Principles and Practices of Air Quality Management

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Workshop on:
"Multipollutant Air Quality Management"

Desert Research Institute

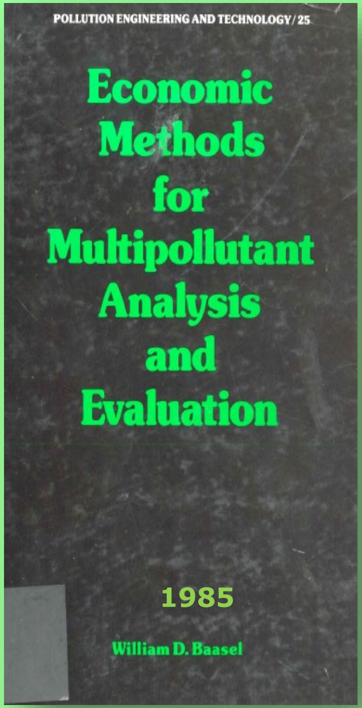
Reno, NV

February 17, 2022

Background and Motivation

- Most sources emit more than one air pollutant, but their emissions are separately measured and regulated
- **Adverse effects from multi-pollutants may be more than the sum of effects from individual pollutants (synergistic effect)**
- Secondary pollutants, such as O_3 and a portion of $PM_{2.5}$, result from interactions among several primary pollutants
- **Non-health effects, such as climate change and visibility, are rising in importance**

Air Quality Management should consider multiple pollutants and their multiple effects



POLLUTION ENGINEERING AND TECHNOLOGY/25

Economic Methods for Multipollutant Analysis and Evaluation

1985

William D. Baasel

AIR QUALITY MANAGEMENT OF MULTIPLE POLLUTANTS

Air quality management of multiple pollutants and multiple effects

J.C. Chow and J.G. Watson

Keynote address paper, CASANZ Conference, Auckland, July 31 - Aug 2

2011

2010 CRITICAL REVIEW

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Multipollutant Air Quality Management

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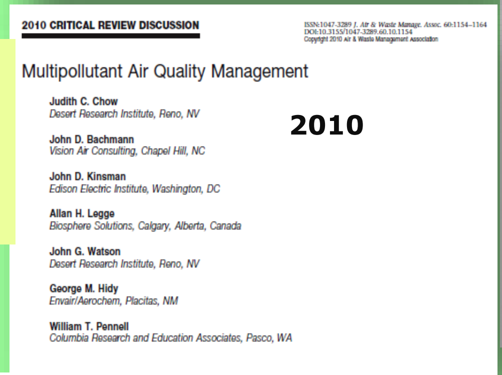
W.T. Pennell



2010 CRITICAL REVIEW DISCUSSION

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Multipollutant Air Quality Management

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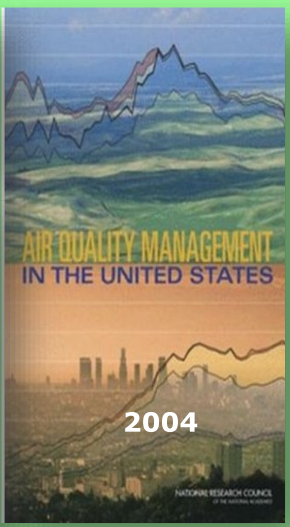


AIR QUALITY MANAGEMENT IN THE UNITED STATES

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

2004

TECHNICAL PAPER

Optimization of multipollutant air quality management strategies: A case study for five cities in the United States

Kuo-Jen Liao* and Xiangting Hou

Department of Environmental Engineering, Texas A&M University–Kingsville, Kingsville, TX, USA

**Please address correspondence to: Kuo-Jen Liao, Department of Environmental Engineering, Texas A&M University–Kingsville, 917 W. Ave. B - MSC 213, Kingsville, TX 78363, USA; e-mail: kuo-jen.liao@tamuk.edu*

2015

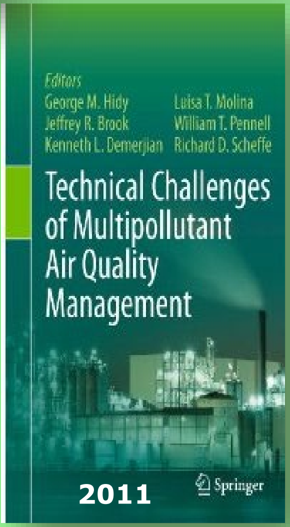
Commentary

2009

Is There Evidence for Synergy Among Air Pollutants in Causing Health Effects?

Joe L. Mauderly[1] and Jonathan M. Samet[2]

[1]National Environmental Respiratory Center, Lovelace Respiratory Research Institute, Albuquerque, New Mexico, USA; [2]Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA



Editors
George M. Hidy
Jeffrey R. Brook
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Technical Challenges of Multipollutant Air Quality Management

Springer

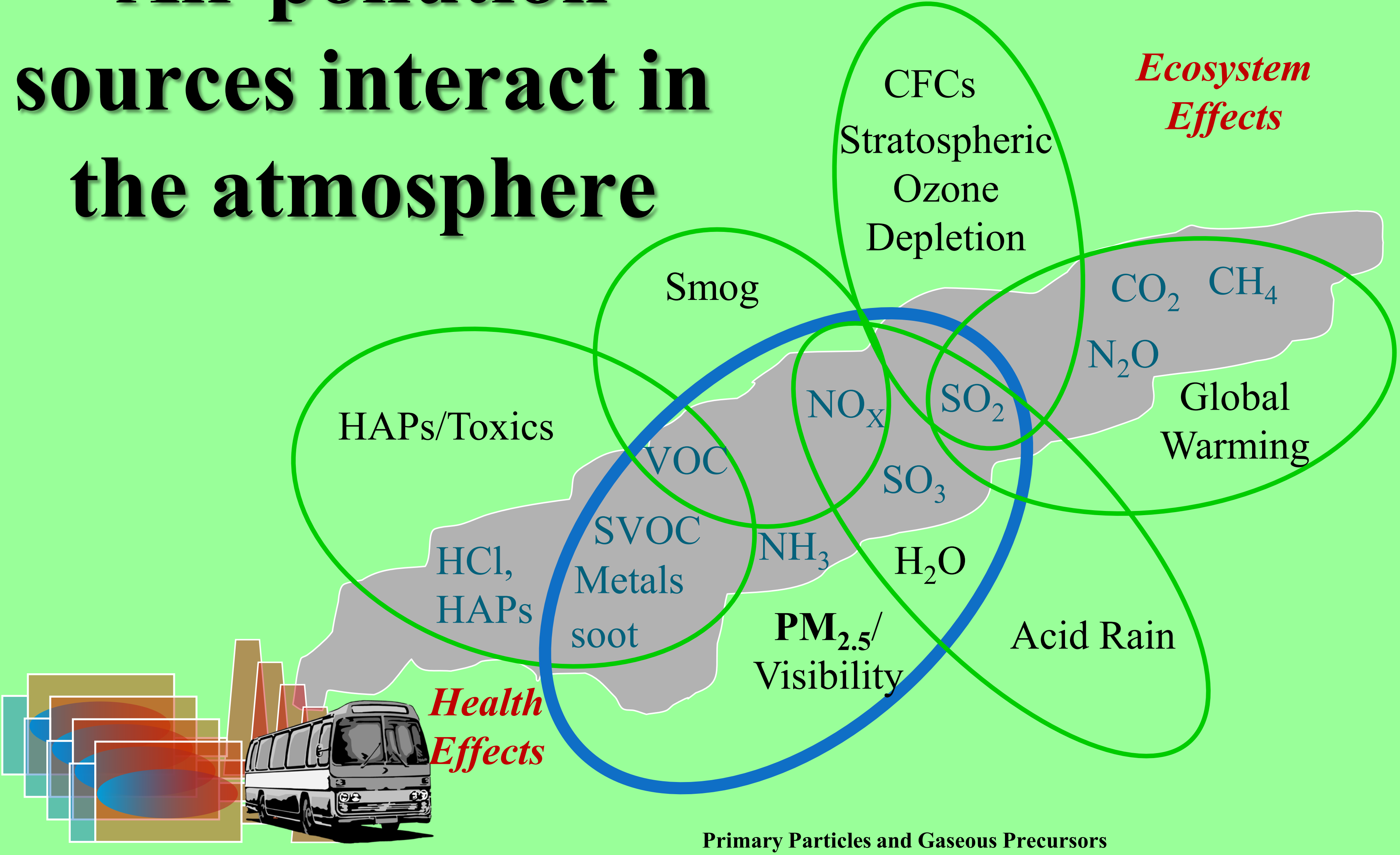
2011

Emphasis has been on multi-pollutant effects on human health

Presentation Objectives

- Identify pollutants of concern and their adverse environmental effects
- **Introduce emerging approaches for air quality management**
- Describe incremental steps toward a multi-pollutant, multi-effect strategy

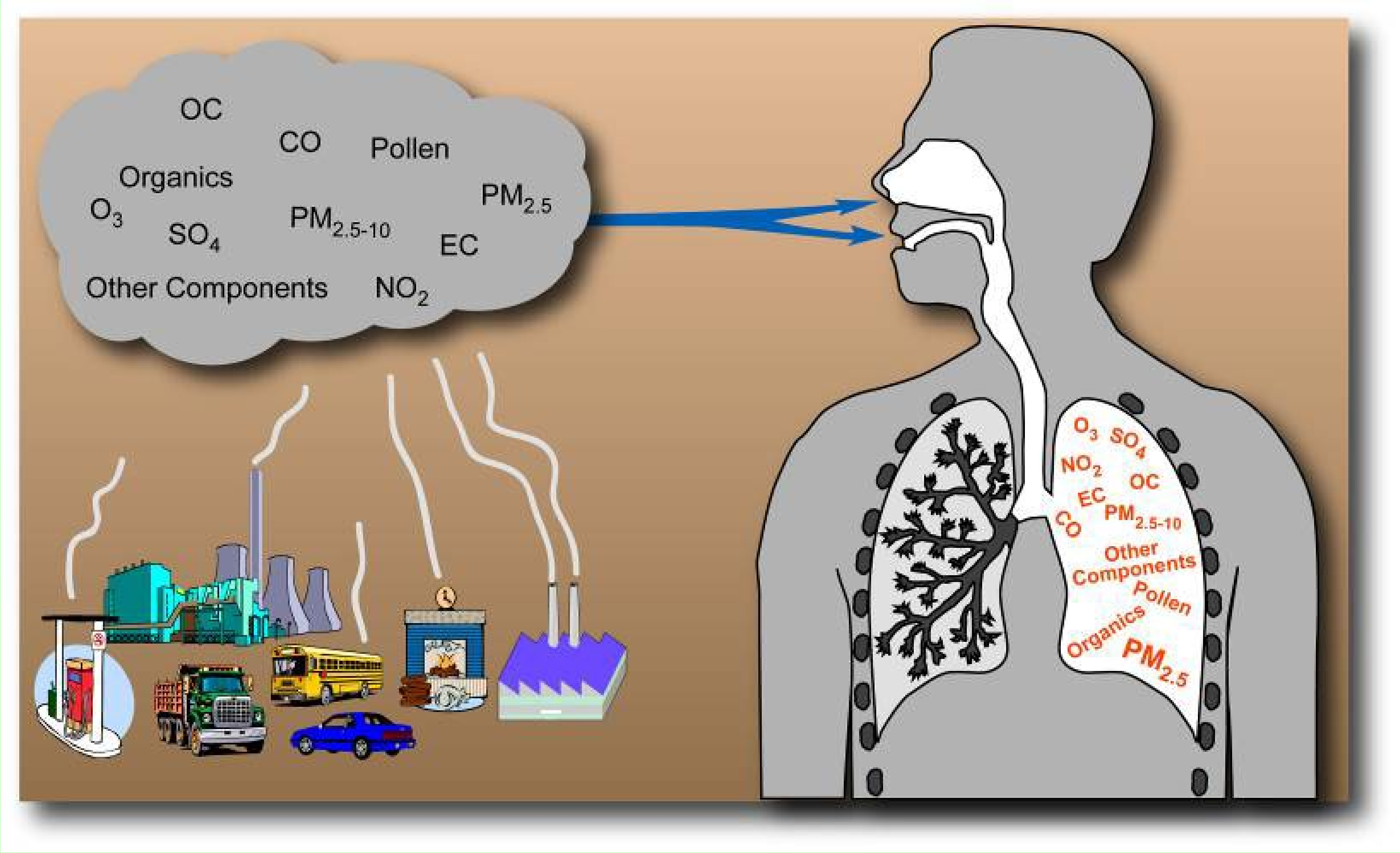
Air pollution sources interact in the atmosphere



Primary Particles and Gaseous Precursors

Combustion processes

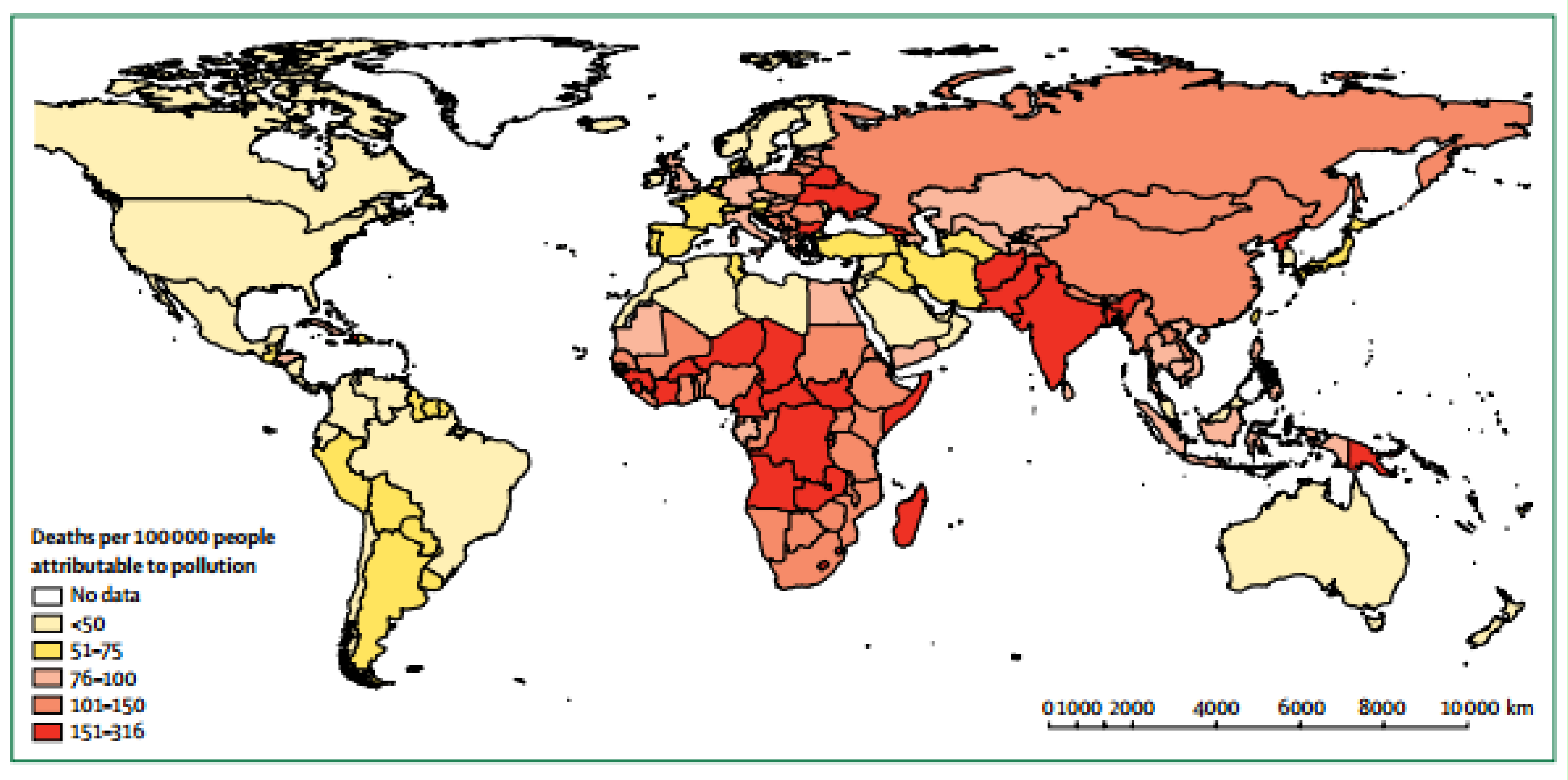
Gaseous and particle pollutants cause adverse health effects



