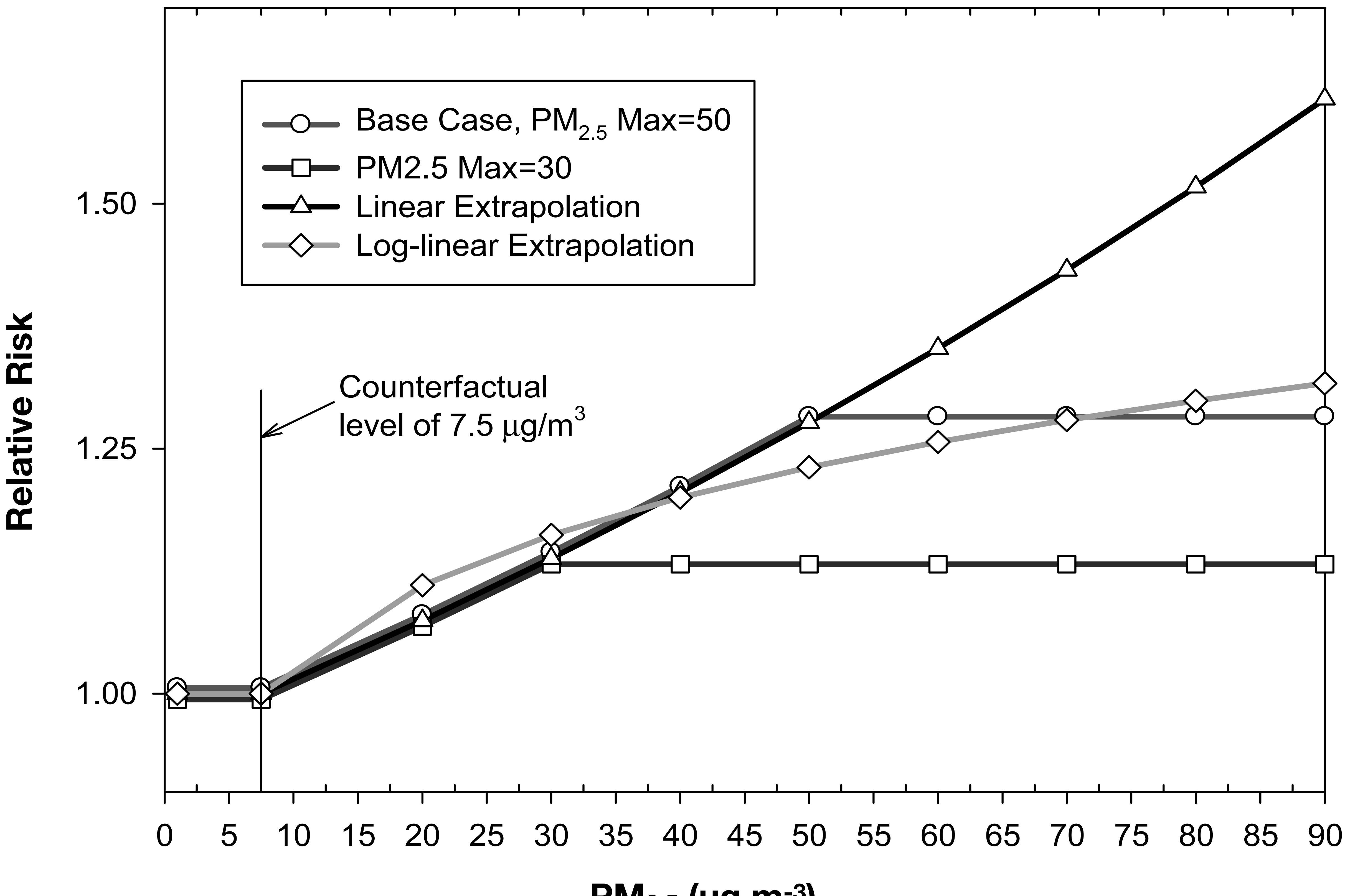


8% of global population meets WHO 10 μg m^{-3} air quality guideline

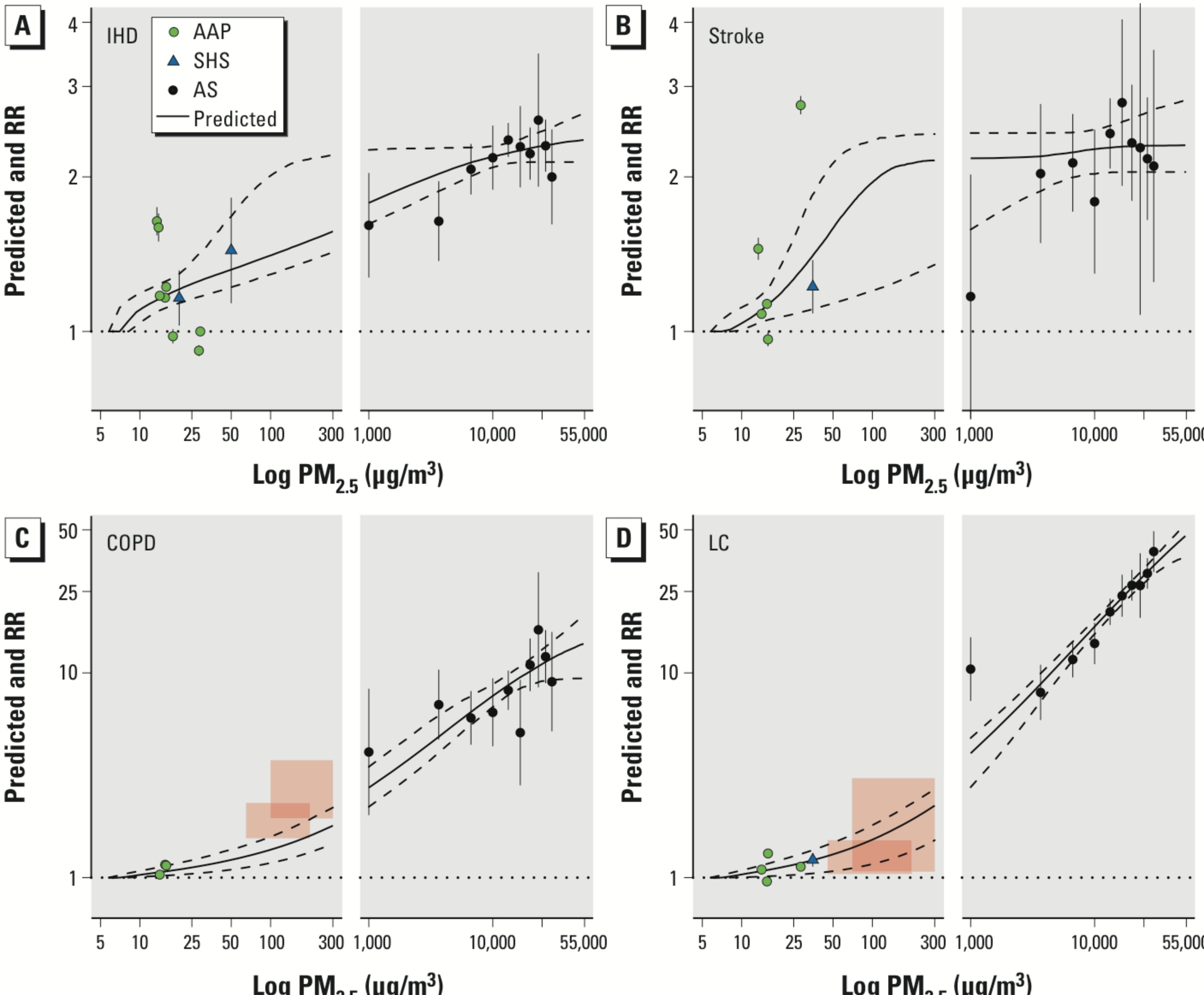
50% of world population lives in areas > 35 μg m^{-3}