http://www.epri.com/

Environmental pollution resulted in 3.2 million deaths in Southeast Asia

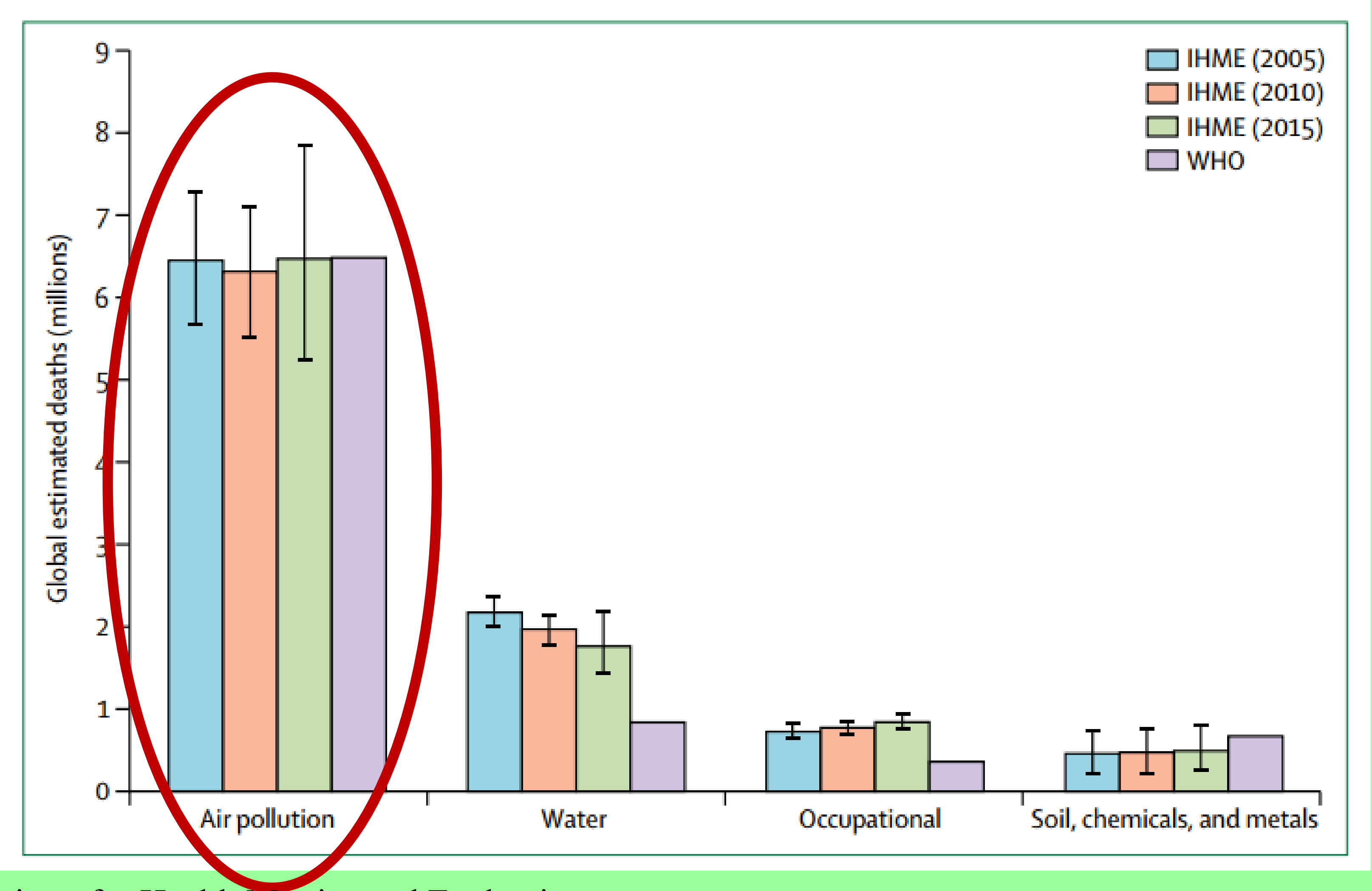
(Number of deaths per 100,000 people that are attributable to all forms of pollution, 2015)



Mortality rate attributed to household and ambient air pollution in Indonesia is 85 per 100,000 people (WHO, 2010)

Landrigan et al. (2017) *The Lancet Commissions*

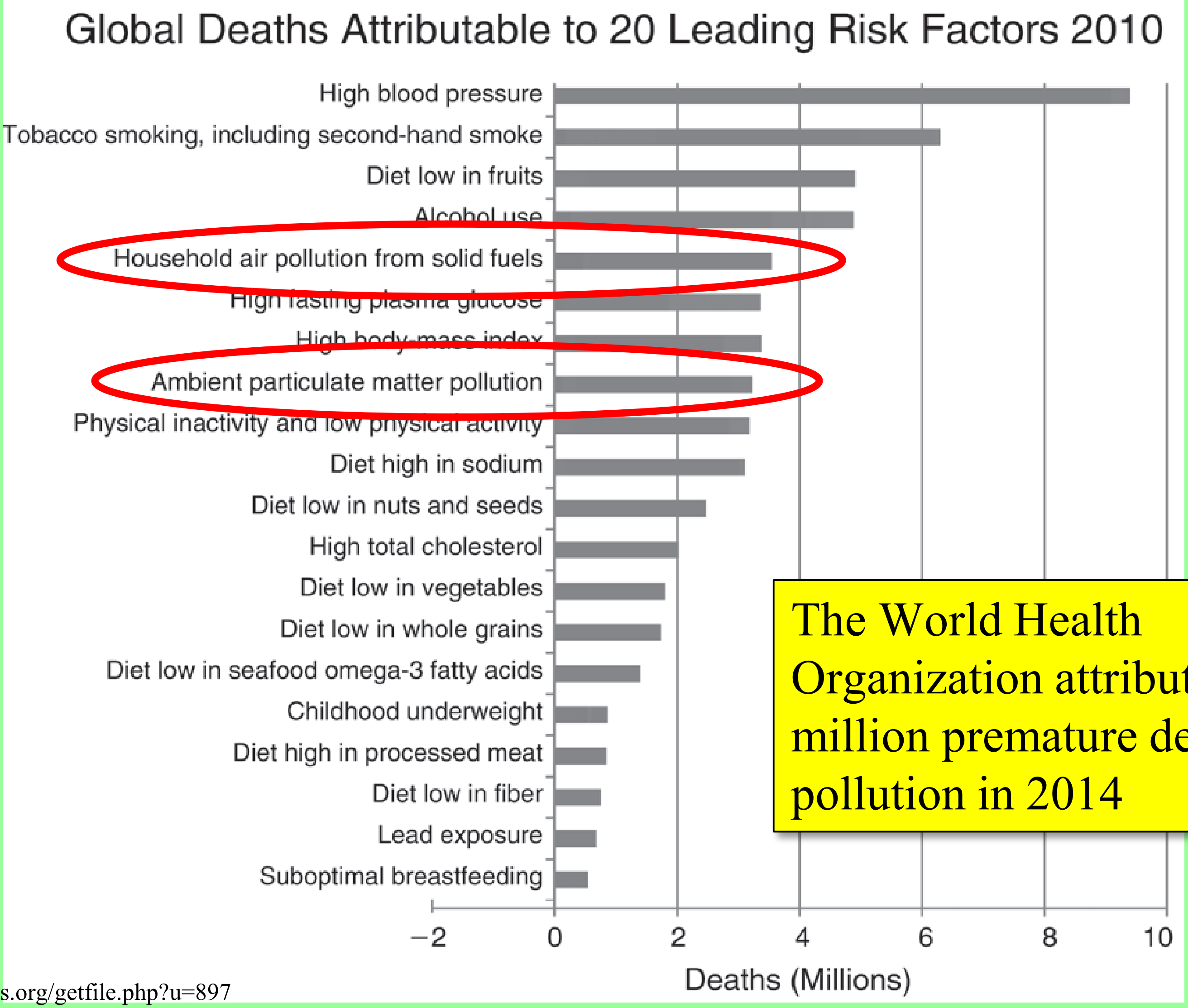
Air pollution ranked highest in global burden of disease study



IHME: Institute for Health Metrics and Evaluation
WHO: World Health Organization

Landrigan et al. (2017) *The Lancet Commissions*

Indoor and outdoor air pollution are ranked top 10 risks for global burden of disease



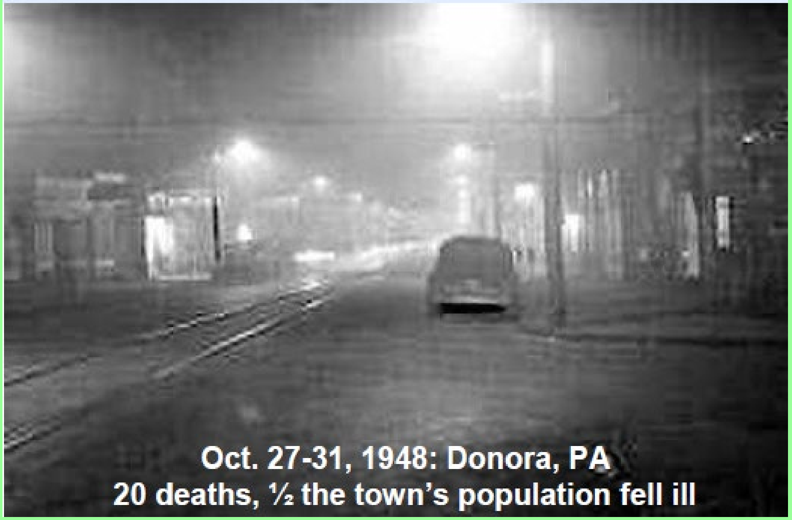
The World Health Organization attributed ~7 million premature deaths to air pollution in 2014

From: http://pubs.healtheffects.org/getfile.php?u=897

Heavy smog has been associated with excess mortality rates since the 1930s

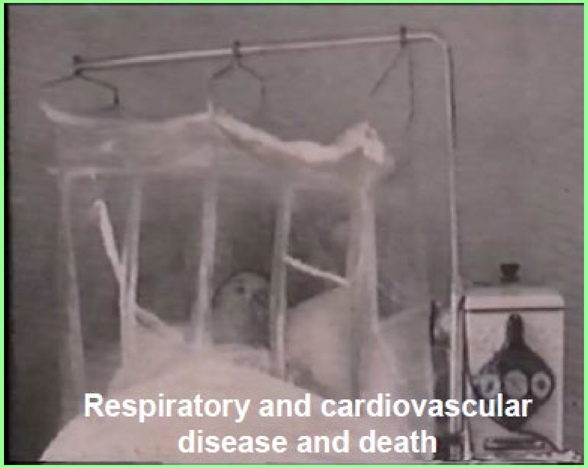
(Killer Smog Episodes)

Dec. 1-5, 1930: Meuse Valley, *Belgium*
60 deaths (10x expected)



Oct. 27-31, 1948: Donora, PA
20 deaths, ½ the town's population fell ill

Dec. 5-9, 1952: London--1000's of excess deaths



Respiratory and cardiovascular disease and death

Courtesy of Pope, 2010

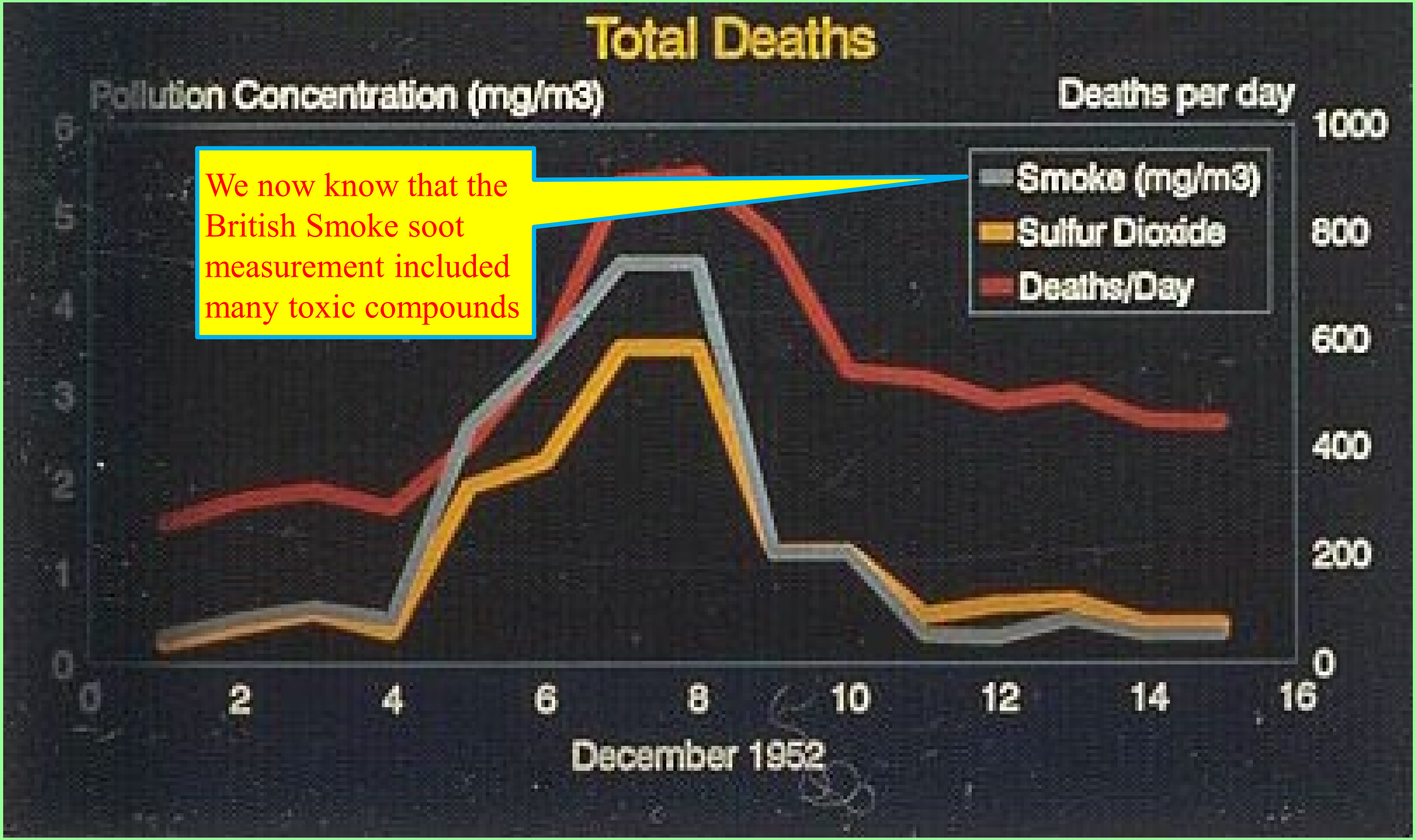
Pollution caused low visibility during daytime in London (December, 1952)

Particle levels exceeded 3,000 µg/m^3

National Archives

Soiling, poor visibility, and bad health were related to soot and SO_2

Excess mortality found during the 1952 London fog episode (4,000 extra deaths in a week)



We now know that the British Smoke soot measurement included many toxic compounds

Adverse effects result from different pollutant mixtures

Air Pollutant	**Effects**
• Criteria pollutants (i.e., CO, SO_2, NO_2, O_3, $PM_{2.5}$/$PM_{10,}$ and, Pb)	• Adverse health and ecosystem effects
• Light scattering and absorbing PM and gases (e.g., $SO_4^=$, NO_3^-, NH_4^+, OC, EC, sea salt, soil, and NO_2)	• Adverse visibility, health and ecosystem effects
• Hazardous Air Pollutants (HAPs, or toxics; e.g., persistent organic pollutants [POPs] and metals [e.g., As, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn])	• Carcinogenic health effects (cancer, reproductive or birth defects) • Adverse environmental effects (bioaccumulation of Hg in fish and lakes)
• Oxidizing pollutants (e.g., H^+, $SO_4^=$, and O_3)	• Destruction of forests, crops, and lakes
• Depositing pollutants (e.g., SO_2, HNO_3, O_3, soot [BC], and soil dust)	• Soiling and degradation of buildings, antiquities, vehicles, and clothing
• Reduced sulfur compounds and certain VOCs	• Unpleasant odors
• Climate forcers (e.g., BC, O_3, CO_2, CH_4, and halocarbons [Freon-122])	• Alter earth's radiation balance (e.g., absorbing electromagnetic radiation, depleting stratospheric O_3, and changing cloud cover and water vapor)

Climate change became a global health threat in the 21st century

THE LANCET

UCL

Lancet and University College London Institute for Global Health Commission

Managing the health effects of climate change

Anthony Costello, Mustafa Abbas, Adriana Allen, Sarah Ball, Sarah Bell, Richard Bellamy, Sharon Friel, Nora Groce, Anne Johnson, Maria Kett, Maria Lee, Caren Levy, Mark Maslin, David McCoy, Bill McGuire, Hugh Montgomery, David Napier, Christina Pagel, Jinesh Patel, Jose Antonio Puppim de Oliveira, Nanneke Redclift, Hannah Rees, Daniel Rogger, Joanne Scott, Judith Stephenson, John Twigg, Jonathan Wolff, Craig Patterson*

Executive summary

Climate change is the biggest global health threat of the 21st century

Effects of climate change on health will affect most populations in the next decades and put the lives and wellbeing of billions of people at increased risk. During

increase carbon biosequestration through reforestation and improved agricultural practices. The recognition by governments and electorates that climate change has enormous health implications should assist the advocacy and political change needed to tackle both mitigation and adaptation.

Lancet 2009; 373: 1693–733

See **Editorial** page 1659

See **Comment** page 1663

See **Perspectives** page 1669

Institute for Global Health
(Prof A Costello FRCPCH,

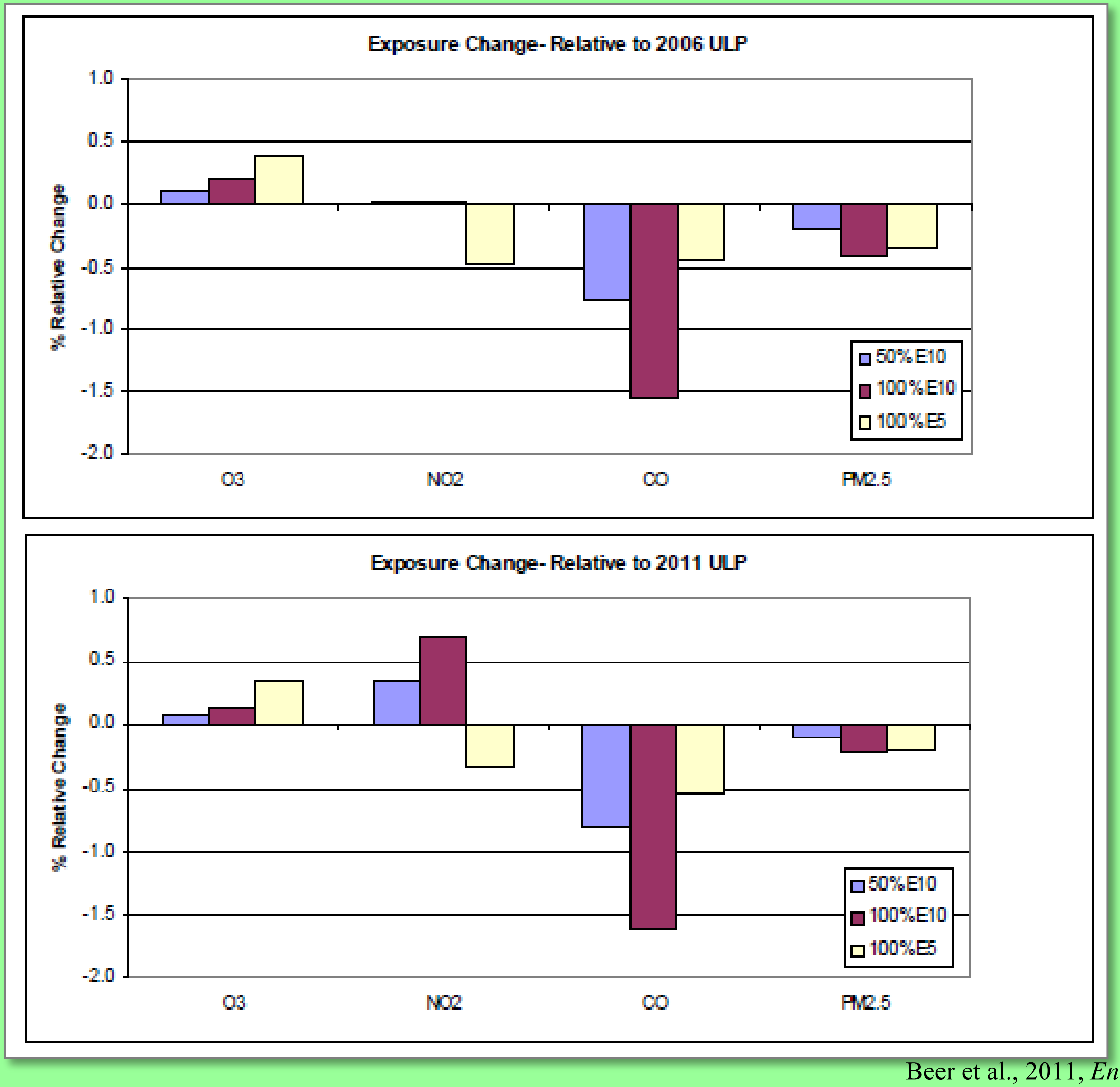
Costello et al., 2009, *Lancet*

The same sources that affect health create urban brown clouds

Actions taken to benefit one effect may adversely influence other effects

(Health benefits to Sydney, Australia population by blending 5–10% ethanol in gasoline)

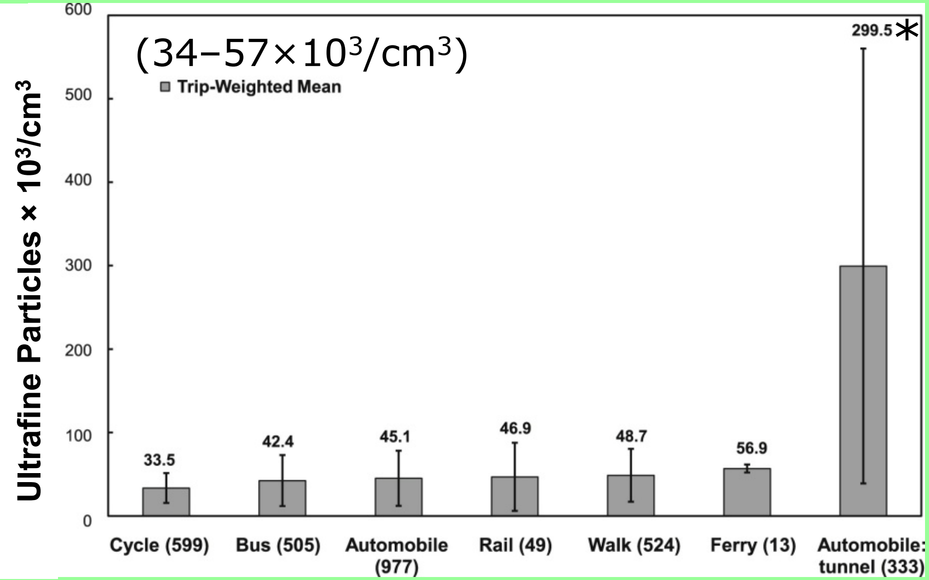
50%E10:	50% uptake of 10% ethanol
100%E10:	100% uptake of 10% ethanol
100%E5:	100% uptake of 5% ethanol



Beer et al., 2011, *Energies*

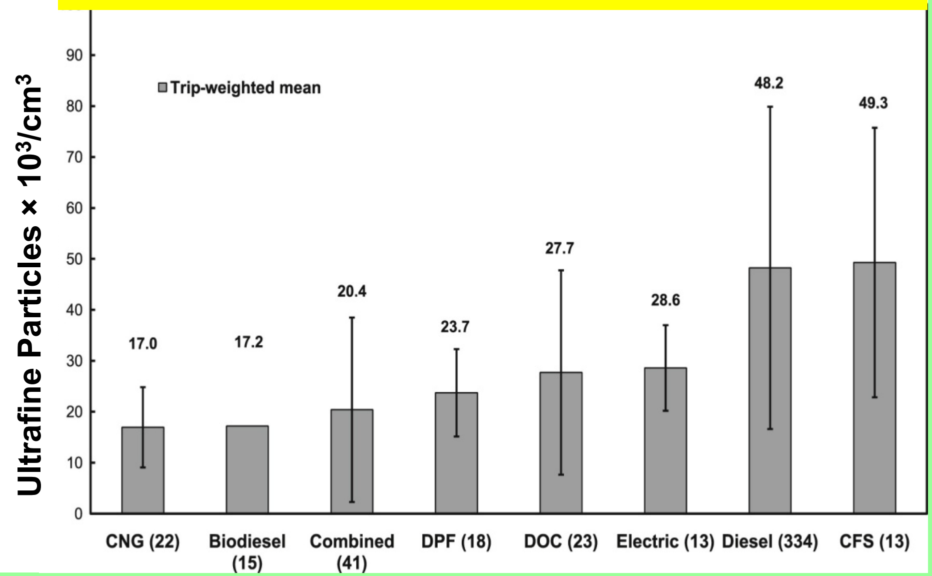
Some pollutants that cause adverse effects are not yet measured or managed

Ultrafine particles varied depending on transport modes



Mode of Transportation
(number of trips)

Ultrafine particles in buses varied by threefold depending on fuel type and emission control device(s) used



Type of Bus/Fuel (number of trips)

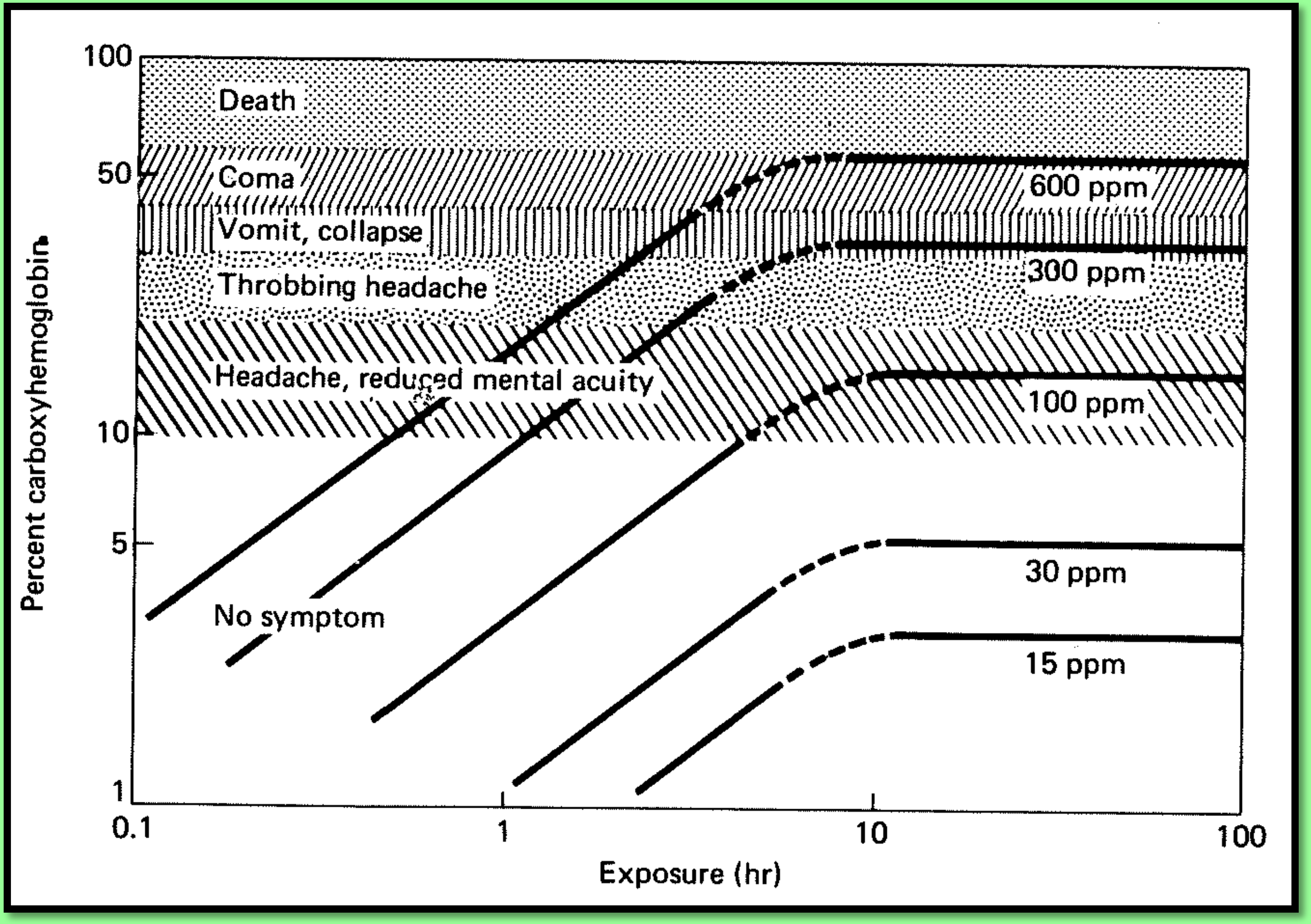
CNG: Compressed natural gas
DOC: Diesel with oxidation catalyst
DPF: Diesel with diesel particulate filter
CFS: Diesel with crankcase filtration system

*** Five to six times higher exposure in tunnel (299×10^3/cm^3)**

Knibbs et al., 2011, *Atmos. Environ.*

Levels for adverse health differ by pollutant

(CO has a well defined chemical character and health end-point)



Seinfeld, 1986

PM has multiple components and multiple health end-points that are not as well defined