Apte et al. *in prep*

$PM_{2.5}$ and relative risk - an early guess

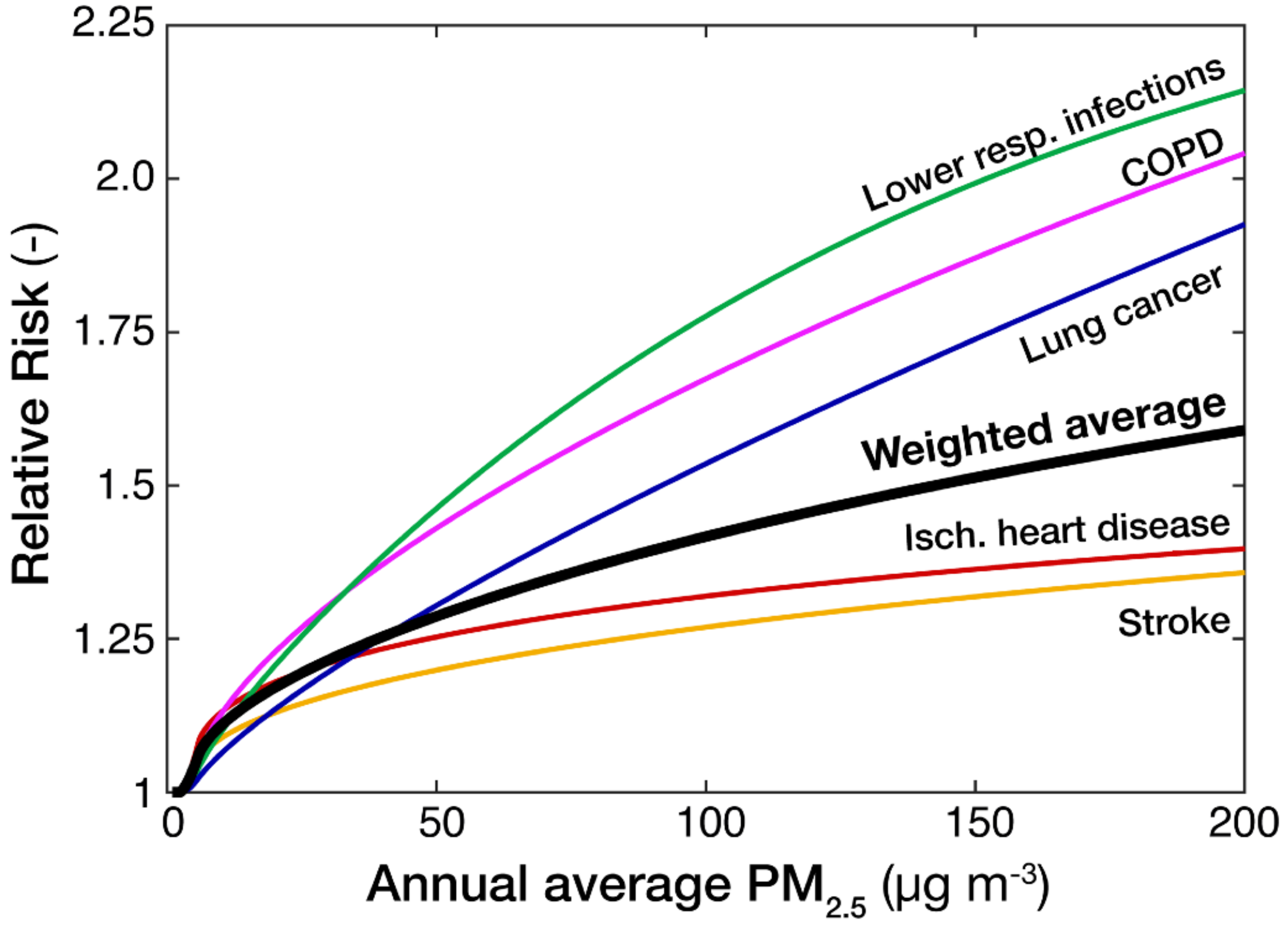


Exposure-response function synthesis



Graphic: Burnett et al., *Environ. Health Persp.* 2014, 122, 397–403

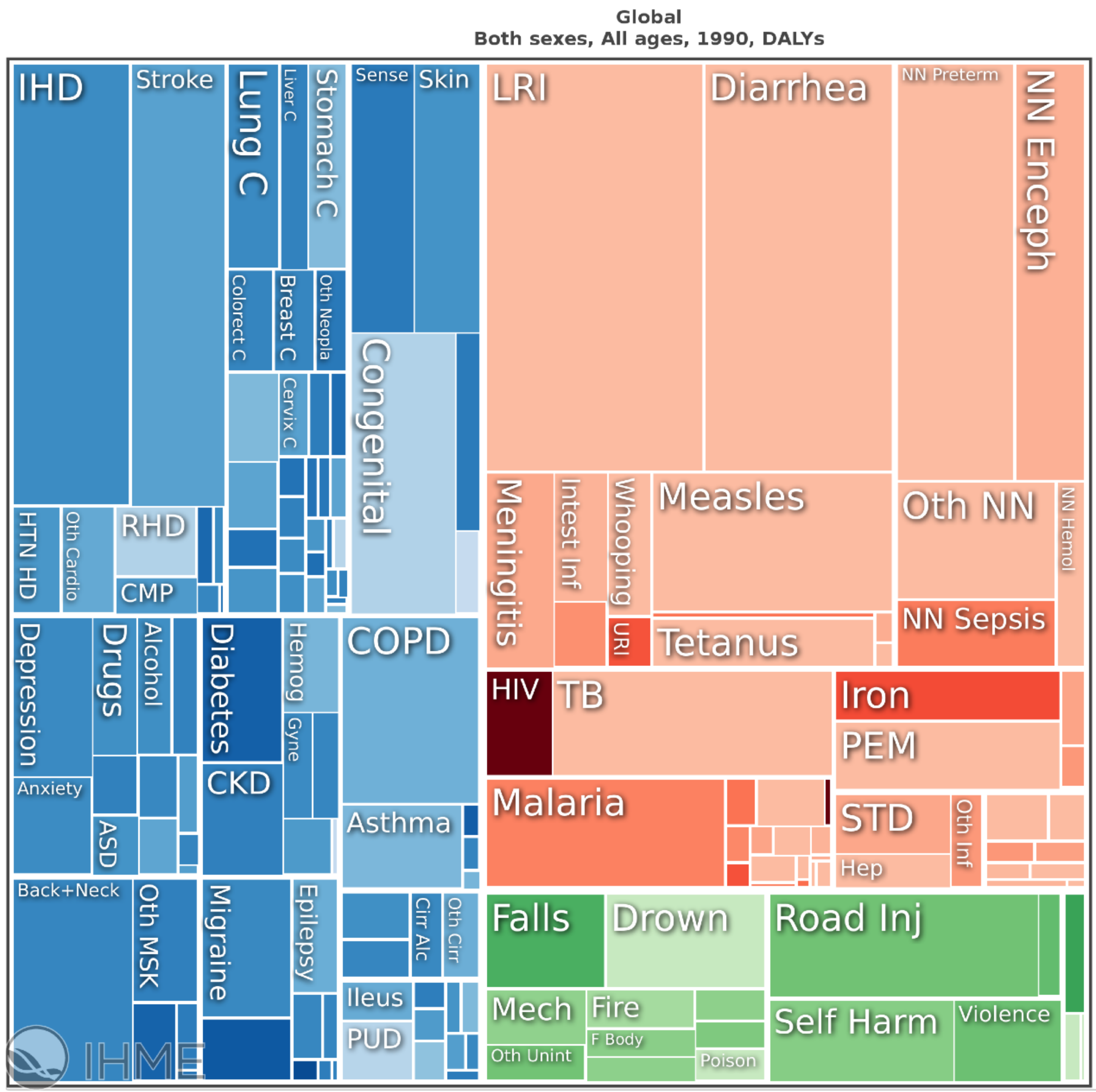
Integrated Exposure-Response Function



Relative risks rise rapidly, then flatten.

Apte et al. *in prep*

What causes ill-health and death? 1990



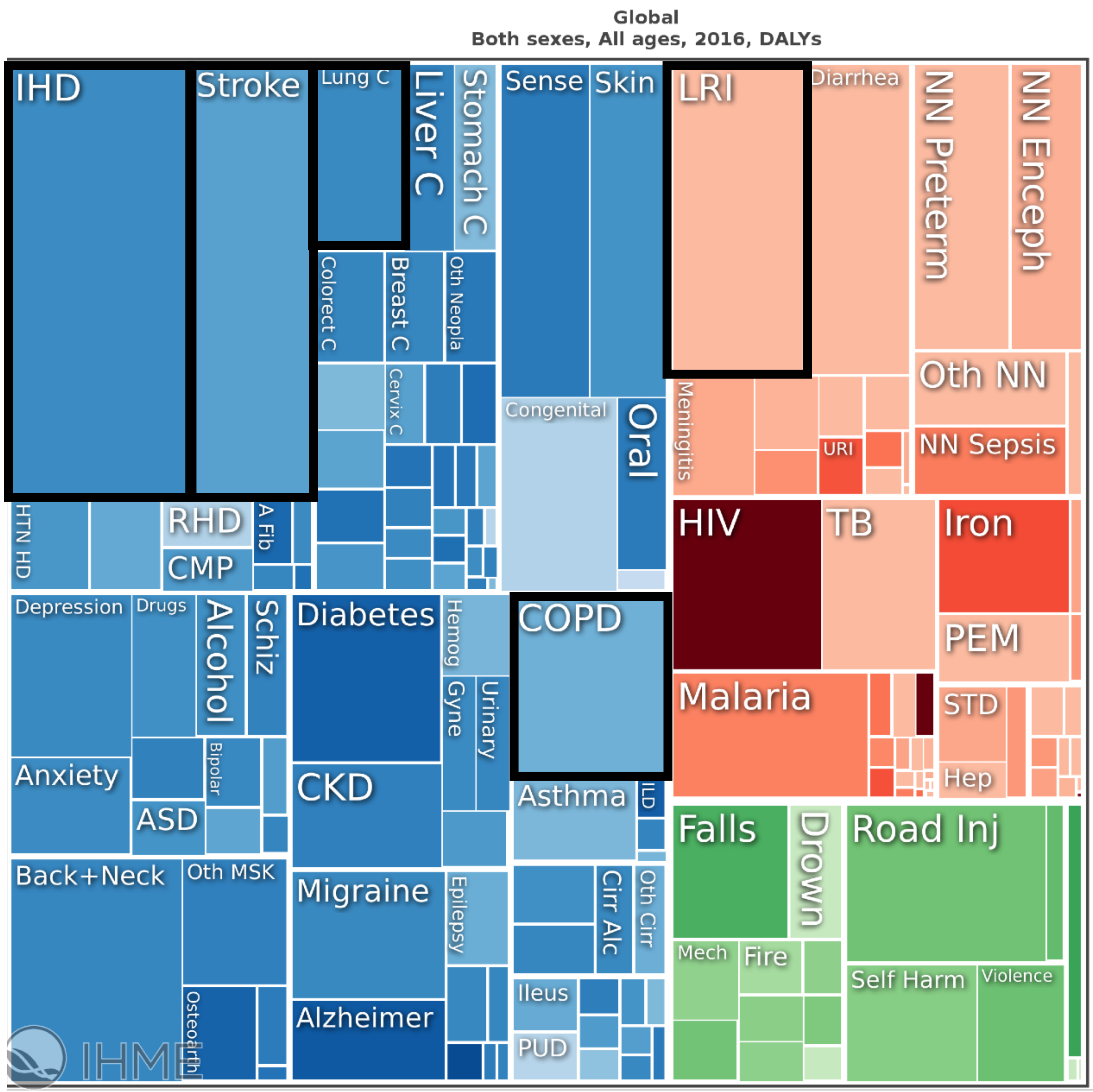
DALY*: metric of lost life

- Communicable
- Non-Communicable
- Accidental

*DALY = disability-adjusted life year

Data: Global Burden of Disease, IHME 2017, http://ihmeuw.org/478y

What causes ill-health and death? 2016



DALY: metric of lost life

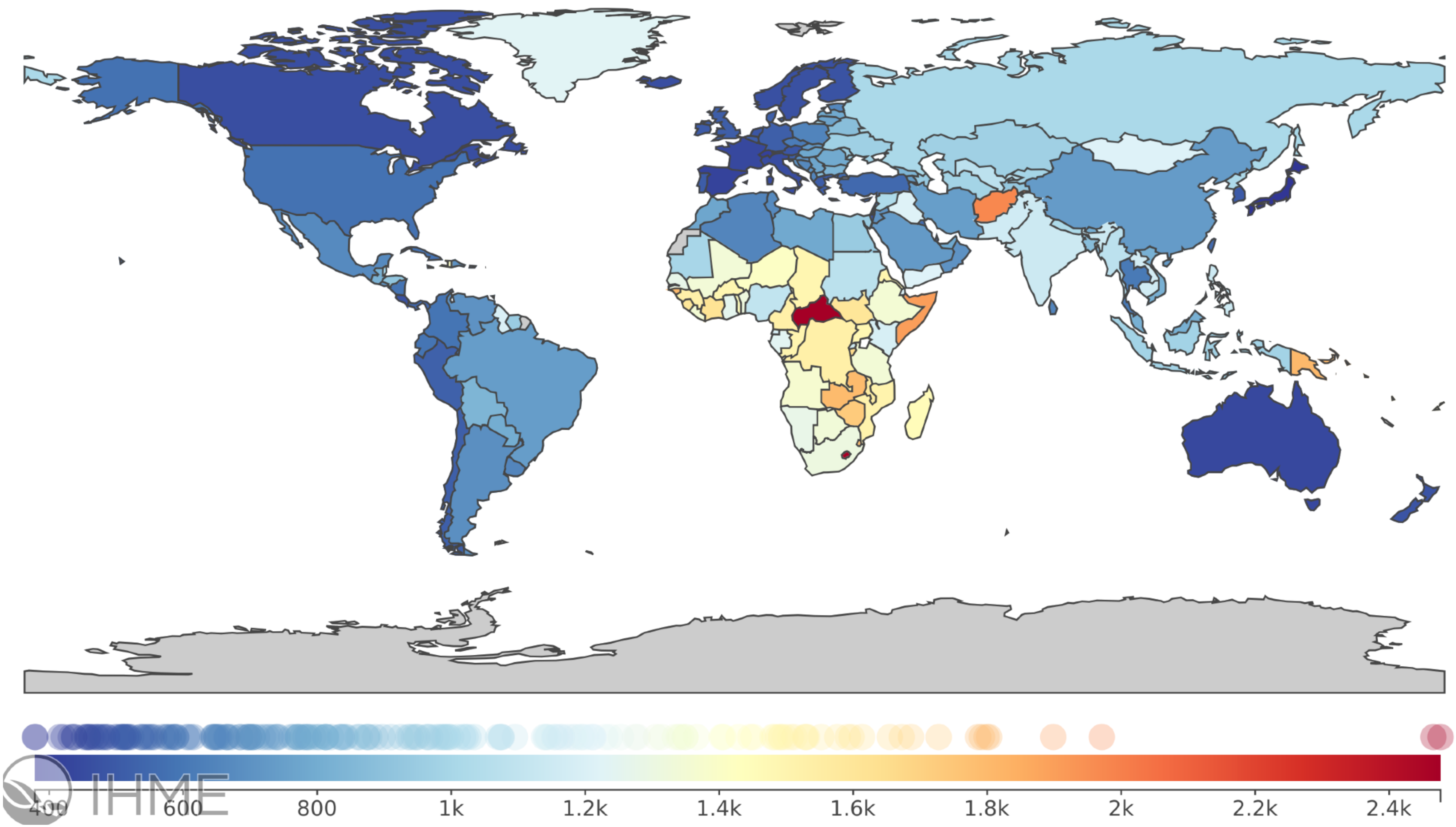
Risk Transition:
↓ Communicable
↑ Chronic