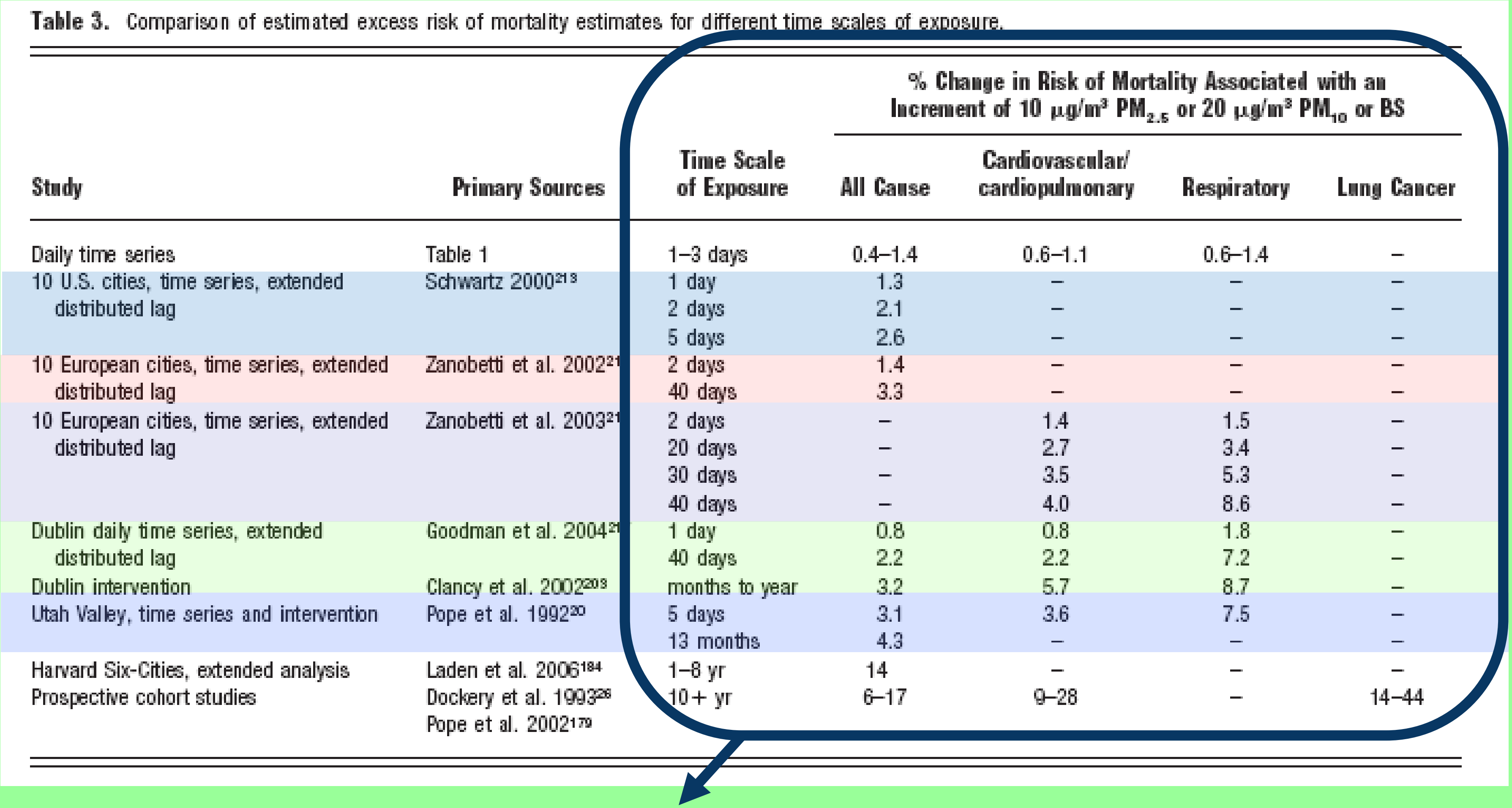


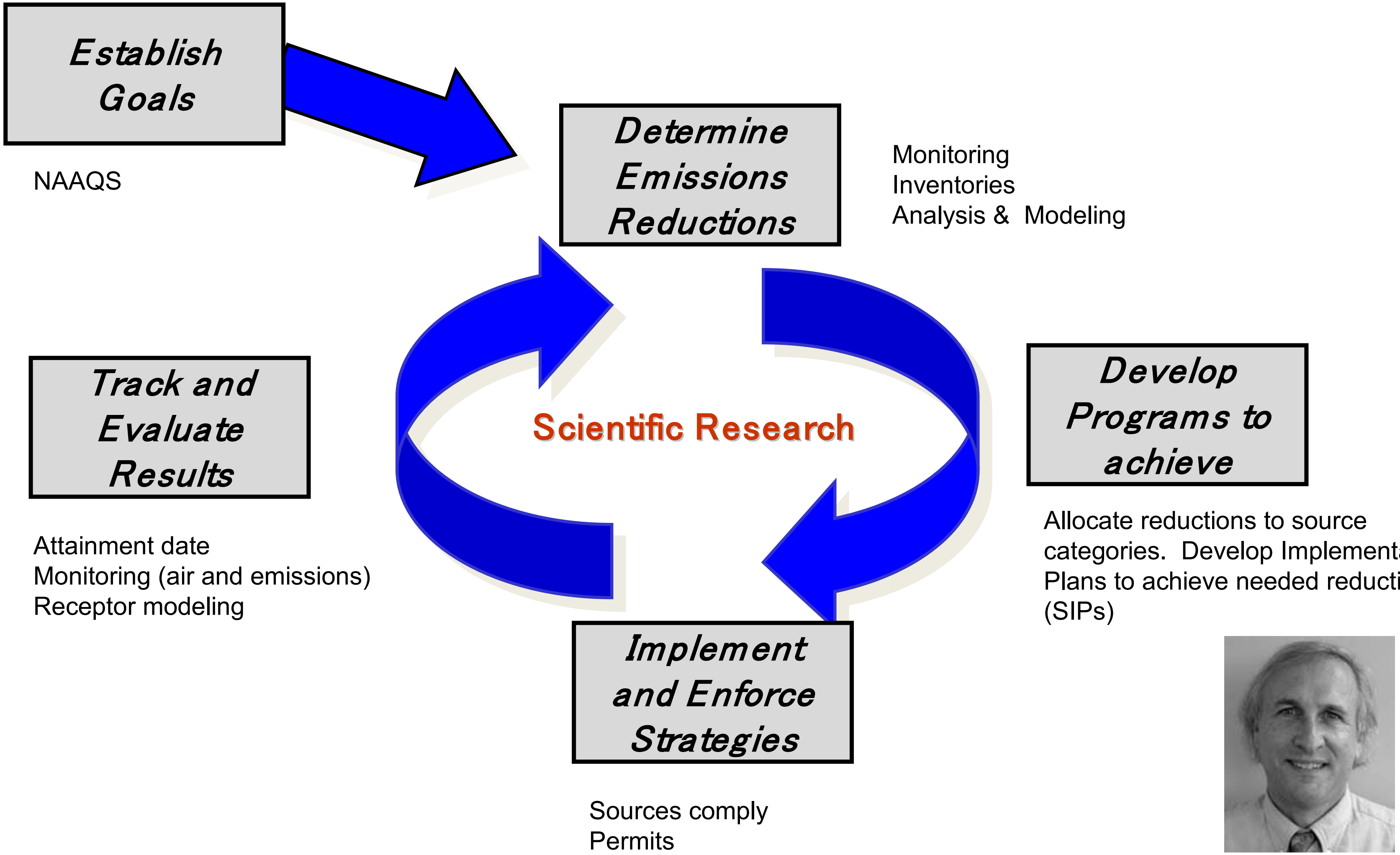
Table 3. Comparison of estimated excess risk of mortality estimates for different time scales of exposure.

Study	Primary Sources	Time Scale of Exposure	% Change in Risk of Mortality Associated with an Increment of 10 $\mu g/m^3$ $PM_{2.5}$ or 20 $\mu g/m^3$ PM_{10} or BS: All Cause	Cardiovascular/ cardiopulmonary	Respiratory	Lung Cancer
Daily time series	Table 1	1–3 days	0.4–1.4	0.6–1.1	0.6–1.4	–
10 U.S. cities, time series, extended distributed lag	Schwartz 2000[213]	1 day	1.3	–	–	–
		2 days	2.1	–	–	–
		5 days	2.6	–	–	–
10 European cities, time series, extended distributed lag	Zanobetti et al. 2002[21	2 days	1.4	–	–	–
		40 days	3.3	–	–	–
10 European cities, time series, extended distributed lag	Zanobetti et al. 2003[21	2 days	–	1.4	1.5	–
		20 days	–	2.7	3.4	–
		30 days	–	3.5	5.3	–
		40 days	–	4.0	8.6	–
Dublin daily time series, extended distributed lag	Goodman et al. 2004[21	1 day	0.8	0.8	1.8	–
		40 days	2.2	2.2	7.2	–
Dublin intervention	Clancy et al. 2002[203]	months to year	3.2	5.7	8.7	–
Utah Valley, time series and intervention	Pope et al. 1992[20]	5 days	3.1	3.6	7.5	–
		13 months	4.3	–	–	–
Harvard Six-Cities, extended analysis	Laden et al. 2006[184]	1–8 yr	14	–	–	–
Prospective cohort studies	Dockery et al. 1993[28] Pope et al. 2002[179]	10+ yr	6–17	9–28	–	14–44

PM-mortality effect estimates are consistently larger for longer time scales of exposure.

Pope and Dockery, 2006, *JAWMA*

U.S. EPA has applied an iterative process for air quality management since 1970



Establish Goals

NAAQS

Determine Emissions Reductions

Monitoring
Inventories
Analysis & Modeling

Scientific Research

Develop Programs to achieve

Allocate reductions to source categories. Develop Implementation Plans to achieve needed reductions. (SIPs)

Implement and Enforce Strategies

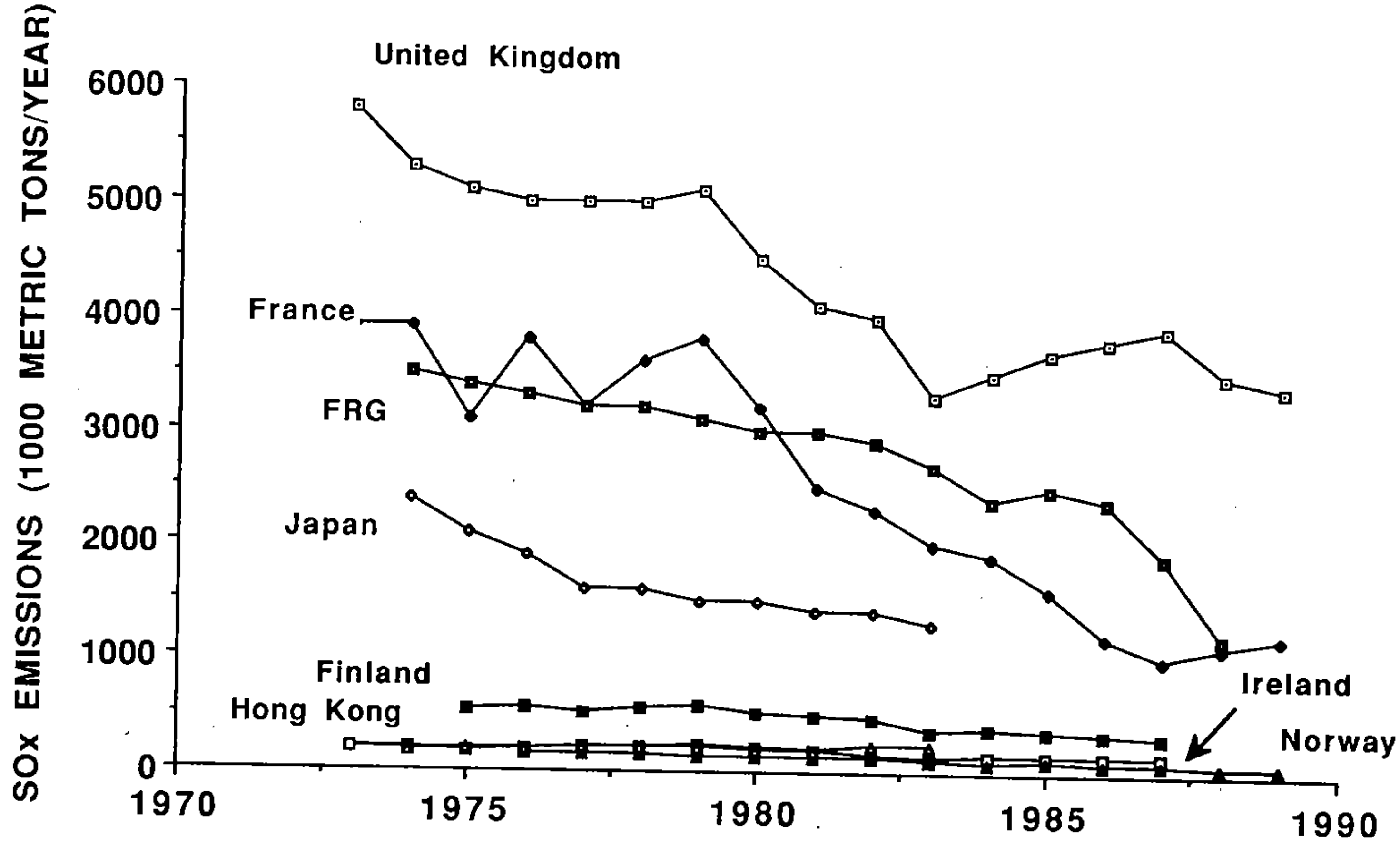
Sources comply
Permits
Enforcement

Track and Evaluate Results

Attainment date
Monitoring (air and emissions)
Receptor modeling

Bachmann, 2007, *JAWMA*

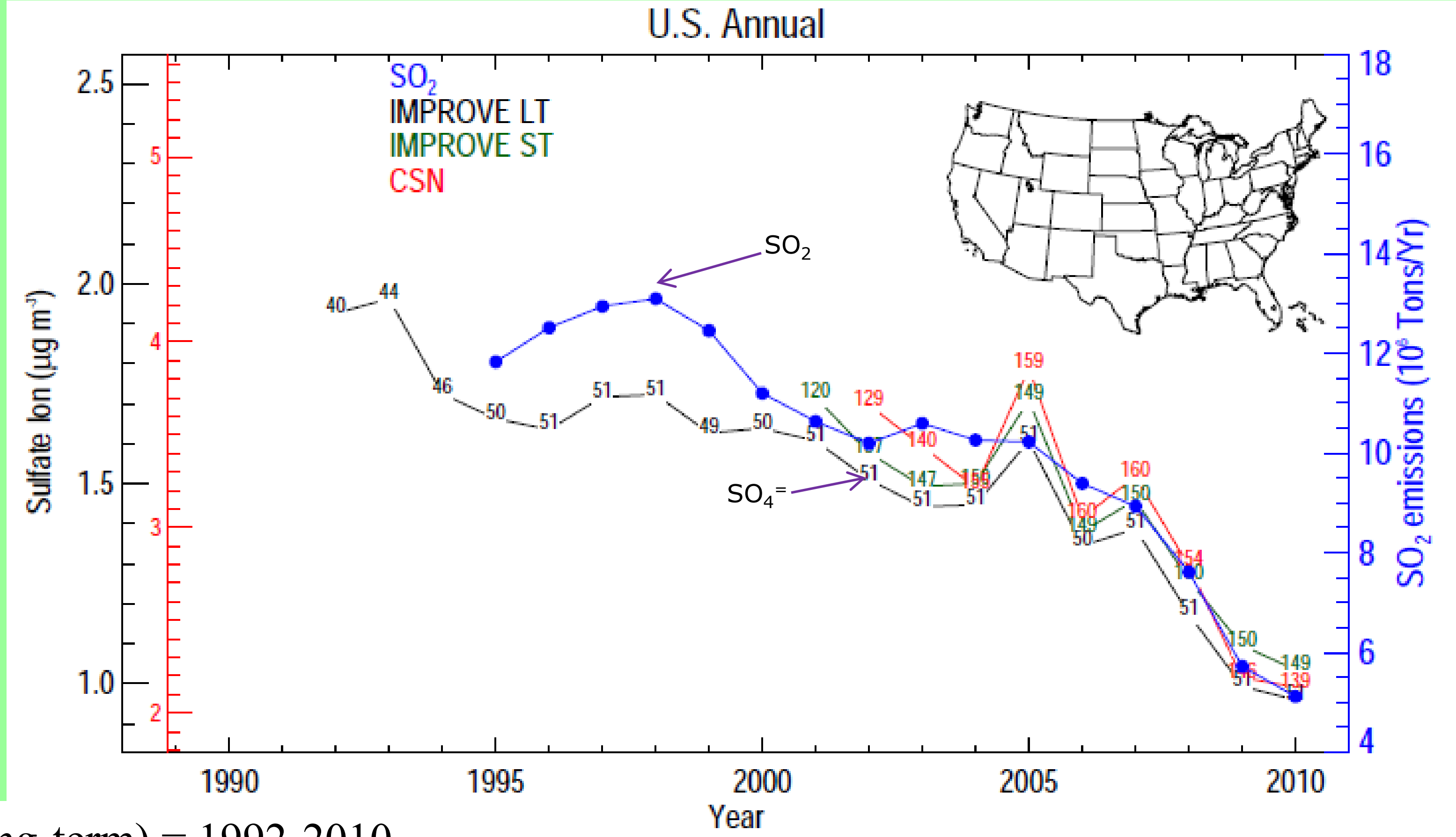
Sulfur oxides (SO$_x$) emission reductions are apparent since the 1970s



Bachmann, 2007, *JAWMA*

Reduction in SO_2 emissions also reduced sulfate concentrations

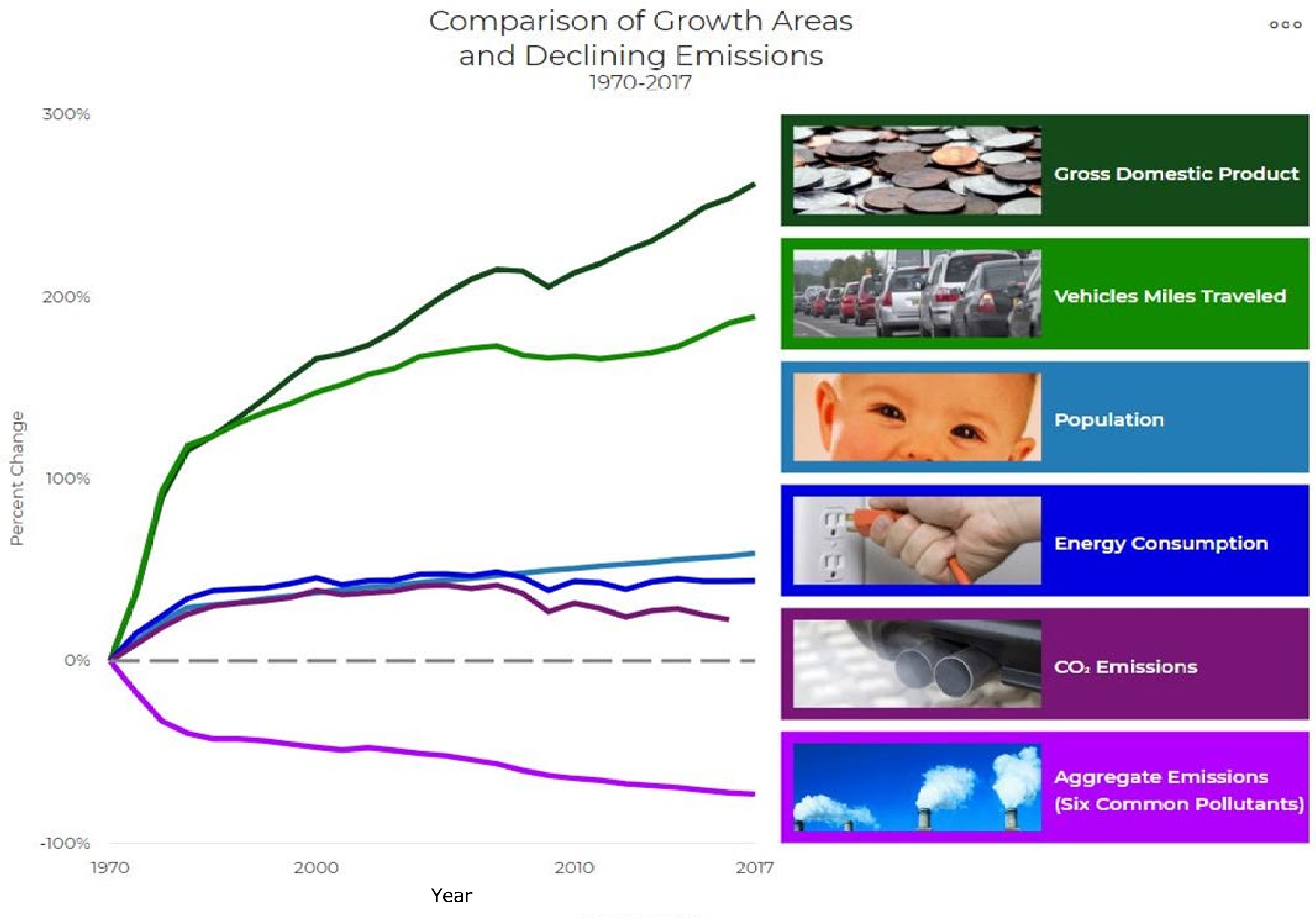
(Emission reduction effectiveness are ~6% per year for SO_2 and 3-6% per year for $SO_4^=$)



LT (long-term) = 1992-2010
ST (short-term) = 2001-2010

Hand et al. (2012) *Atmos Chem & Phys*

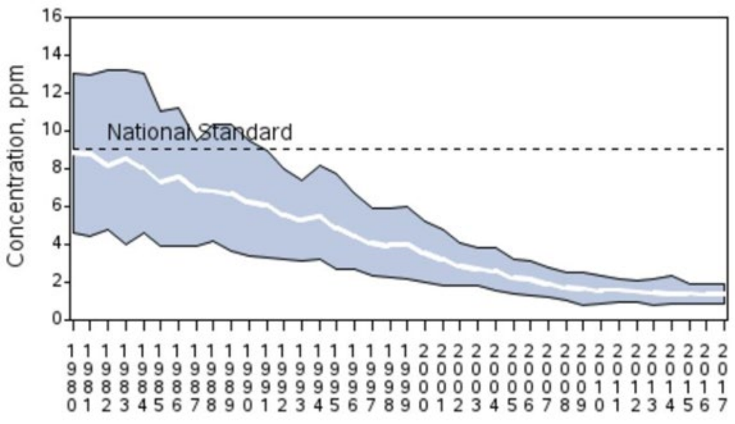
U.S. emission reduction does not adversely affect economic growth



https://gispub.epa.gov/air/trendsreport/2017/#growth_w_cleaner_air/

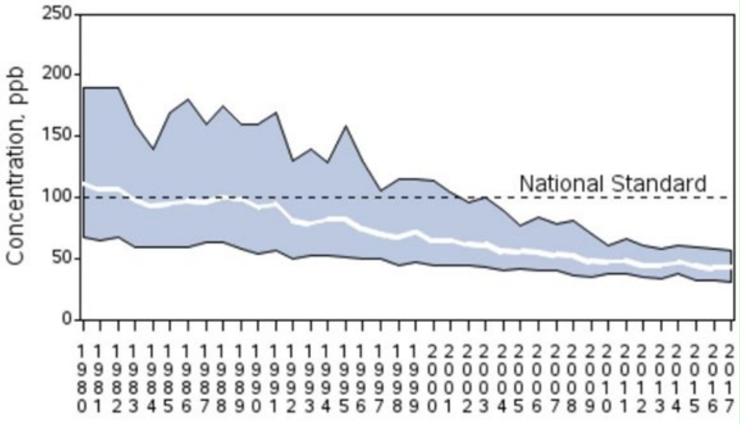
Improvement in U.S. air quality is shown by decreasing ambient trends (1980 – 2017; except $PM_{2.5}$)

CO



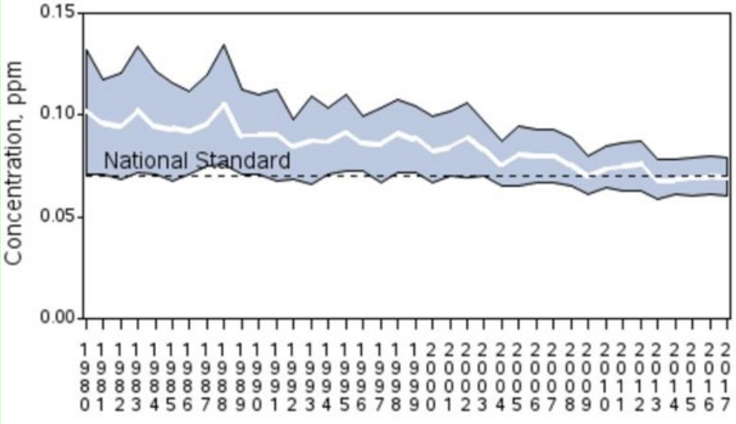
1980 to 2017 : 84% decrease in National Average

NO_2



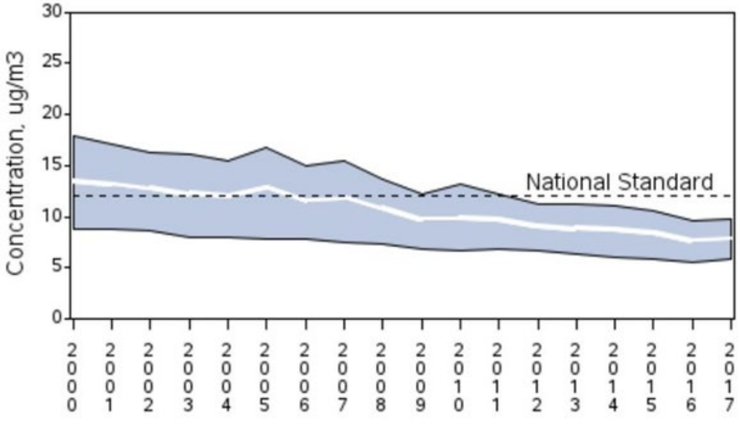
1980 to 2017 : 60% decrease in National Average

O_3



1980 to 2017 : 32% decrease in National Average

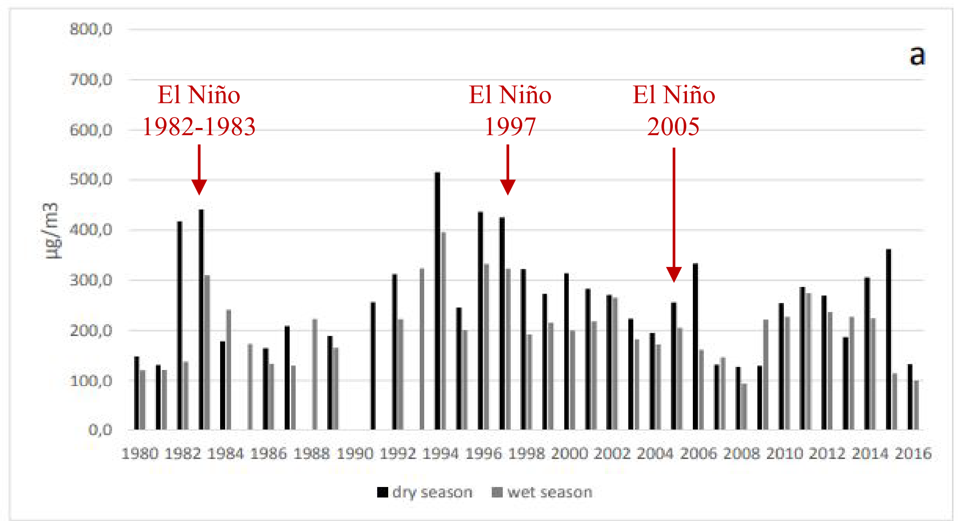
$PM_{2.5}$



2000 to 2017 : 41% decrease in National Average

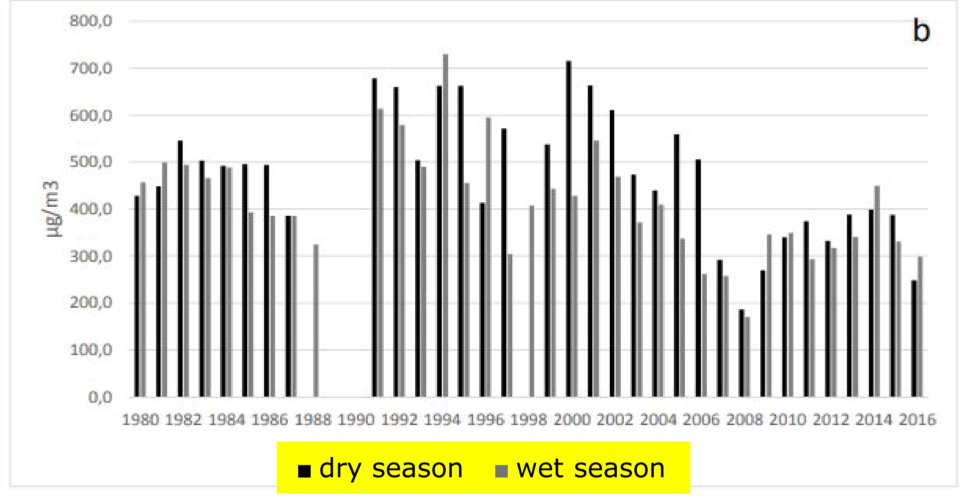
https://www.epa.gov/air-trends

Long-term suspended particulate matter (SPM) concentrations in Jakarta shows decreasing trend (1980-2016)



a) **Ancol** (N. Jakarta, coastal site)

(Effect by precipitation)



b) **Glodok** (W. Jakarta, center business site)

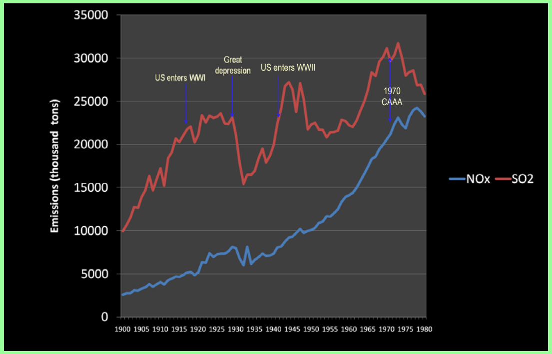
(No apparent effect by precipitation)

*dry season (May-Sep); wet season (Nov-Mar)

Kusumaningtyas et al., 2018, *AAQR*

Air quality measurements are used to address multiple monitoring objectives

- Determine compliance with air quality standards
  (0 – 50 Km)

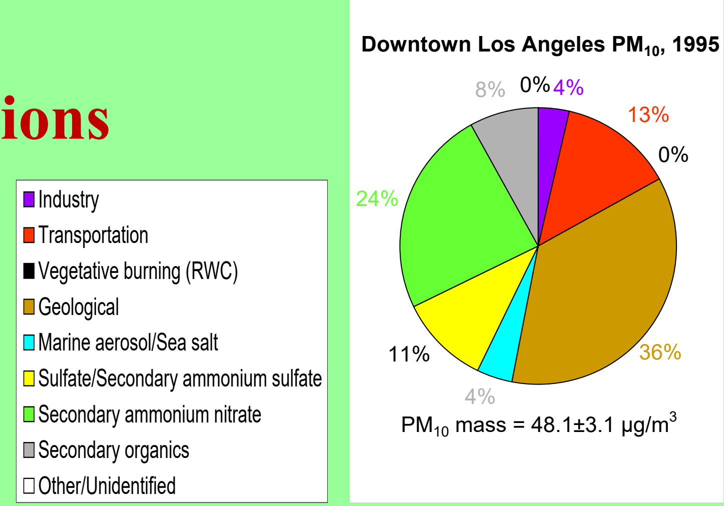


- **Understand atmospheric processes**
  (0 – 1,000 Km)

- Develop/test air quality models
  (0 – 1,000 Km)

- **Identify and quantify source contributions**
  (0 – 100 Km)

- Estimate immediate and long-term hazards
  (0 – 100 Km)

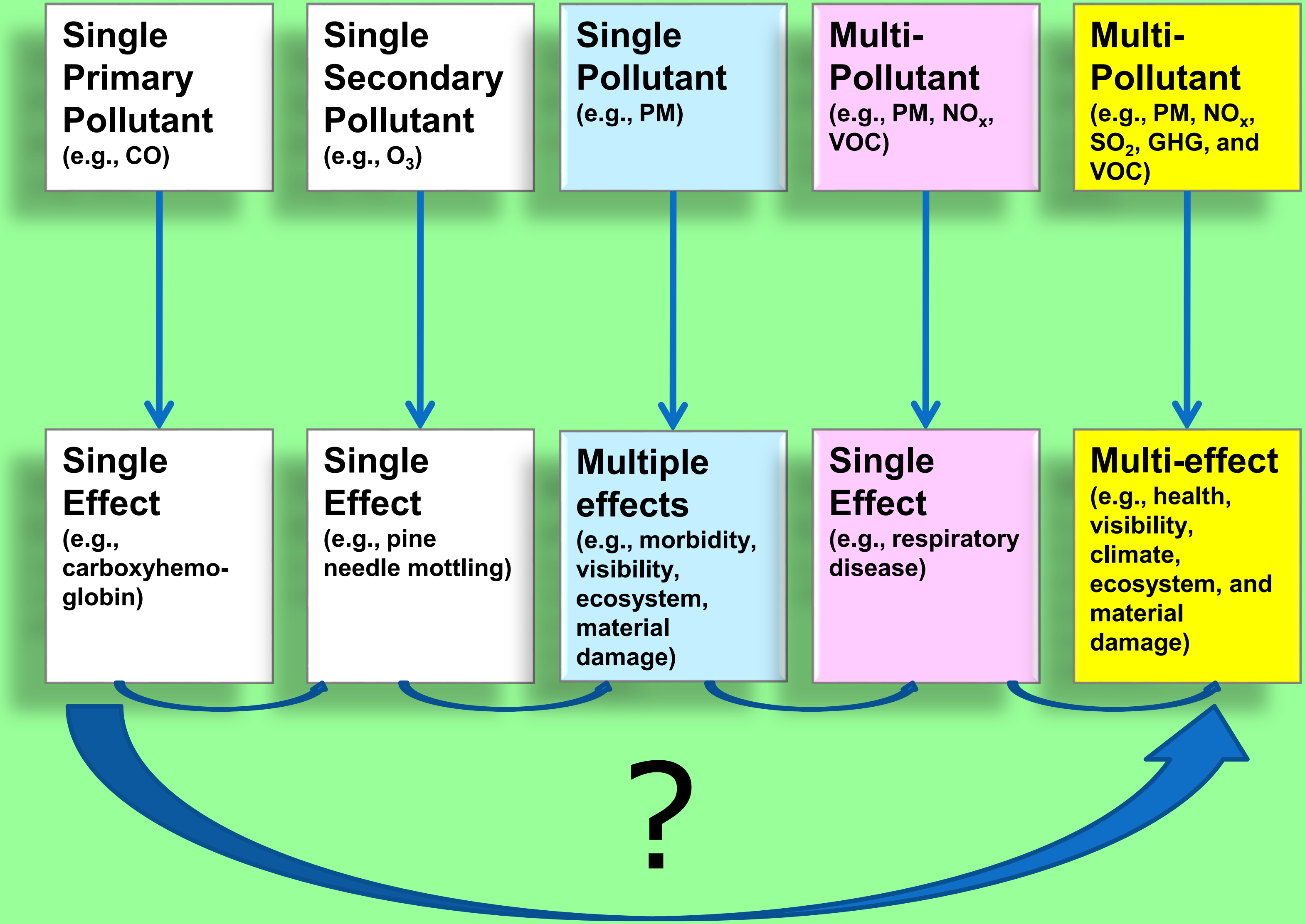


Air quality measurements and modeling are key components of air quality management

- Forecast future air quality (0 – 100 Km)
- **Relate emissions and air quality to effects**
  - Health impacts (0 – 100 Km)
  - Material and ecosystem damage (0 – 100 Km)
  - Visibility degradation (0 – 1,000 Km)
  - Climate change (> 10,000 Km)

- Evaluate control strategy effectiveness (trends; 0 – 1,000 Km)

Air Quality Management should consider multi-pollutants and multi-effects, but how to get there?