Fastest changes are in developing world

Diseases of poverty → diseases of plenty

Data: Global Burden of Disease, IHME 2017, http://ihmeuw.org/478y

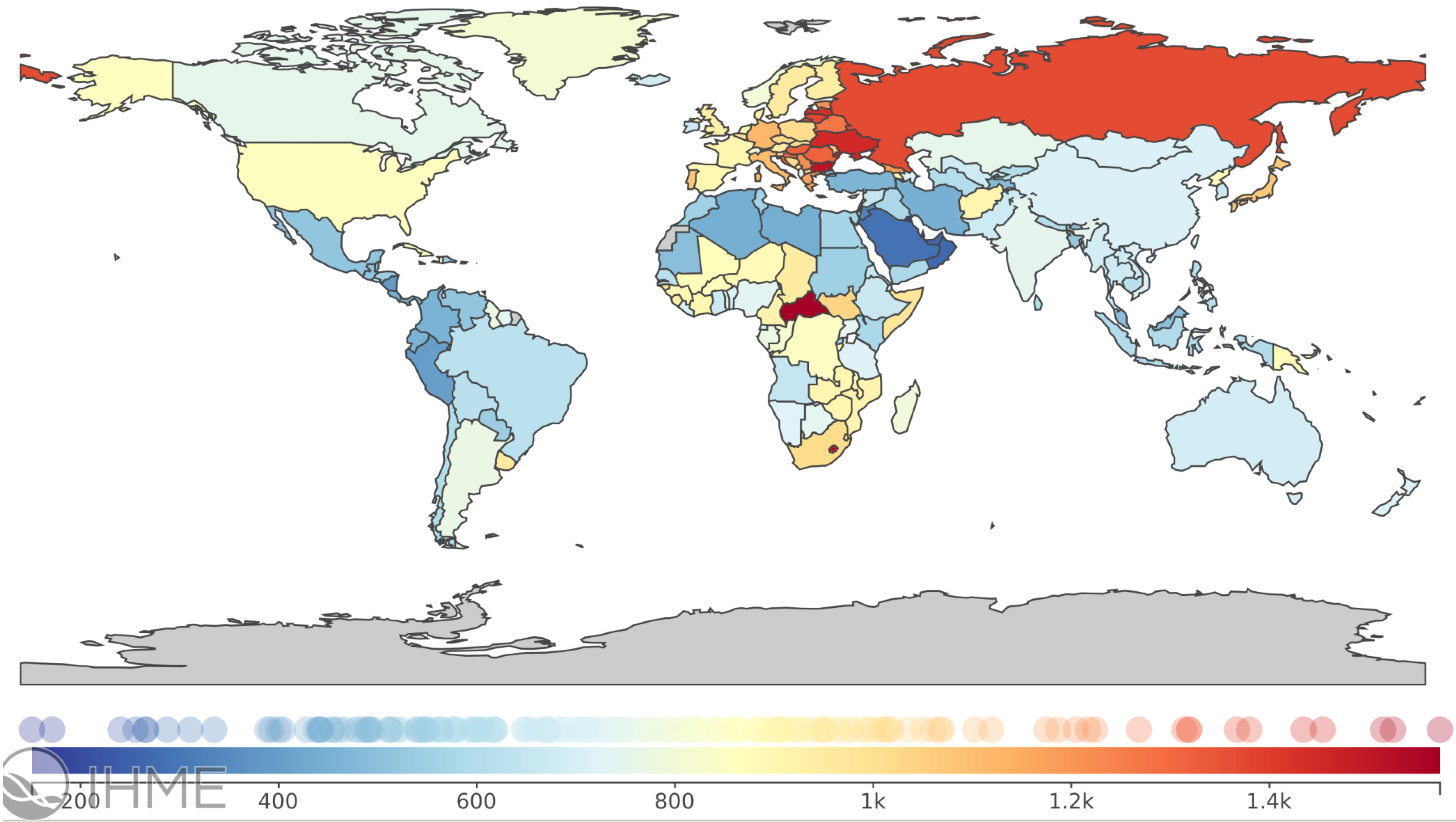
Age-standardized mortality: all-cause



Age-Standardized All-Cause Mortality Rate per 100k

Data: Global Burden of Disease, IHME 2017

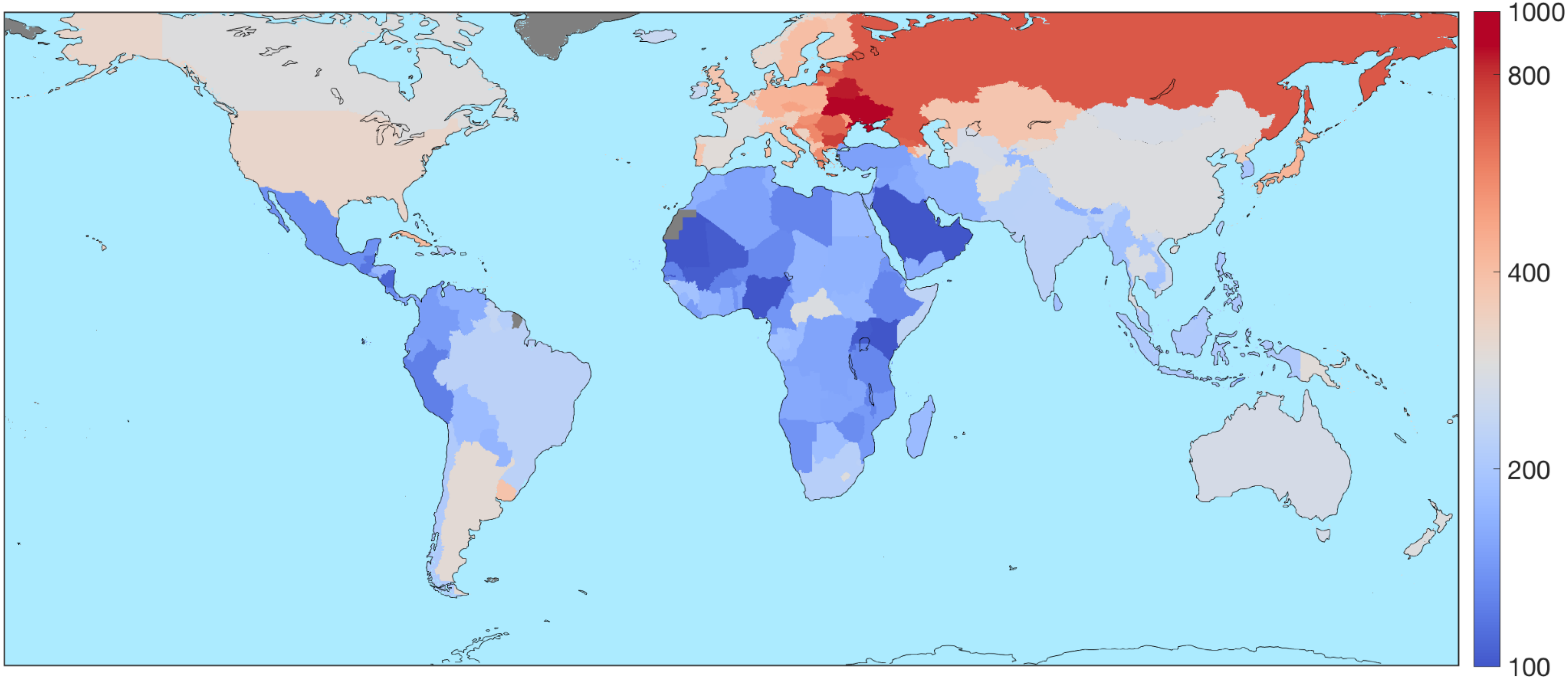
Crude mortality: all-cause



Crude All-Cause Mortality Rate per 100k

Data: Global Burden of Disease, IHME 2017

Global “underlying” mortality

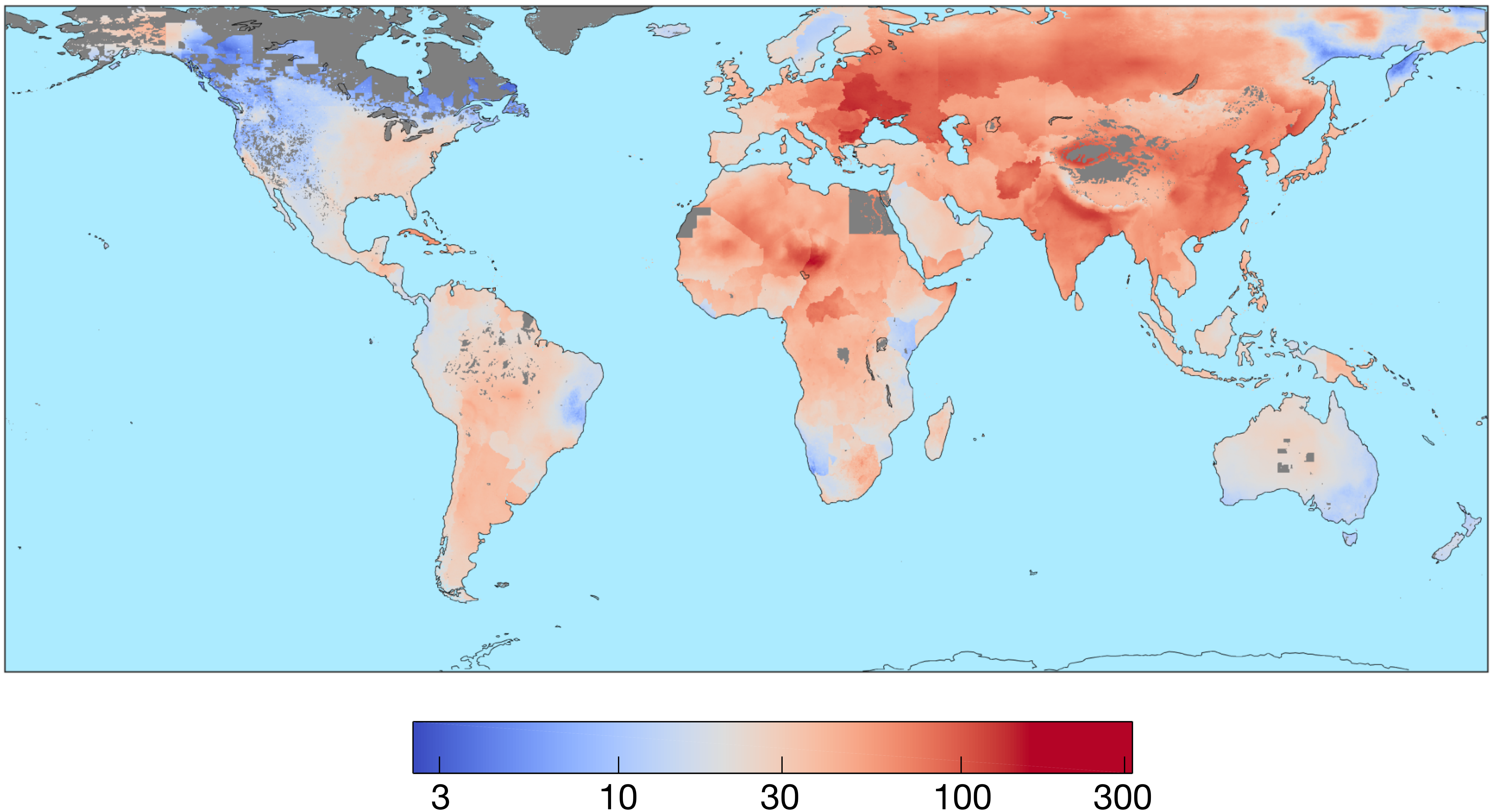


Crude death rate per 100k people
Heart disease + stroke, COPD + respiratory infection + lung cancer

Underlying mortality: hypothetical mortality rate if pollution = 0

Apte et al. *in prep*

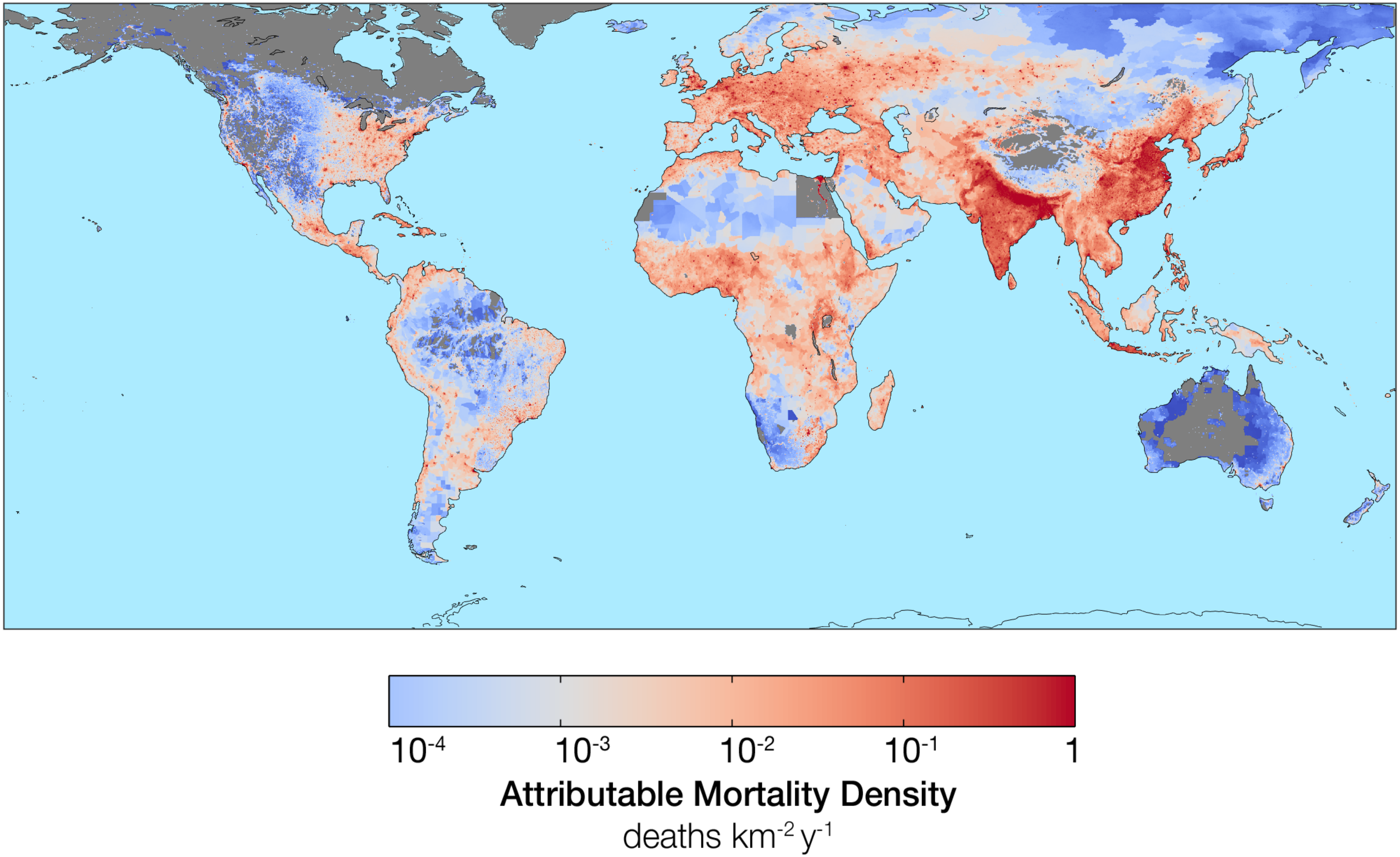
Attributable mortality per capita



Per-capita Attributable Mortality
deaths per 100,000 person-y

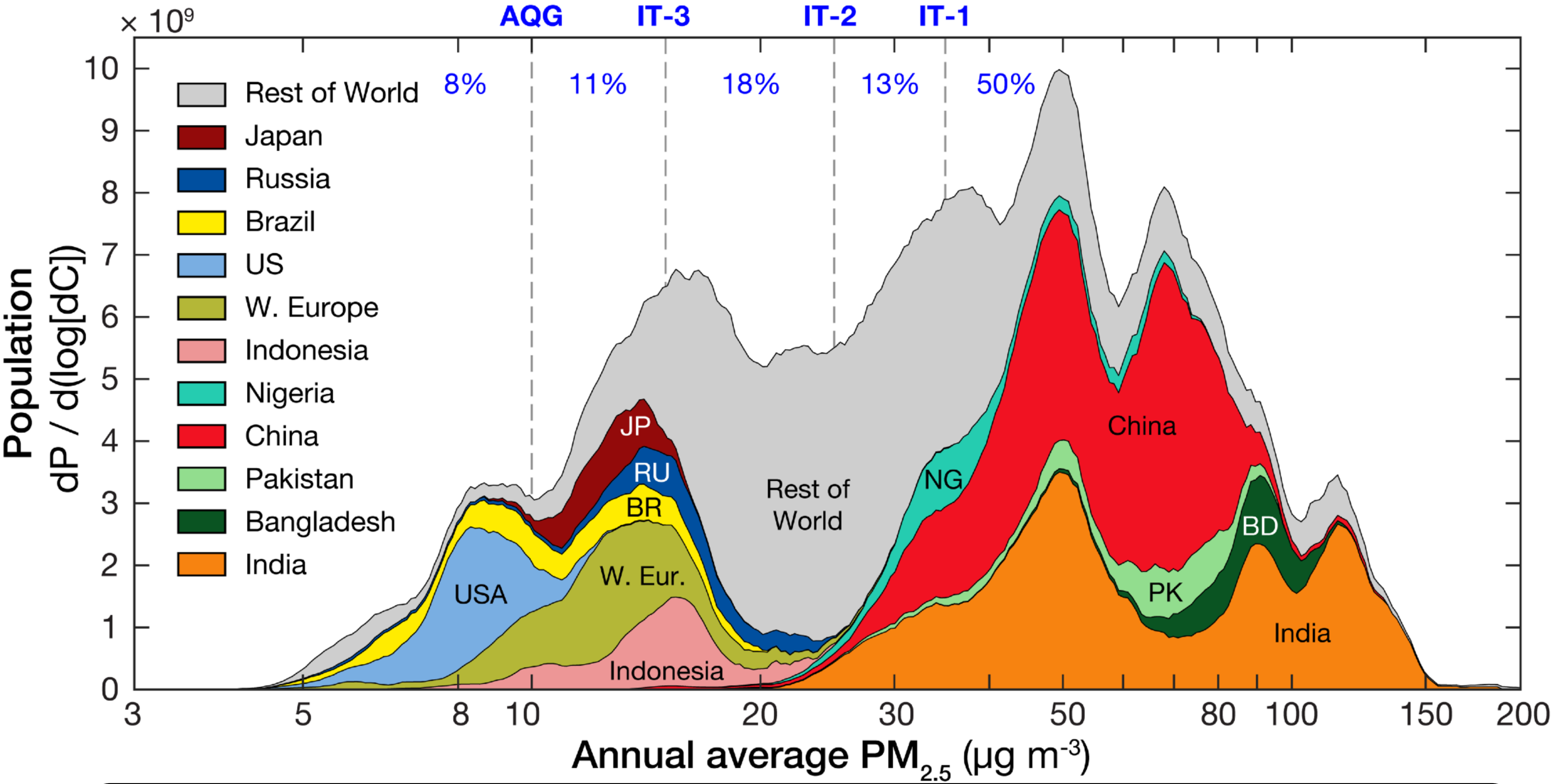
Apte et al. *in prep*

Global mortality from ambient $PM_{2.5}$



Apte et al. *in prep*

Population-concentration distribution

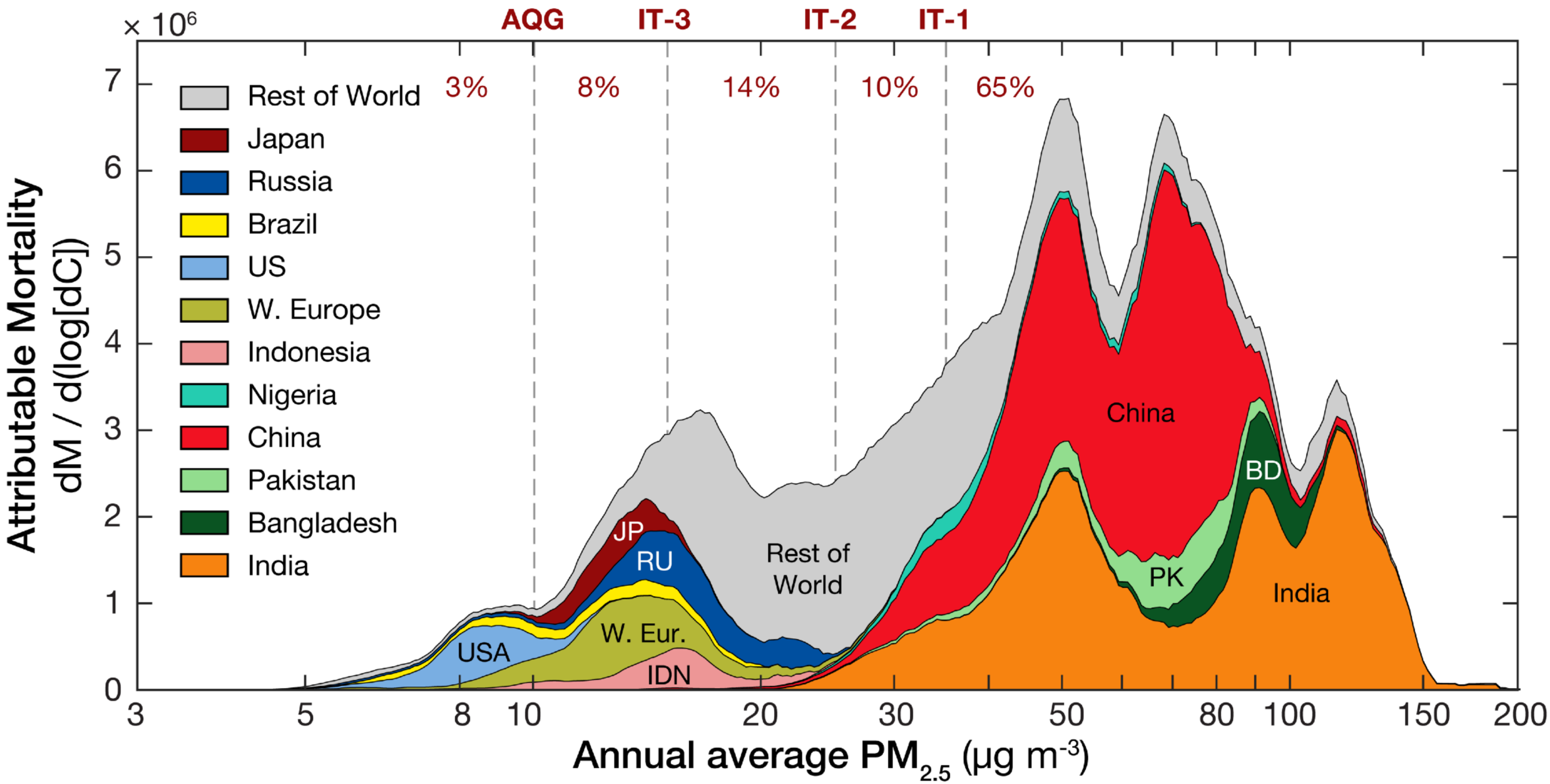


8% of global population meets WHO 10 µg m^{-3} air quality guideline

50% of world population lives in areas > 35 µg m^{-3}

Apte et al. *in prep*

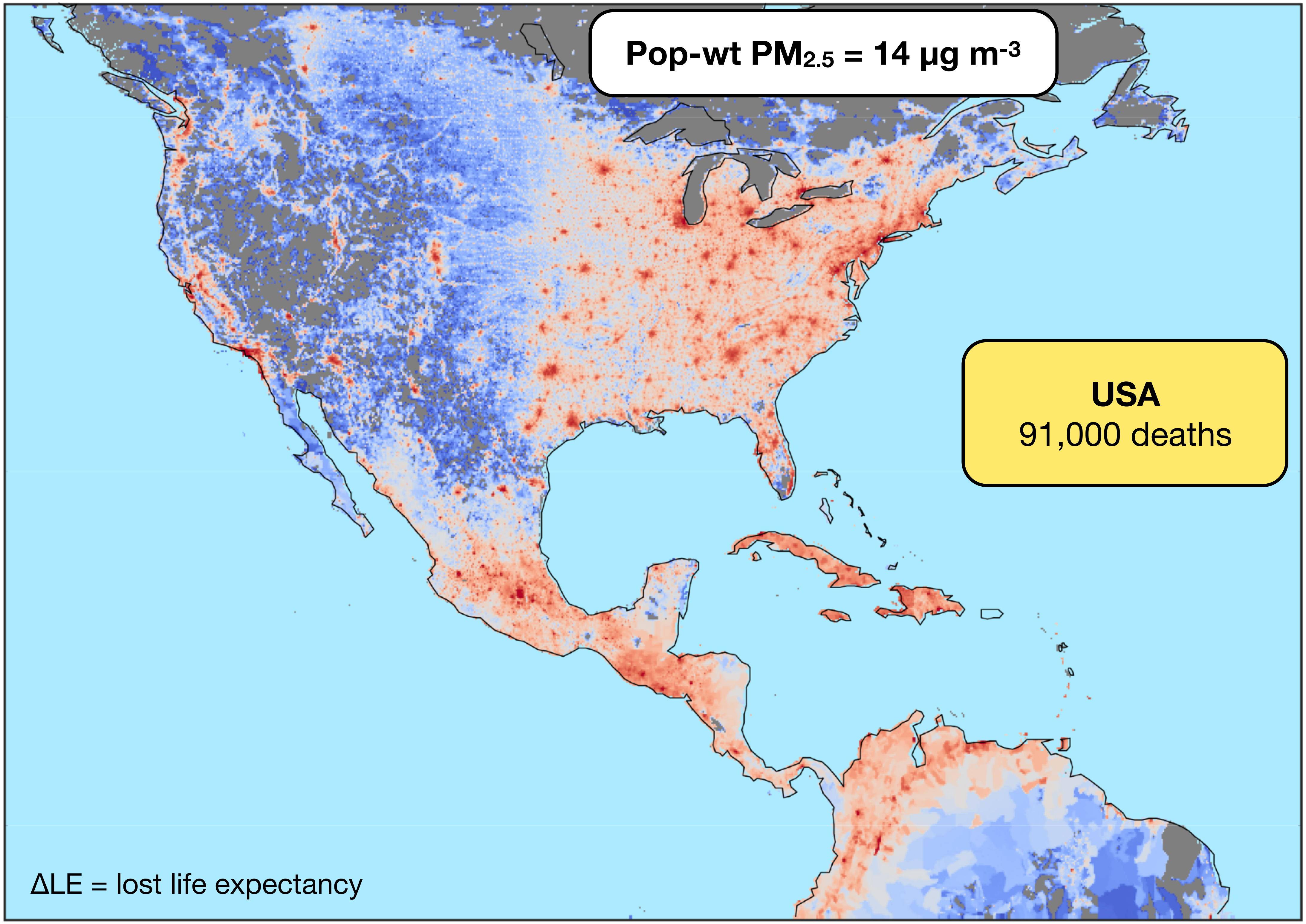
Global mortality distribution



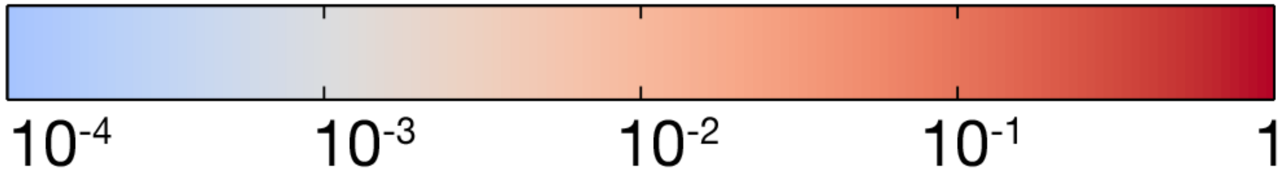
Key update: in GBD 2010, only 40% of deaths were in areas > 35 μg m^{-3}

Apte et al. *in prep*

N. America: 8% of pop, 4% of deaths

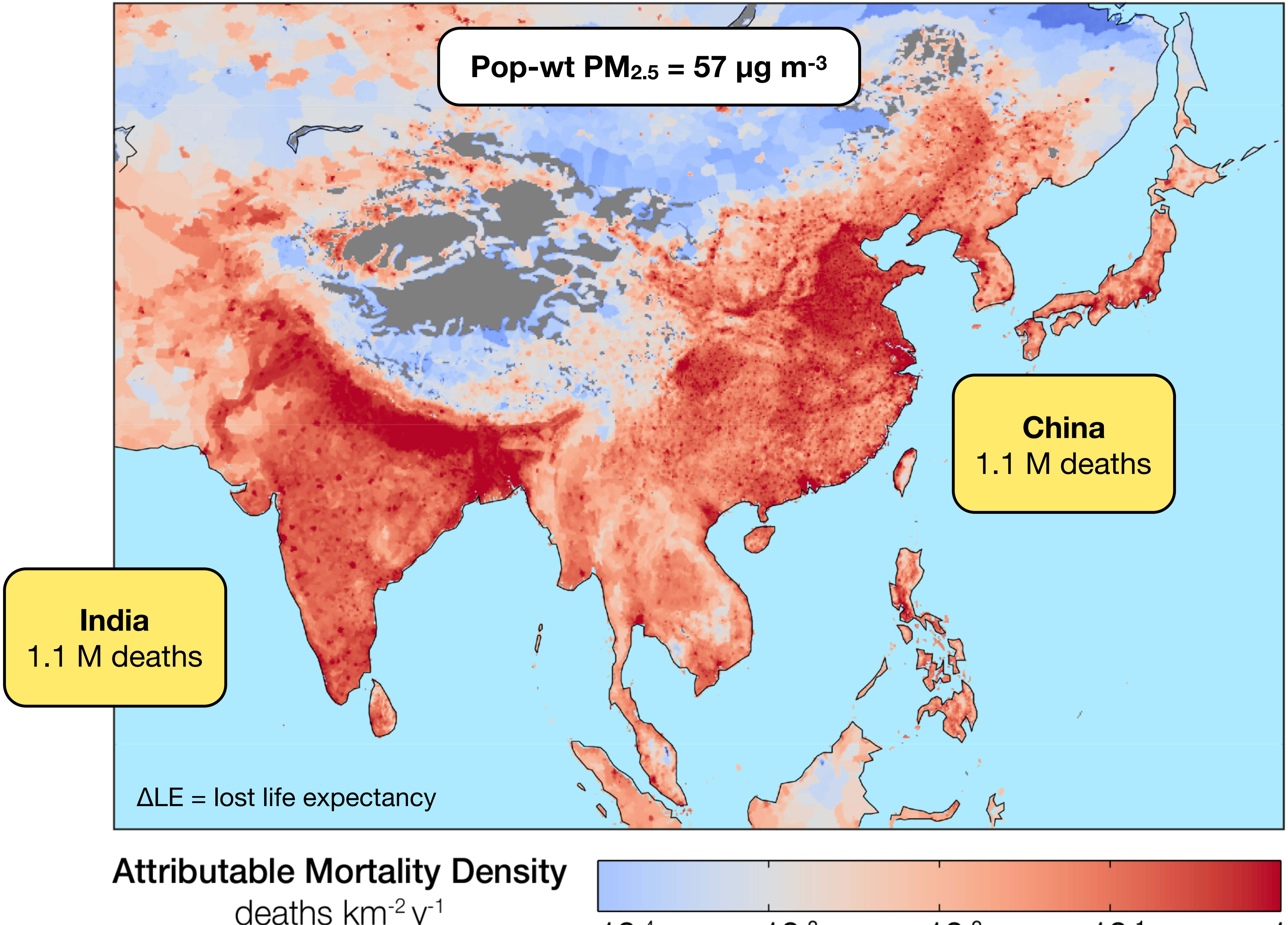


Attributable Mortality Density