Single Primary Pollutant (e.g., CO)

Single Secondary Pollutant (e.g., O_3)

Single Pollutant (e.g., PM)

Multi-Pollutant (e.g., PM, NO_x, VOC)

Multi-Pollutant (e.g., PM, NO_x, SO_2, GHG, and VOC)

Single Effect (e.g., carboxyhemoglobin)

Single Effect (e.g., pine needle mottling)

Multiple effects (e.g., morbidity, visibility, ecosystem, material damage)

Single Effect (e.g., respiratory disease)

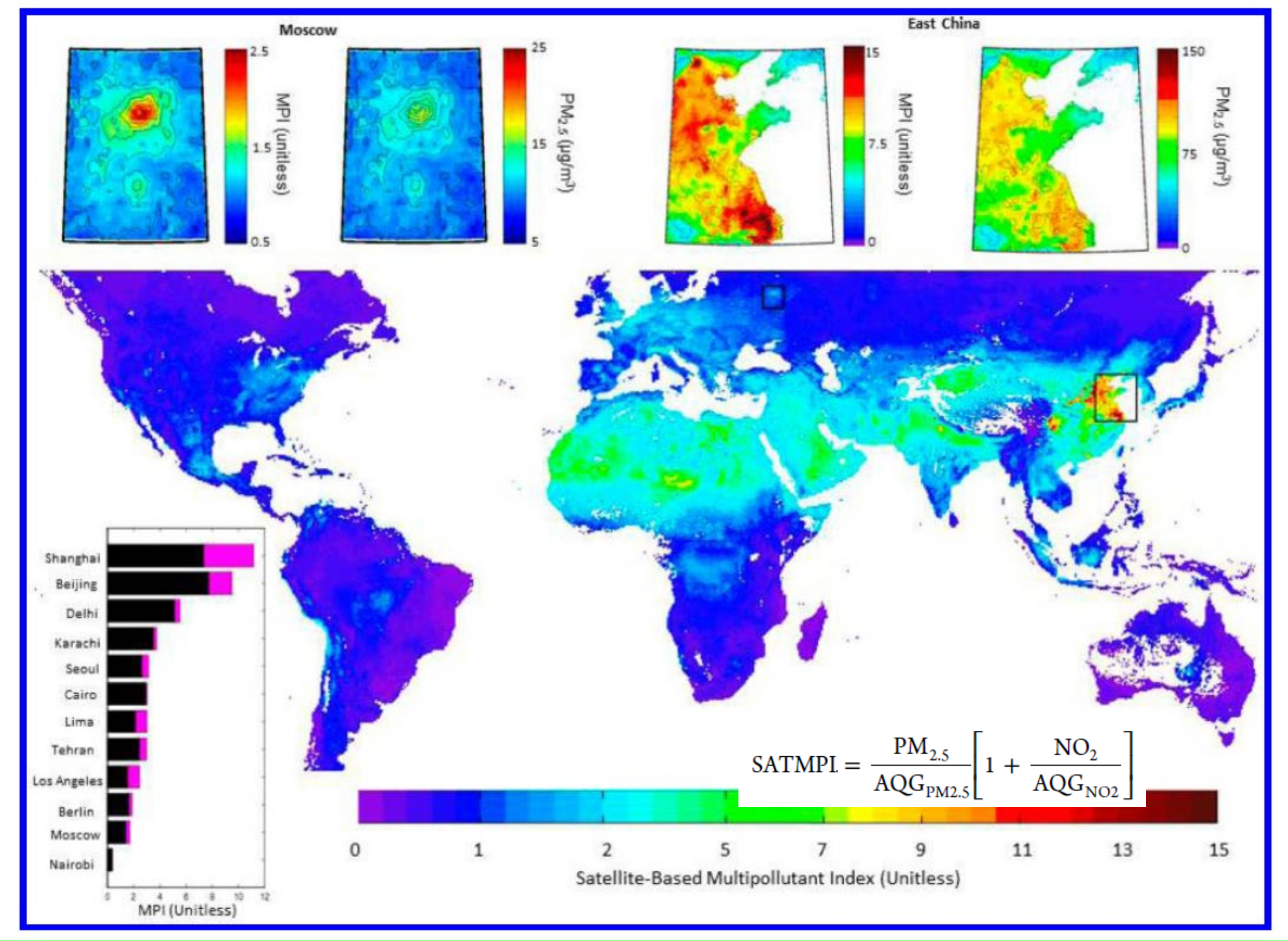
Multi-effect (e.g., health, visibility, climate, ecosystem, and material damage)

?

Watson, 2010

Satellite-based multipollutant indices (MPI) indicate global hot spots, but they are insufficient for evaluating ground-based exposures

Black and violet indicate the $PM_{2.5}$ and NO_2 contributions, respectively



$$\mathrm{SATMPI} = \frac{PM_{2.5}}{AQG_{PM2.5}}\left[1 + \frac{NO_2}{AQG_{NO2}}\right]$$

*AQG: WHO Air Quality Guideline of 10 μg/m³ for $PM_{2.5}$ and 40 μg/m³ for NO_2

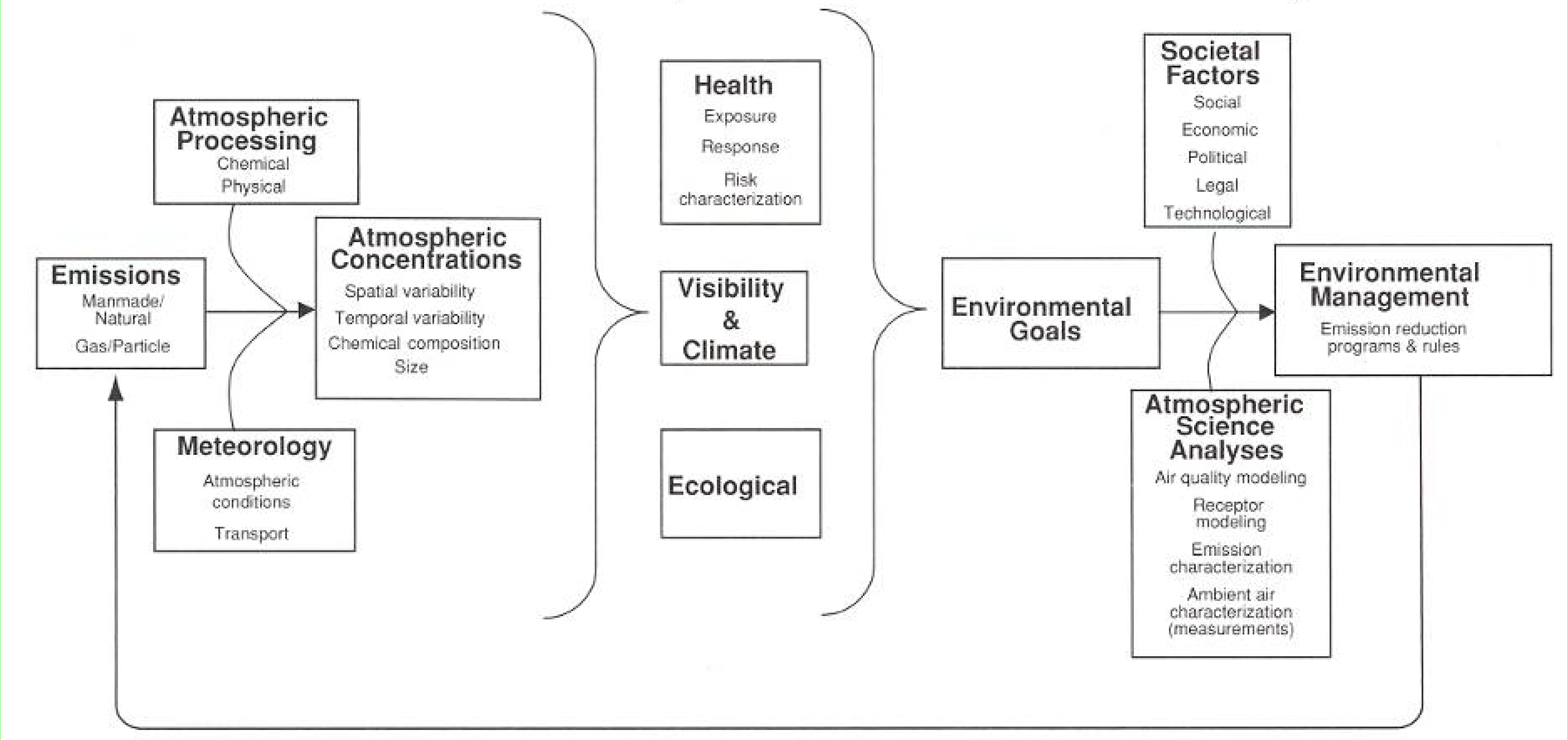
Cooper et al. (2012). Science & Technology

Air quality management considers multiple sources, pollutants, effects, and assessment methods

The Atmospheric Environment

Exposure and Impacts

Analysis and Public Policy

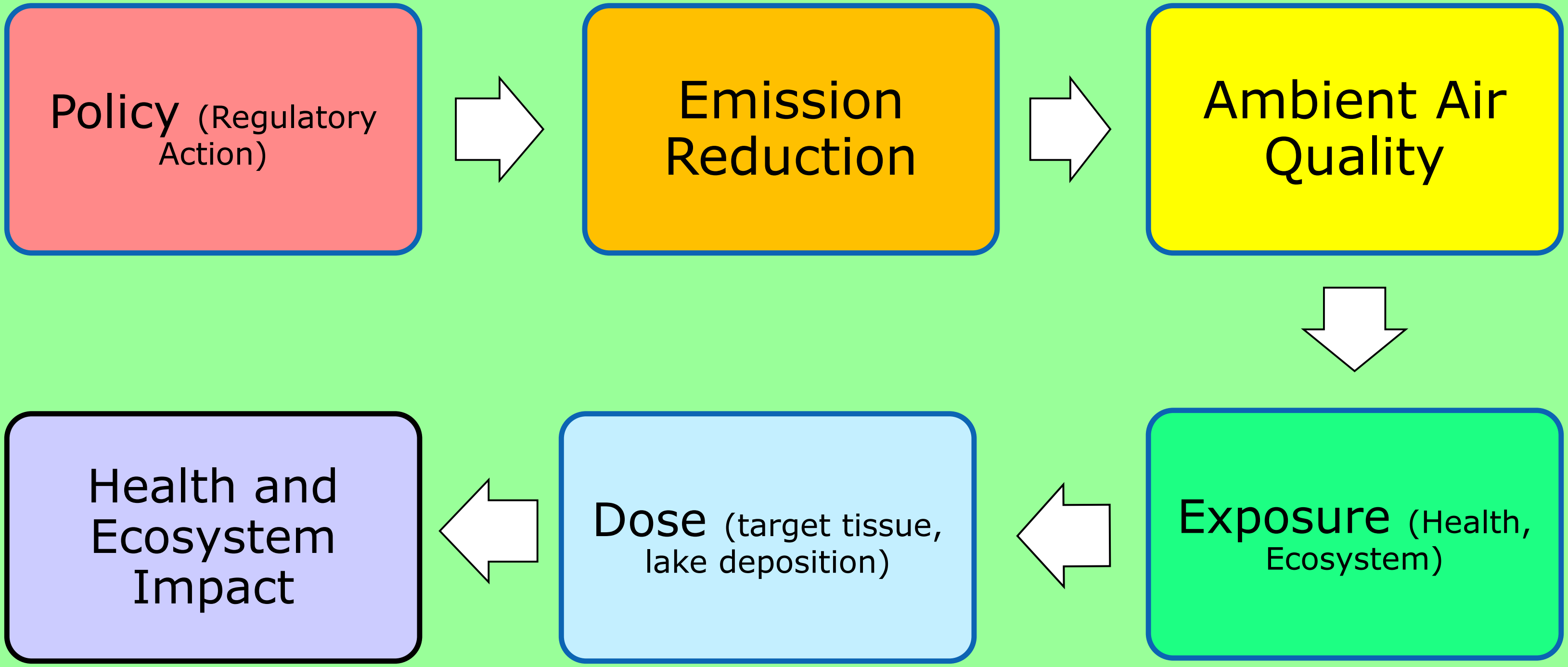


McMurry et al. (2004). Particulate Matter Science for Policy Makers

Single pollutant monitoring approaches are hard to change

- Large investments have been made in existing networks (e.g., equipment and expertise)
- **Overlapping networks with different operations disguise real costs**
- Increase in workload for local pollution agencies (e.g., lack of funding)
- **Deficiencies in collaboration**
- Lack of awareness for alternative methods (e.g., influence by vendors for turnkey systems)
- **Absence of long-term commitments from government and other agencies**

Accountability must be measured at various stages to demonstrate pollution control effectiveness



Policy (Regulatory Action)

Emission Reduction

Ambient Air Quality

Exposure (Health, Ecosystem)

Dose (target tissue, lake deposition)

Health and Ecosystem Impact

NRC, 2004; Bell et al., 2010, *Environ. Sci. Technol.*

Challenges in Accountability Research

- **Track changes in emissions and air quality**
- Evaluate health response and environmental changes for air quality effects
- **Estimate economic values**
  (e.g., sensitivity analysis)
- Anticipate unintended consequences and assess long-term responses

Bell et al., 2010, *Environ. Sci. Technol.*

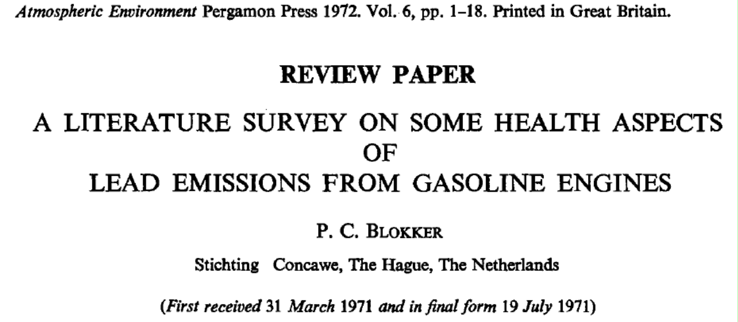
Example of the Law of Unintended Consequences*

Leaded gasoline was introduced in 1923 (tetra-ethyl lead, called ethyl) permitted higher engine compression ratios that improved fuel efficiency

* Any intervention in a complex system always creates unanticipated and often undesirable outcomes.

"Ethyl IS TO GASOLINE what VITAMINS are to FOOD"

There is ample evidence that excessive lead impairs intelligence



Atmospheric Environment Pergamon Press 1972. Vol. 6, pp. 1–18. Printed in Great Britain.

REVIEW PAPER

A LITERATURE SURVEY ON SOME HEALTH ASPECTS OF LEAD EMISSIONS FROM GASOLINE ENGINES

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(*First received* 31 *March* 1971 *and in final form* 19 *July* 1971)

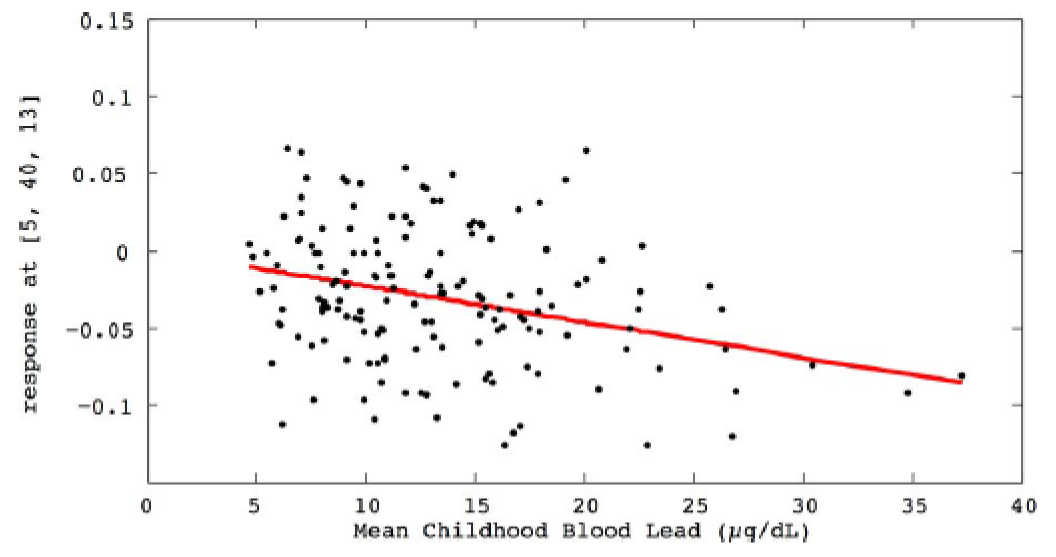


Figure 2. Regional Brain Volume Loss for the Cincinnati Lead Study Participants

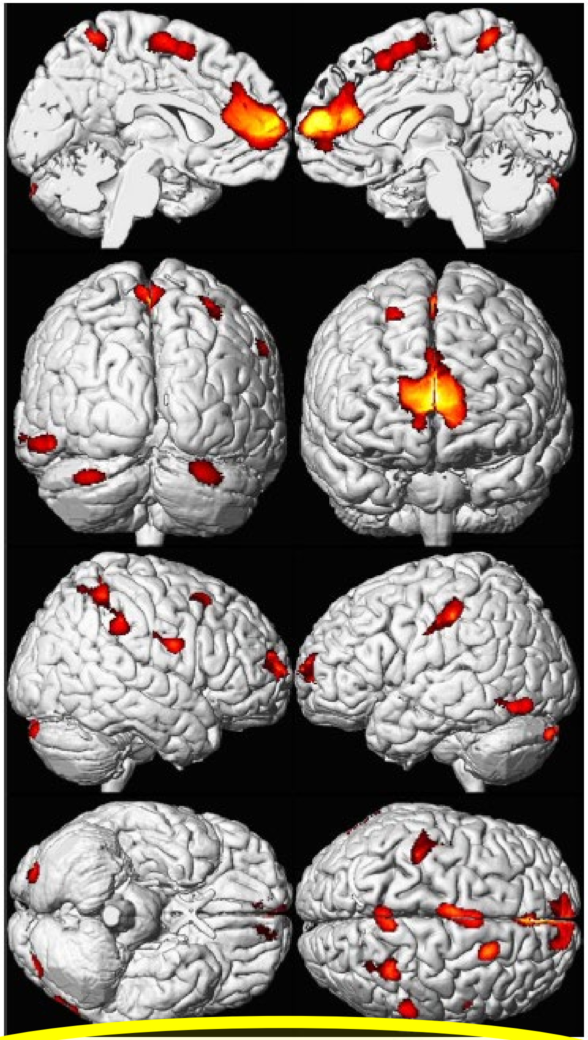
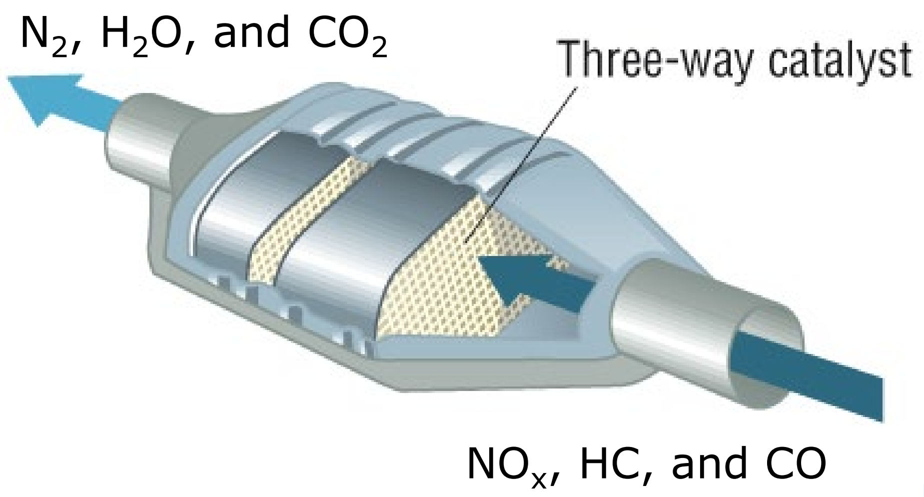


Figure 1. Regional Brain Volume Loss for the Cincinnati Lead Study Participants

A composite representation of regions with significant volume loss for male and female CLS participants ($n = 157$) associated with mean childhood blood lead concentrations is shown with red and yellow clusters overlaid upon a standard brain template (seen at multiple angles; the first row presents views from the midline of the left and right hemispheres, respectively; the second row demonstrates views from the back and front of the cerebrum, respectively; the third row shows the lateral right and left hemispheres; and the fourth row shows views from below and above the cerebrum. Brain template source reference [51]. doi:10.1371/journal.pmed.0050112.g001

Cecil et al. (2008) *PLoS Med*

Yet lead additives were not prohibited until multipollutant controls were implemented with catalytic converters



Catalytic converters were installed on gasoline-powered vehicles in the early 1970s to reduce oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO).