deaths km^{-2} y^{-1}



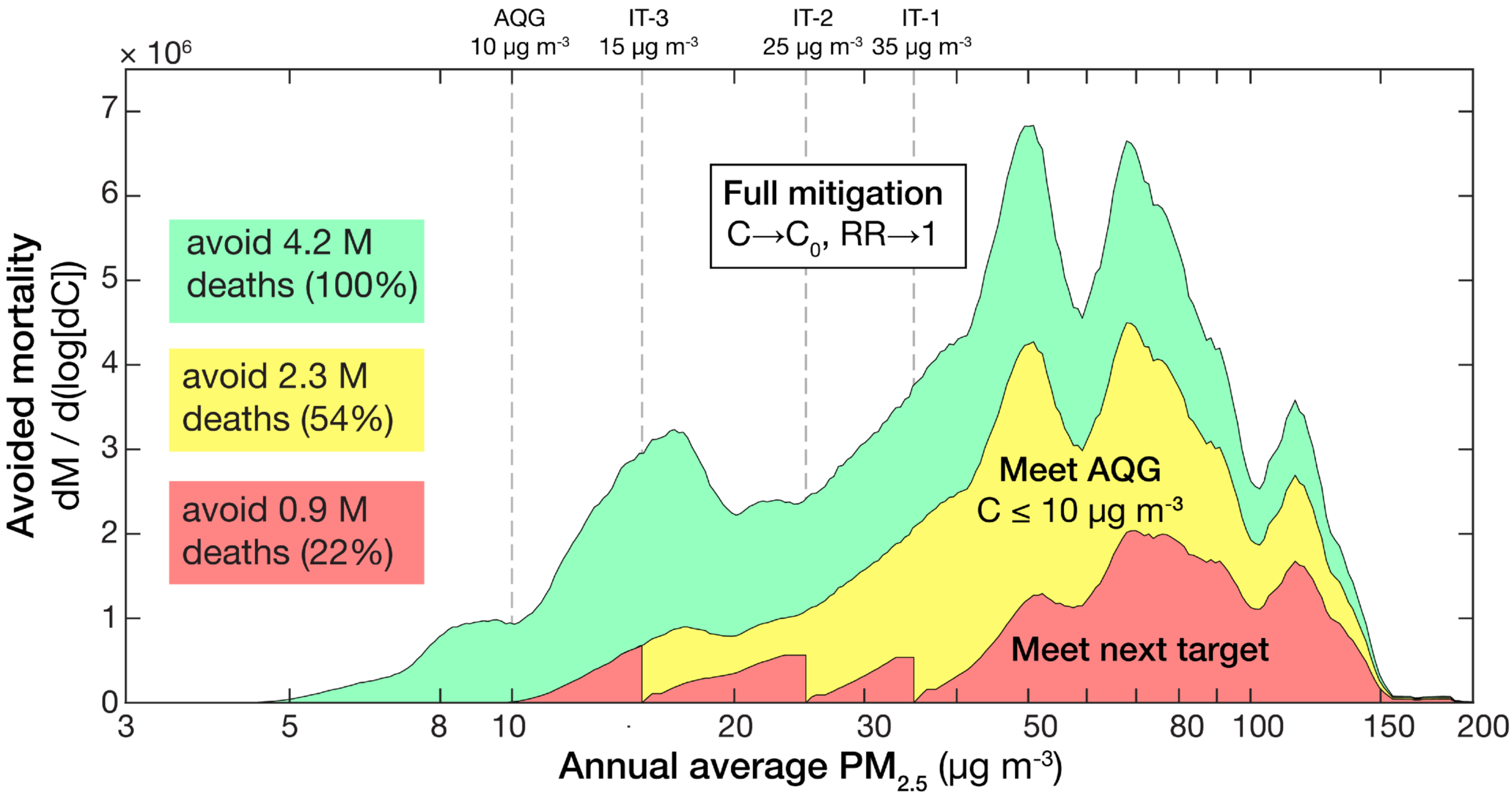
Apte et al. *in prep*

Asia: 51% of pop, 68% of deaths



Apte et al. *in prep*

Health benefits of cleaner global air



Apte et al. *in prep*

Mortality reduction from limiting $PM_{2.5}$

Limit to:	World	China	India	EU	USA
35 $\mu g\ m^{-3}$	18%	23%	30%	-	-
25 $\mu g\ m^{-3}$	27%	36%	42%	-	-
15 $\mu g\ m^{-3}$	41%	53%	57%	3%	-
10 $\mu g\ m^{-3}$	54%	64%	67%	18%	1%

Apte et al. *in prep*

Reducing mortality: clean vs. dirty

- **Polluted locales:**
  - high per-capita mortality risk
  - very large reductions in $PM_{2.5}$ likely needed
  - programs for sustained improvement required
  - opportunity to coordinate clean air and decarbonization

- **Cleaner locales:**
  - large number of deaths
  - large potential to further reduce attributable mortality from PM
  - New air quality policies to allow reductions in places that already meet WHO/EPA NAAQS levels?

How does this translate into LE?

Environmental Science & Technology LETTERS

ACS AuthorChoice

Letter

Cite This: *Environ. Sci. Technol. Lett.* XXXX, XXX, XXX−XXX

pubs.acs.org/journal/estlcu

Ambient $PM_{2.5}$ Reduces Global and Regional Life Expectancy

Joshua S. Apte,[*,†] Michael Brauer,[‡] Aaron J. Cohen,[§] Majid Ezzati,[∥] and C. Arden Pope, III[⊥]

[†]Department of Civil, Architectural and Environmental Engineering, The University of Texas, 301 East Dean Keeton Street, Stop C1700, Austin, Texas 78712, United States

[‡]School of Population and Public Health, The University of British Columbia, 2206 East Mall, Vancouver, British Columbia V6T1Z3, Canada

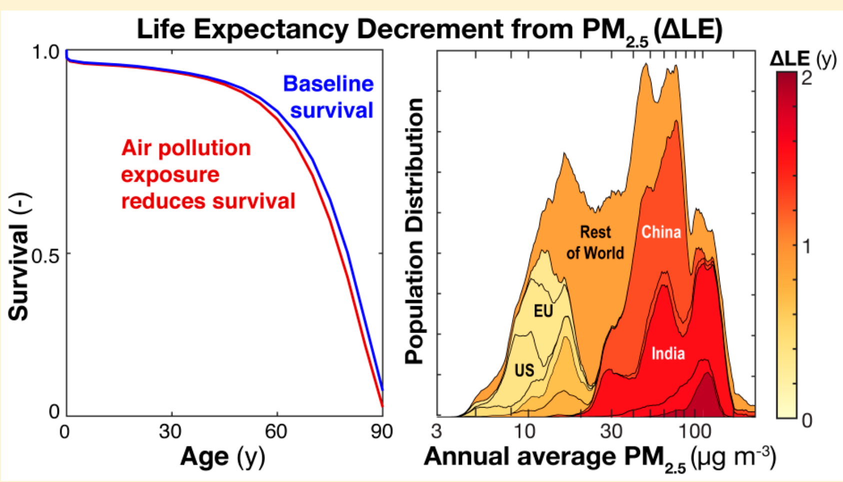
[§]Health Effects Institute, 75 Federal Street, Suite 1400, Boston, Massachusetts 02110, United States

[∥]MRC-PHE Centre for Environment and Health, Imperial College London, London W2 1PG, United Kingdom

[⊥]Department of Economics, Brigham Young University, Provo, Utah 84602, United States

Supporting Information

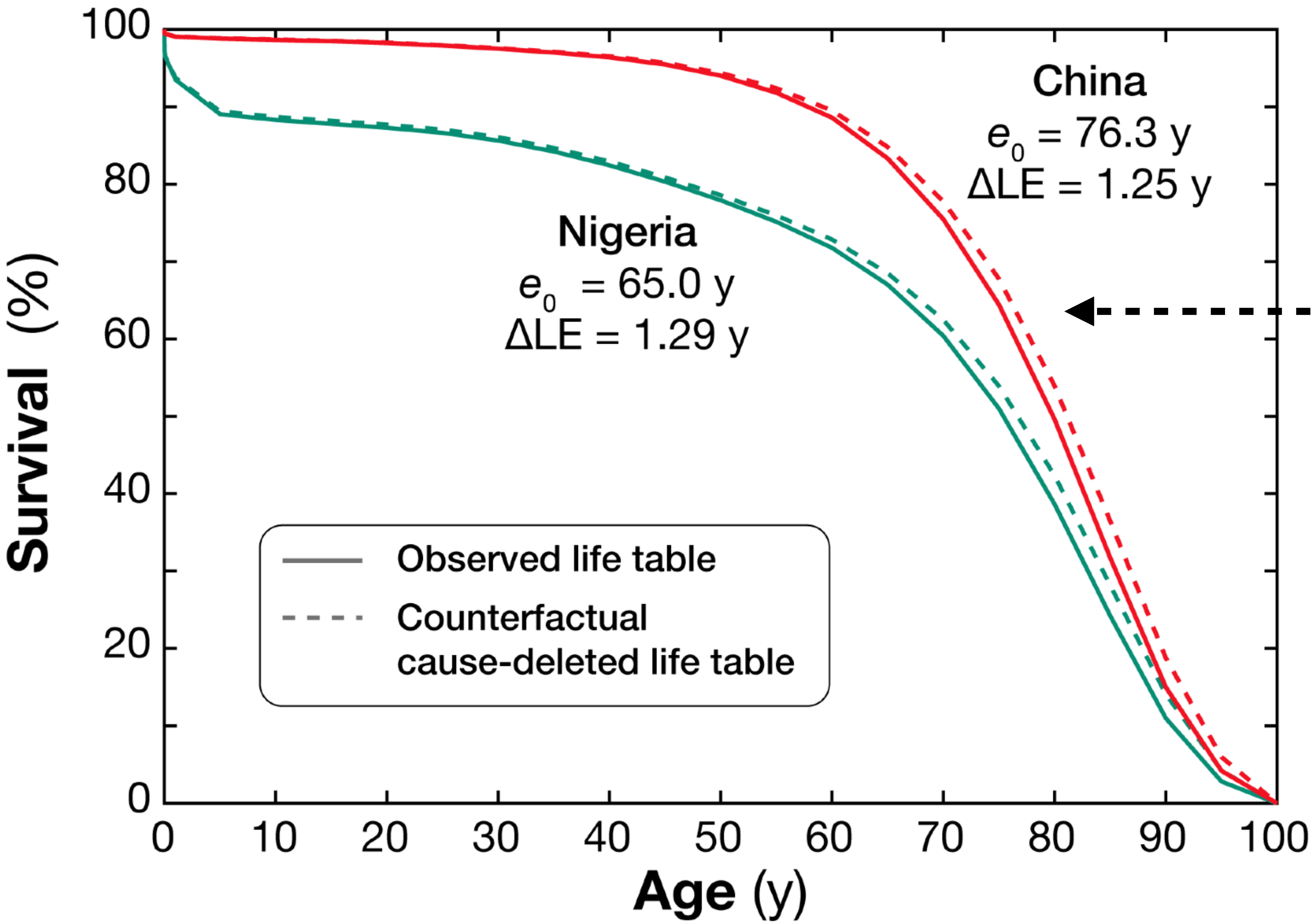
ABSTRACT: Exposure to ambient fine particulate matter ($PM_{2.5}$) air pollution is a major risk for premature death. Here, we systematically quantify the global impact of $PM_{2.5}$ on life expectancy. Using data from the Global Burden of Disease project and actuarial standard life table methods, we estimate global and national decrements in life expectancy that can be attributed to ambient $PM_{2.5}$ for 185 countries. In 2016, $PM_{2.5}$ exposure reduced average global life expectancy at birth by ∼1 year with reductions of ∼1.2−1.9 years in polluted countries of Asia and Africa. If $PM_{2.5}$ in all countries met the World Health Organization Air Quality Guideline (10 $\mu g\ m^{-3}$), we estimate life expectancy could increase by a population-weighted median of 0.6 year (interquartile range of 0.2−1.0 year), a benefit of a magnitude similar to that of eradicating lung and breast cancer. Because background disease rates modulate the effect of air pollution on life expectancy, high age-specific rates of cardiovascular disease in many polluted low- and middle-income countries amplify the impact of $PM_{2.5}$ on survival. Our analysis adds to prior research by illustrating how mortality from air pollution substantially reduces human longevity.



Motivation and approach

- Air pollution causes premature death.
- We care about how long we live. How premature is “premature death?”
- Life expectancy (LE) adds an intuitive and policy-relevant context to existing statistics on mortality.
- **Gap:** systematic assessment of how global $PM_{2.5}$ affects LE at birth.
- **Approach:**
    - Actuarial survival analysis using the most comprehensive dataset on mortality by cause and age around the world: Global Burden of Disease study.
    - “If air pollution were removed as a risk factor for death, how much longer would people live?”

Life expectancy metric



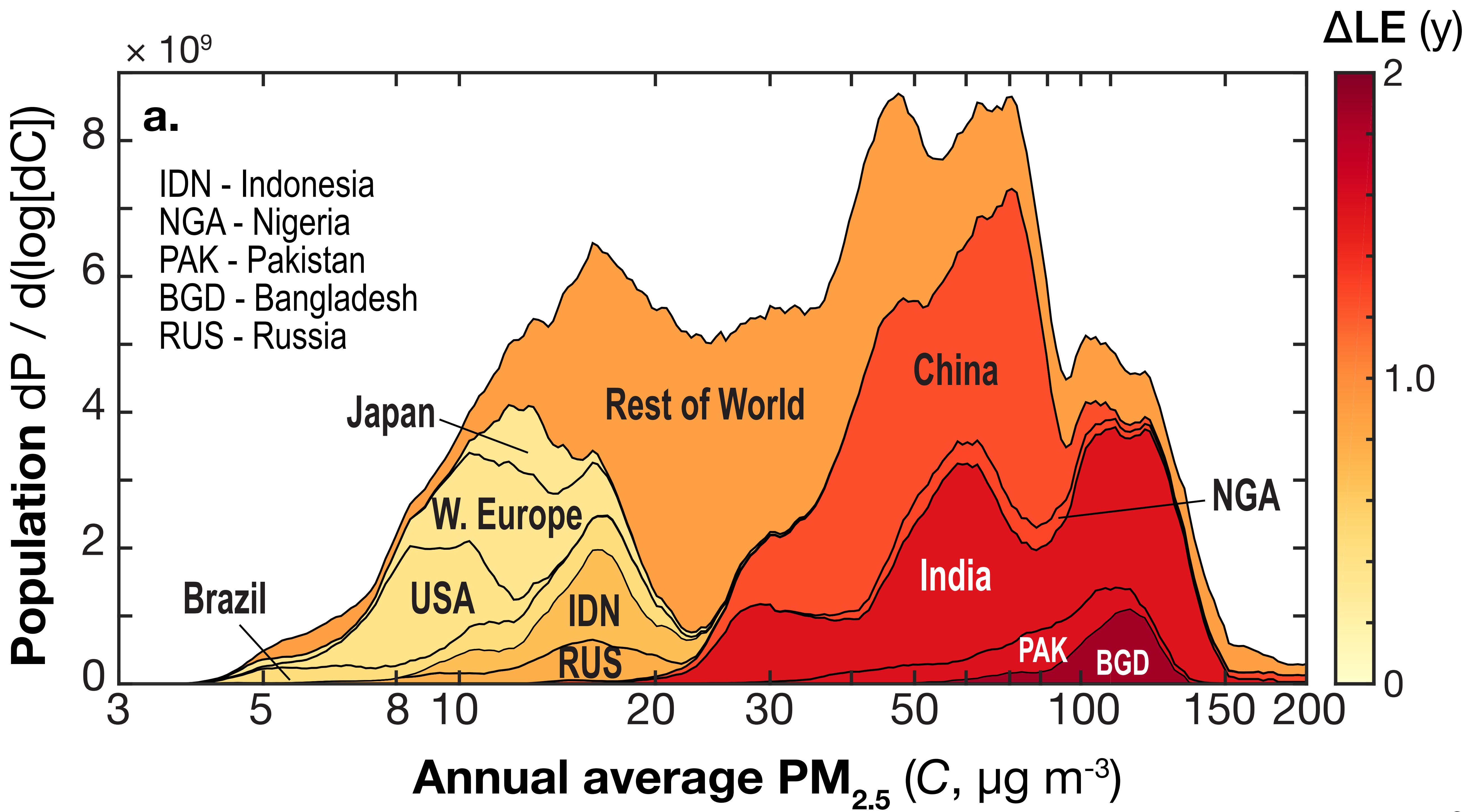
Counterfactual: Survival curve where mortality risk from $PM_{2.5}$ is removed.