Lead poisons the catalysts, so it was necessary to stop adding it to the fuel. The Pb NAAQS was not established until 1978.

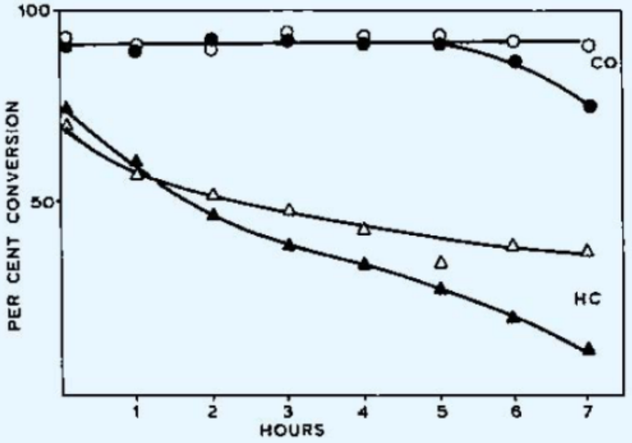


Fig. 5 Simulated poisoning of fresh catalyst

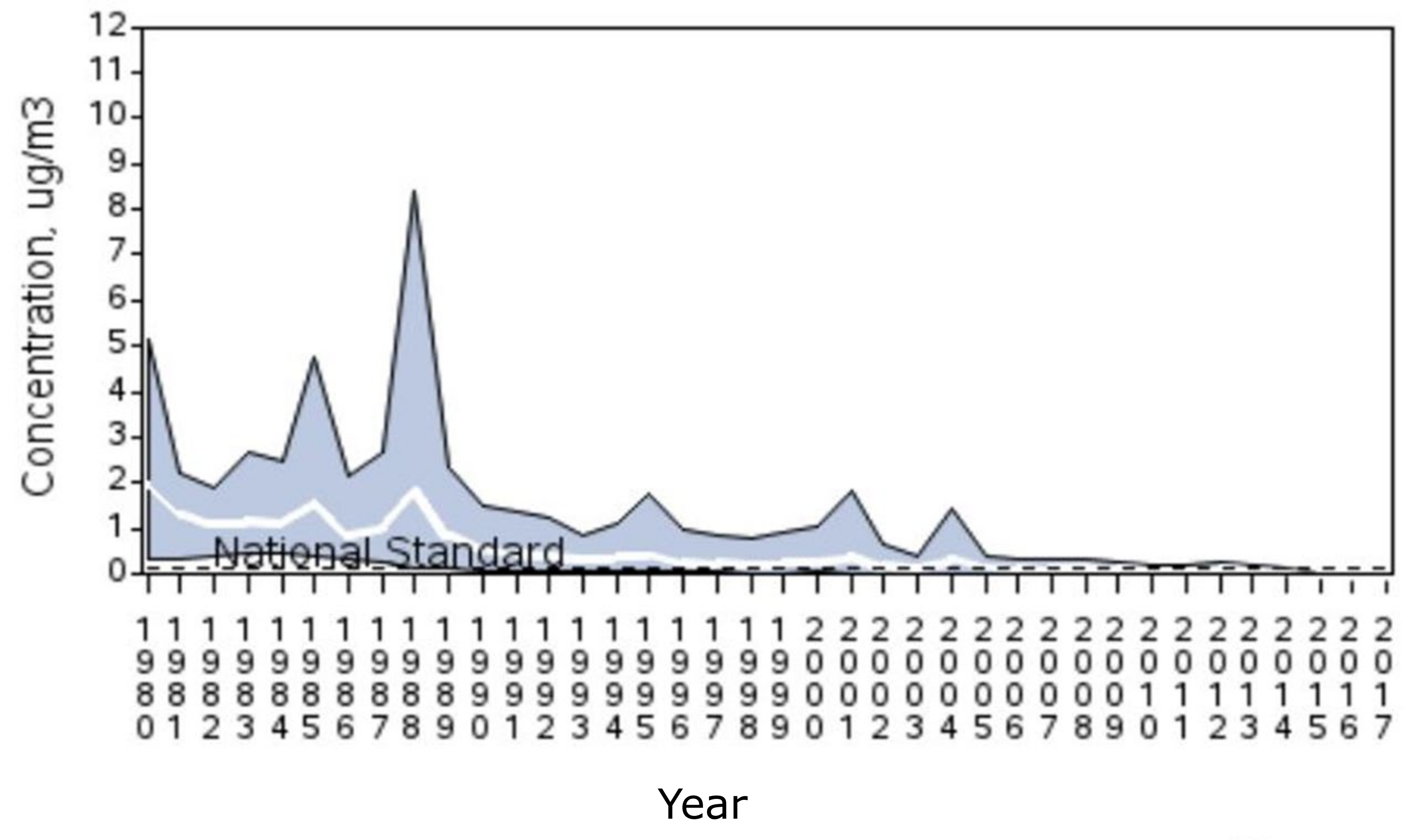
○ △ Lead — 1.5 grams per U.S. gallon

● ▲ Lead — 1.5 grams per U.S. gallon with stoichiometric ethylene dibromide

Cooper (1975) *Platinum Metals Review*

A side-benefit of the multipollutant strategy is a large decrease in lead exposures

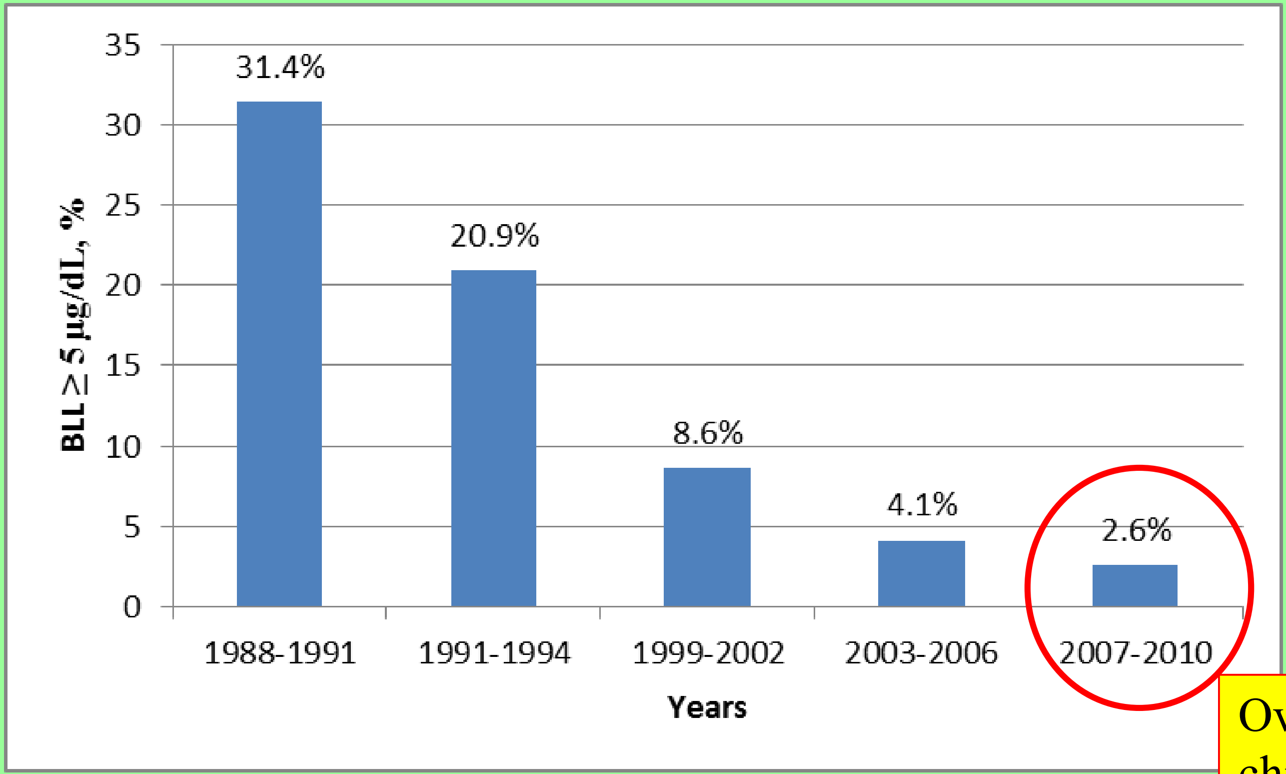
(1980-2017)



As NAAQS for Pb is 0.15 μg/m^3 for 3 month average of TSP

https://www3.epa.gov/airtrends/lead.html

Downward trend is found in blood lead level (BLL) for U.S. children (aged 1-5 years)



Over 535,000 U.S. children

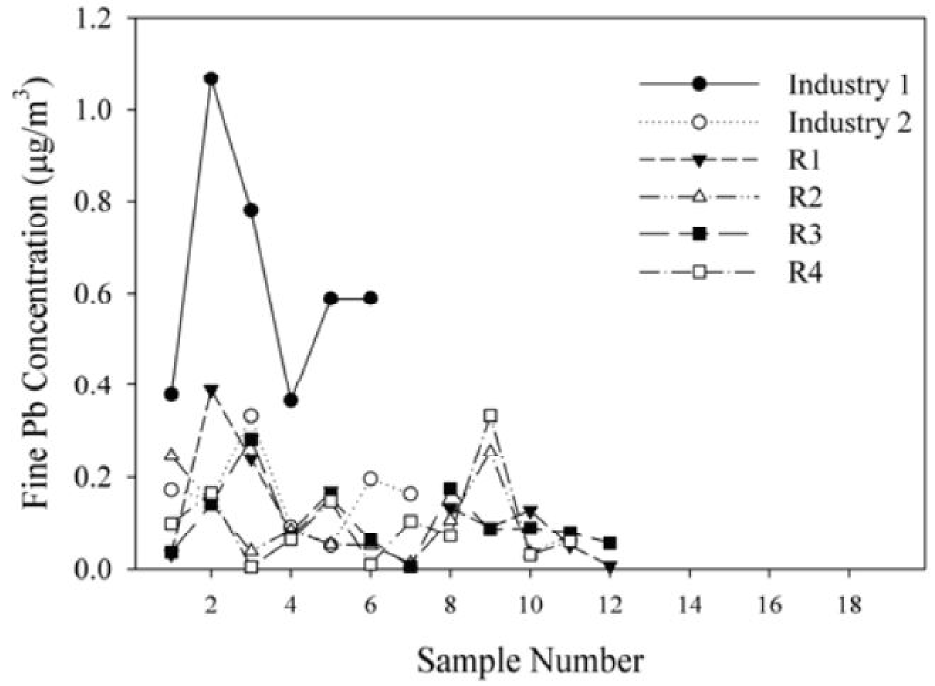
As of May 2012, new reference value is 5 µg per deciliter

Burns and Gerstenberger, 2014, *American Journal of Public Health*

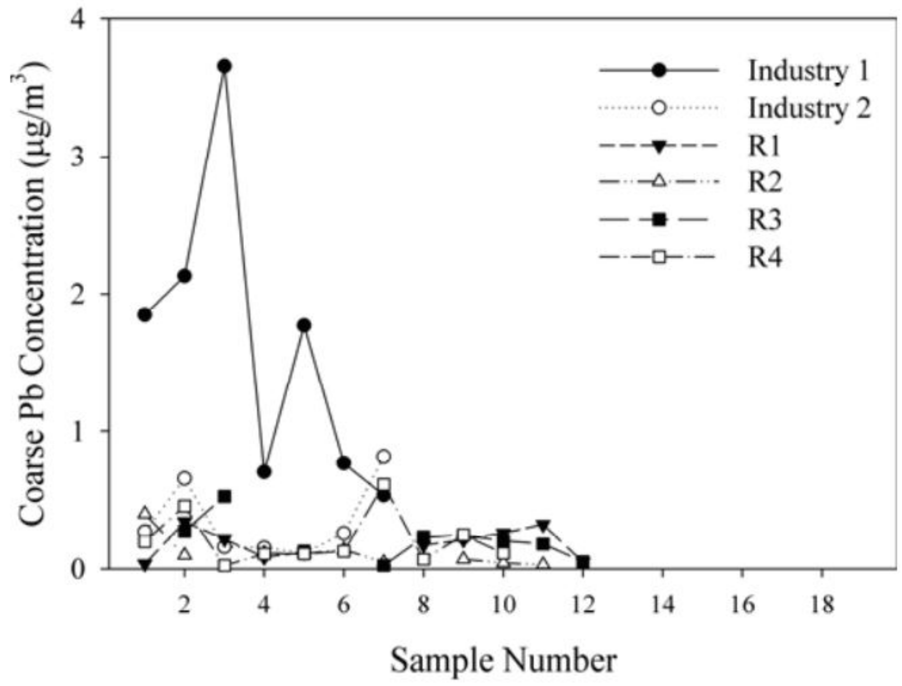
Elevated lead concentrations are found in Serpong, Indonesia

(Aug-Nov 2018)

PM$_{2.5}$



PM$_{10}$



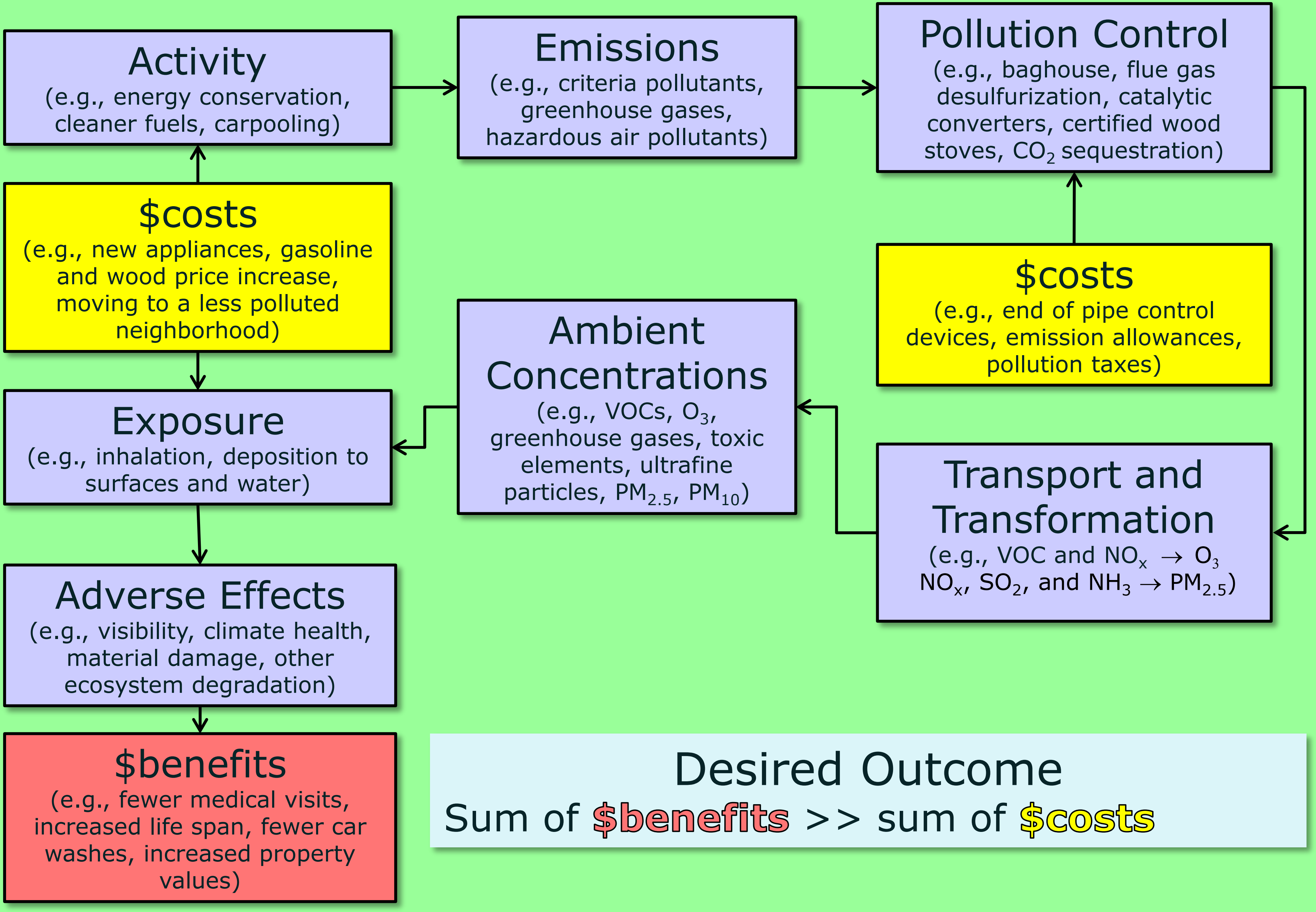
*US NAAQS is 0.15 μg/m^3 (3 months rolling average TSP), much lower than 1 μg/m^3 annual average and 2 μg/m^3 24-hr average standards in Indonesia (Ministry of Environment, 2016)

Santoso et al., 2011, *APR*

Future Steps Toward Multi-pollutant Air Quality Management

- Improve ambient monitoring (e.g., multi-pollutant sensors)
- **Conduct real-world emission tests that are comparable to ambient measurement methods**
- Institute multi-tiered (less costly -> more costly) technologies
- **Evaluate the effects of O_3 and $PM_{2.5}$ control strategies together**
- Incorporate planning and progressive changes in emission reduction strategies
- **Estimate co-benefits for multi-pollutants on multi-effects**

Benefits should exceed costs for multi-effects



Activity
(e.g., energy conservation, cleaner fuels, carpooling)

Emissions
(e.g., criteria pollutants, greenhouse gases, hazardous air pollutants)

Pollution Control
(e.g., baghouse, flue gas desulfurization, catalytic converters, certified wood stoves, CO_2 sequestration)

$costs
(e.g., new appliances, gasoline and wood price increase, moving to a less polluted neighborhood)

$costs
(e.g., end of pipe control devices, emission allowances, pollution taxes)

Ambient Concentrations
(e.g., VOCs, O_3, greenhouse gases, toxic elements, ultrafine particles, $PM_{2.5}$, PM_{10})

Exposure
(e.g., inhalation, deposition to surfaces and water)

Transport and Transformation
(e.g., VOC and $NO_x \rightarrow O_3$
NO_x, SO_2, and $NH_3 \rightarrow PM_{2.5}$)

Adverse Effects
(e.g., visibility, climate health, material damage, other ecosystem degradation)

$benefits
(e.g., fewer medical visits, increased life span, fewer car washes, increased property values)

Desired Outcome

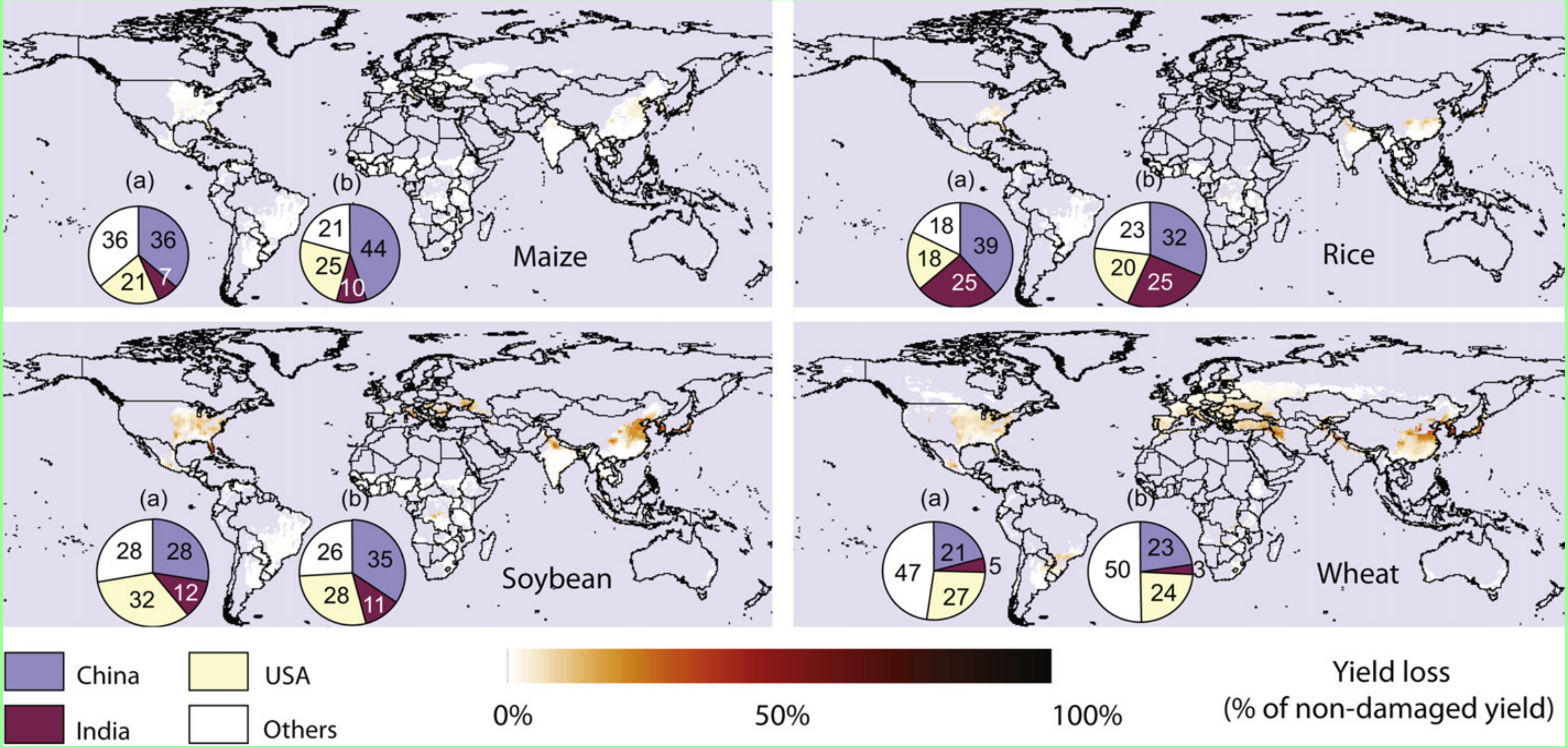
Sum of **$benefits** >> sum of **$costs**

What tools quantify co-benefits?
Some are obvious and need no quantification

Mark IV 5 kW
experimental
downdraft stove

In addition to health, excessive O_3 causes global crop losses

(potential crop losses of 21-44% for China and parts of southeast Asia)



a) percentage share of global land at risk
b) loss of crop production

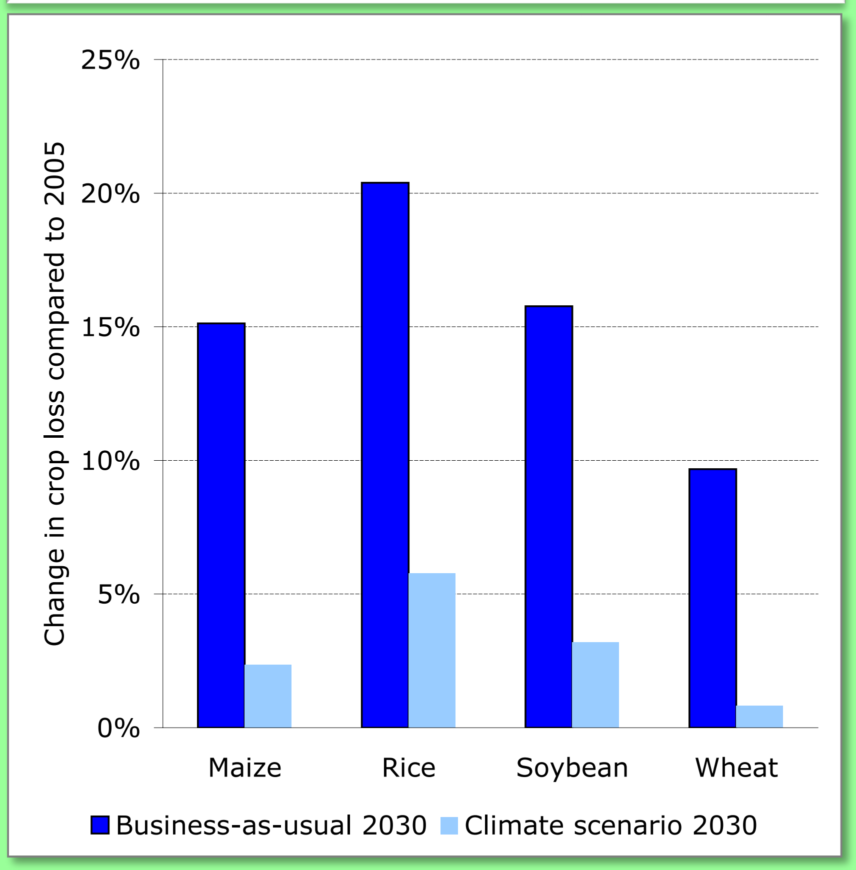
Teixeira et al., 2011, *Atmos. Environ.*

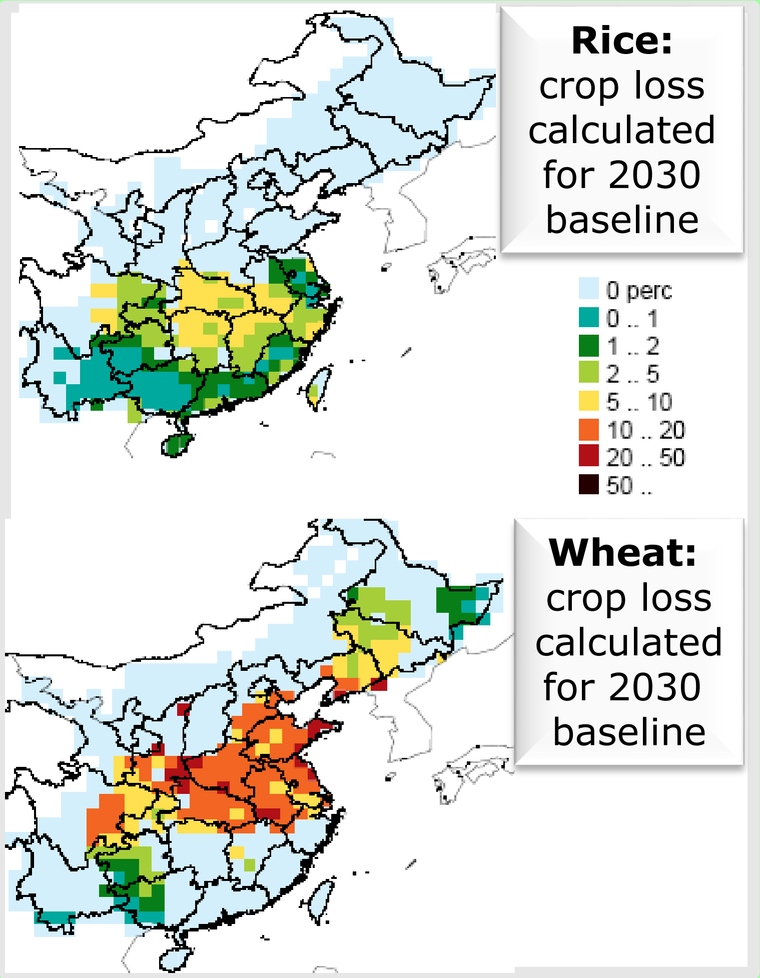
What do co-benefit results look like?

Co-benefits of greenhouse gas mitigation on crop losses

(China)

Change in crop loss due to ground-level ozone compared to 2005



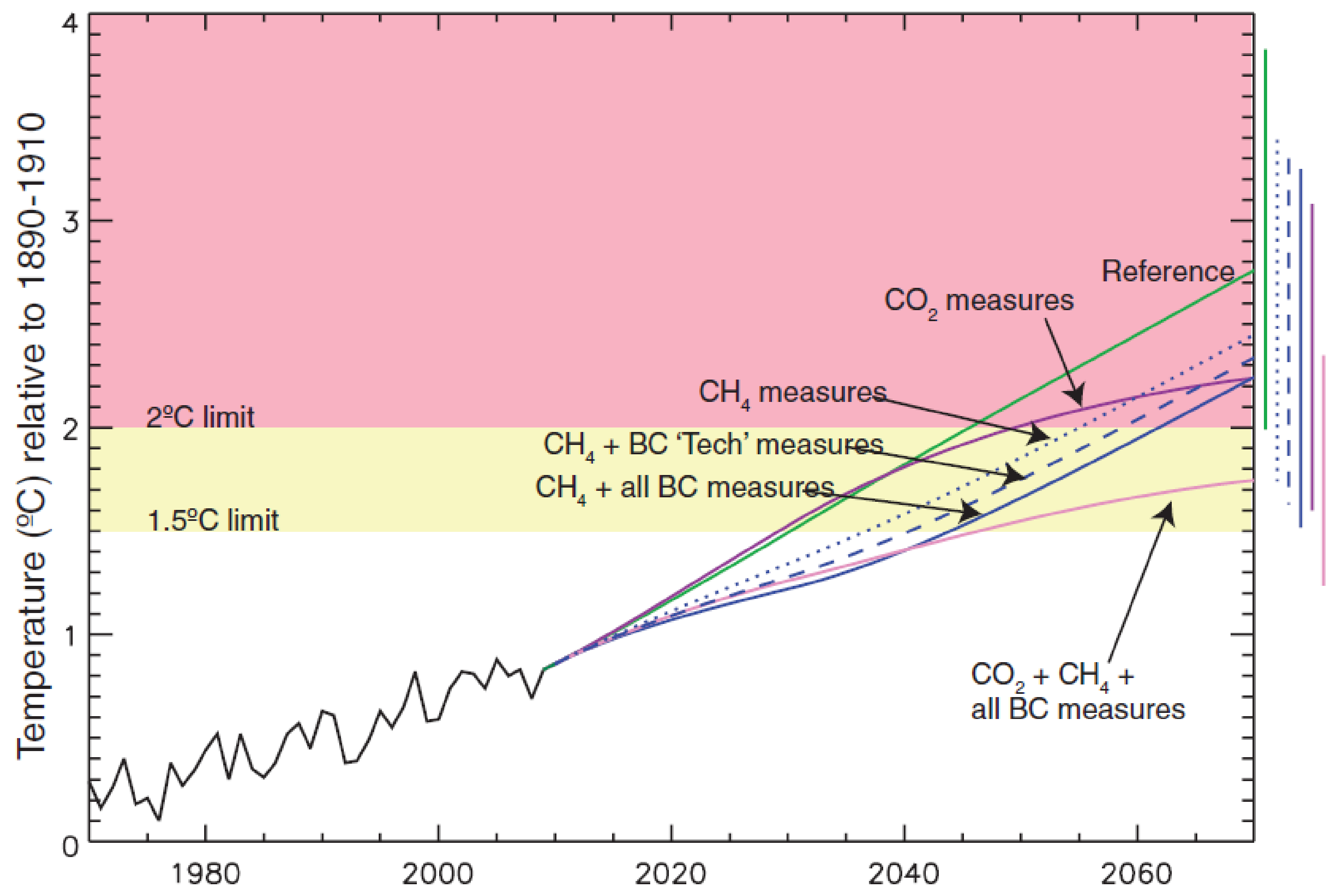


Rice:
crop loss
calculated
for 2030
baseline

Wheat:
crop loss
calculated
for 2030
baseline

GAINS-ASIA http://gains.iiasa.ac.at

Climate co-benefits result from mitigating global CO_2, CH_4, and BC emissions



Shindell et al. (2009) *Science*

Conclusions

- Single pollutant air quality management has been successful in the past, but multi-pollutant/multi-effect approaches are needed for the future.

- **Conceptual multi-pollutant approaches are not yet practical, but incremental steps can be taken to move forward.**

- Co-benefits can be achieved by managing multi-pollutants and multi-effects.

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