ΔLE metric
How much longer would people live without pollution?

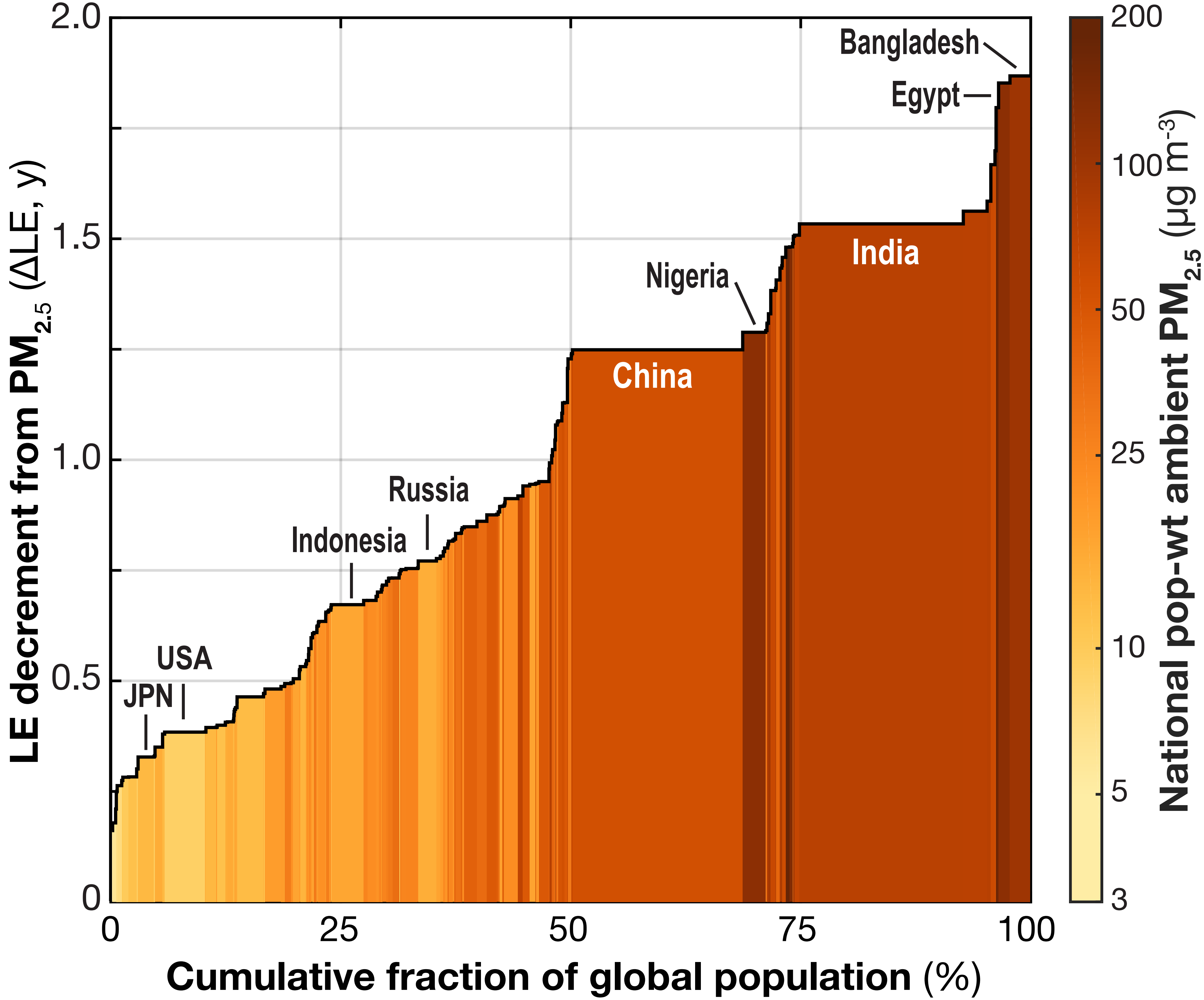
Life Expectancy: Integral of survival curve from initial age to death.

Global distribution of PM and ΔLE

There is great global inequality in $PM_{2.5}$ air pollution.
People in polluted countries live shorter lives because of air pollution.

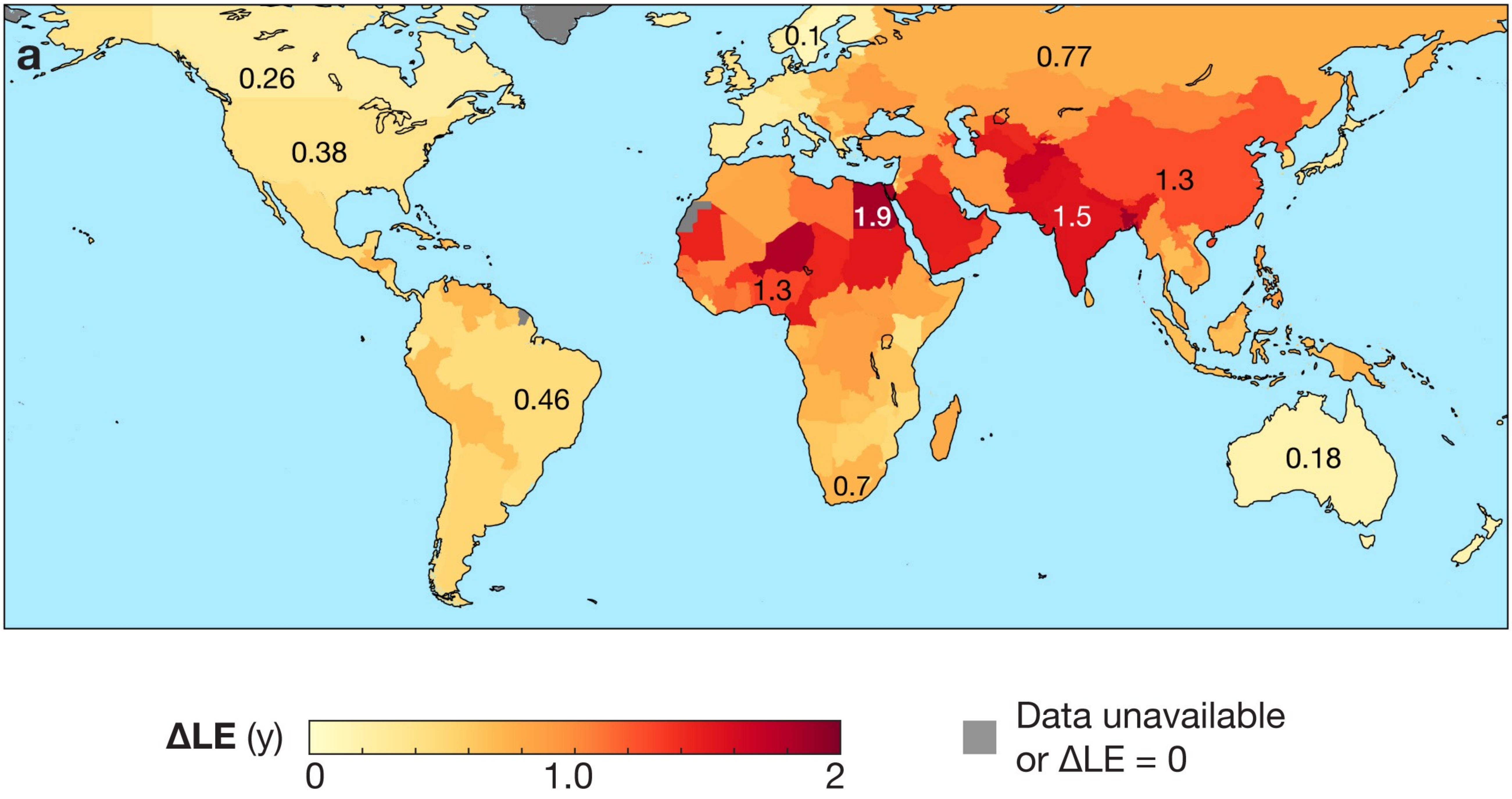


Global distribution of PM and ΔLE



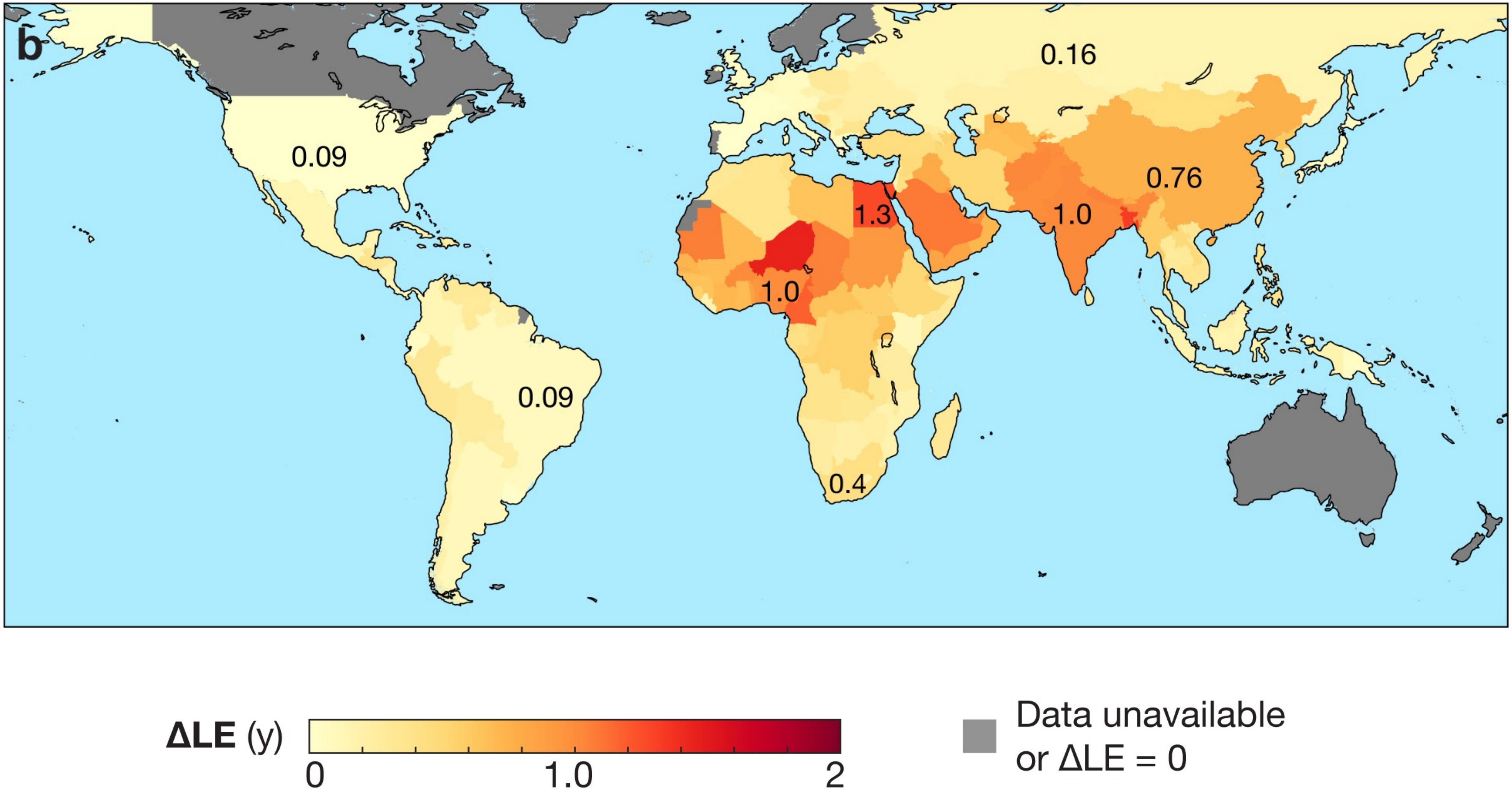
Global distribution of baseline ΔLE

By how many years are lives shortened from $PM_{2.5}$ today?



LE benefit of reaching 10 µg m^{-3}

How many years longer would people live if air quality met WHO guidelines?



ΔLE benefit of cleaner air

Meeting World Health Organization clean air targets could lengthen the *average* life by up to a year.

Limit to:	World	China	India	Nigeria	USA
35 μg m^{-3}	**0.22**	0.25	0.47	0.59	-
25 μg m^{-3}	**0.31**	0.41	0.63	0.73	-
15 μg m^{-3}	**0.46**	0.62	0.86	0.89	-
10 μg m^{-3}	**0.59**	0.76	1.02	1.00	0.01
Baseline	**1.03**	1.25	1.53	1.29	0.38

1 year of life expectancy gained is a *big deal* - see next slide.

ΔLE in context of other risks

Table 1. Global and Regional Life Expectancy and Life Expectancy Decrements for Selected Risk Factors and Causes of Death.

	Global	East Asia	South Asia	N. Africa & Middle East	Sub-Saharan Africa	Latin America	High Income
Baseline LE (y)	72.5	76.3	68.7	73.1	62.8	75.8	80.9
All air pollution	1.65	1.90	2.54	1.54	1.97	0.73	0.40
Ambient $PM_{2.5}$	1.03	1.24	1.56	1.29	0.94	0.54	0.37
Ambient ozone	0.05	0.07	0.10	0.03	0.01	0.02	0.03
Household air pollution	0.72	0.71	1.22	0.30	1.32	0.20	0.01
Tobacco	1.82	2.39	1.51	1.60	0.73	1.23	1.82
Water-sanitation	0.57	0.02	1.02	0.19	1.53	0.13	0.01
Dietary risks	2.67	3.10	2.58	3.13	1.54	1.82	1.91
Unsafe sex	0.37	0.08	0.16	0.04	2.03	0.27	0.07
All cancer	2.37	3.03	1.26	1.70	1.52	2.31	3.53
Lung cancer	0.41	0.67	0.12	0.26	0.09	0.26	0.72
Breast cancer	0.14	0.09	0.10	0.14	0.12	0.16	0.23

Air pollution has similar or larger effect on lifespan than many other risks.
In most regions, air pollution has larger impact than many cancers on LE.

Air pollution reduces elderly survival

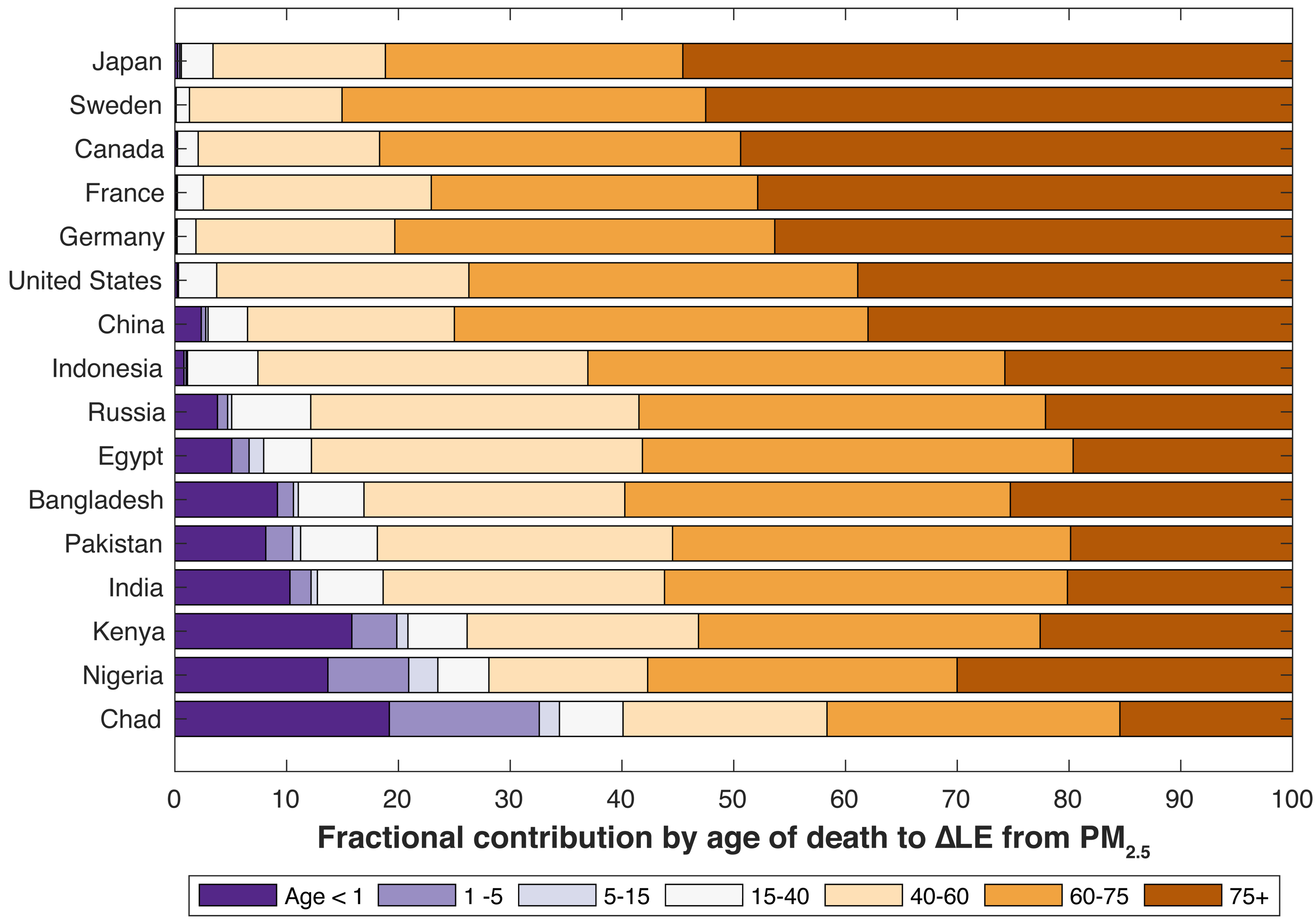
How much would removing mortality from $PM_{2.5}$ air pollution increase the probability of surviving from age 60 to age 85?

India	20%
Egypt	19%
Bangladesh	18%
Nigeria	15%
China	14%
Germany	3%
USA	3%
World	4%

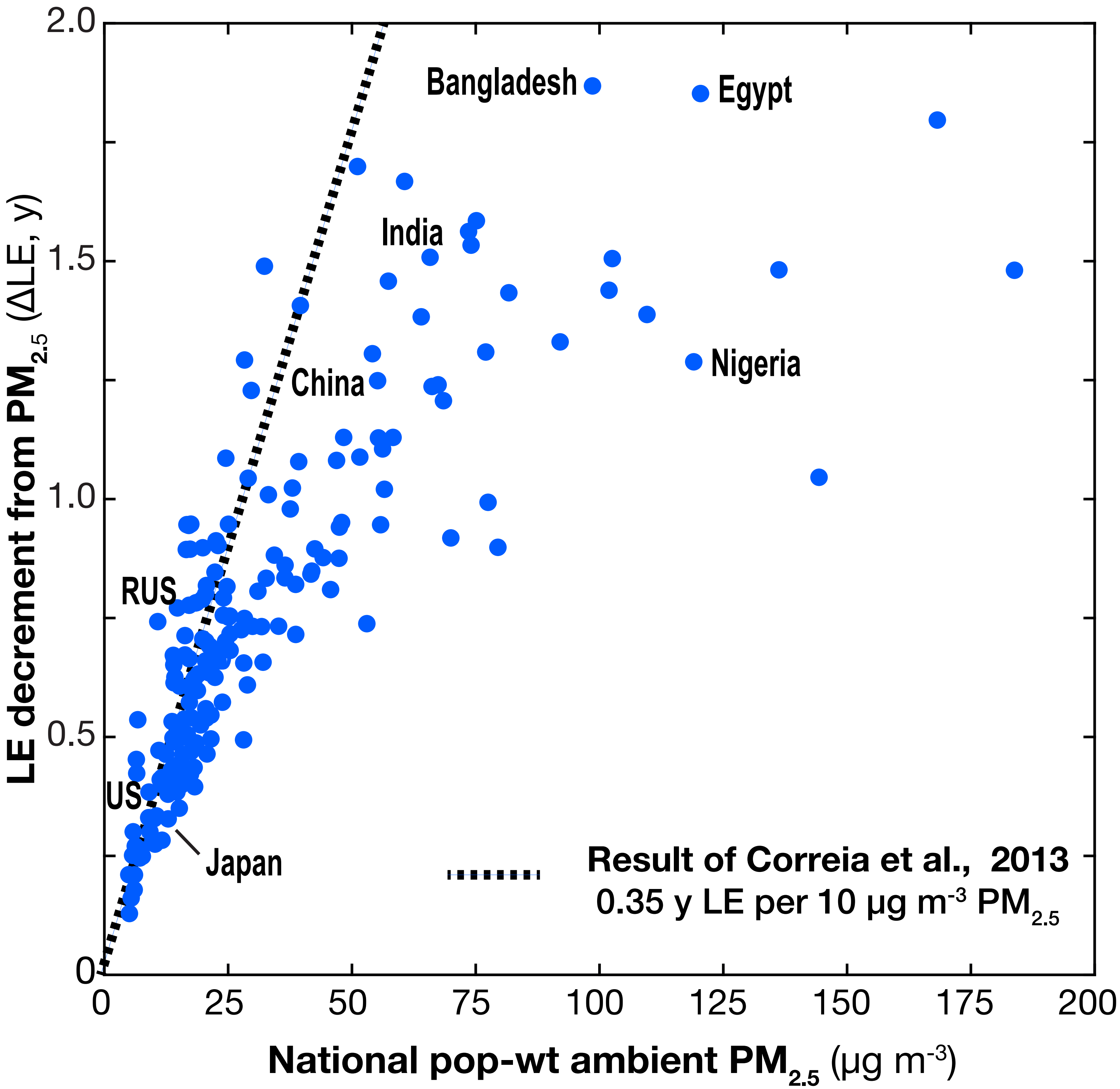
Air pollution has large impact on survival to age 80+ in polluted countries where few people survive to such old ages

Contribution of age-of-death to ΔLE

For most countries, the LE impact of air pollution is from increased mortality for the middle-aged and elderly.



ΔLE vs. $PM_{2.5}$



- Each increase in $PM_{2.5}$ has a larger marginal effect on life expectancy in cleaner countries.
- Our results closely match previous studies that have directly measured LE vs. $PM_{2.5}$ in clean countries.
- Scatter in this plot is important: LE effect of $PM_{2.5}$ depends strongly on baseline health and survival of a country.