ENVE 576
Indoor Air Pollution
Spring 2013

Lecture 12: April 16, 2013
1. Exam solutions and review
2. Indoor air pollution in developing countries

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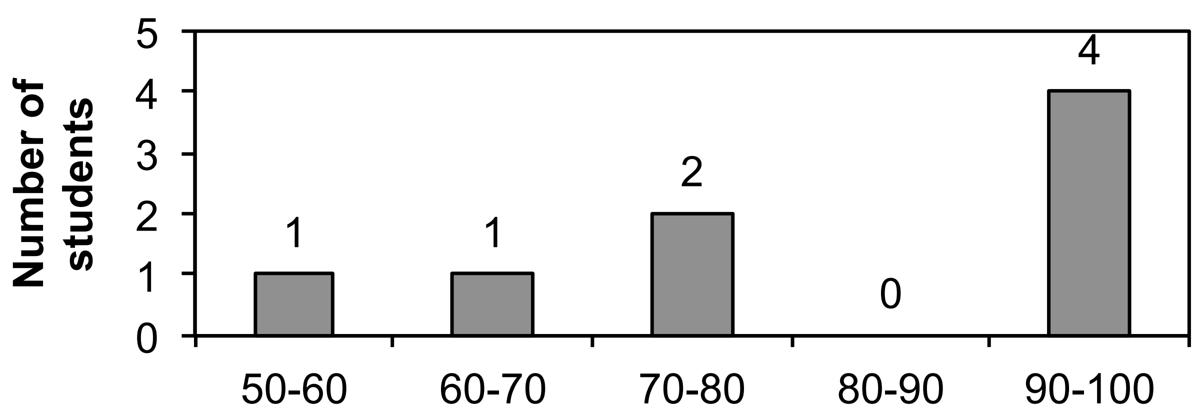
Exam

- Your exams have been graded
  - Returned via email or in class
- Grade distribution:

Problem	**Possible**	**Mean**	**Min**	**Max**
1	35	34 (0.96)	30 (0.86)	35 (1.0)
2	40	34 (0.86)	20 (0.50)	40 (1.0)
3	75	60 (0.80)	35 (0.47)	75 (1.0)
4	75	60 (0.81)	40 (0.53)	75 (1.0)
5	75	53 (0.70)	0 (0.00)	75 (1.0)
Total	300	241	171	293
Total %	**100**	**80%**	**57%**	**98%**



Status of grades

- We have had 4 HW assignments so far (225 total points)
  - 1 more is still scheduled (for a total of 300 points)
- We have had 1 exam (300 points)
- You have a final project and presentation due (400 points)
- Total: 1000 possible points

- Suggestion:
  - We ignore HW 5 and make your final project and presentation worth 475 points (47.5% of your total grade)
  - Will give you more time for your project

Final projects

- Papers and presentations due in 2 weeks
  - Guidelines are on BB
    - 8 pages single-spaced conference paper
    - 12-15 minute technical presentation
  - Pick an environment, a pollutant, and an exposure control strategy
  - New grading system:
    - Paper is worth 300 points
    - Presentation is worth 175 points

- 6 out of 9 of you completed the anonymous course survey online
  - 5 answered the question about when they would prefer to present
    - 3 want to present final projects last day of class (April 30)
    - 2 want to present during our exam time (May 7)

  - So what's it going to be?

Follow-up from last time

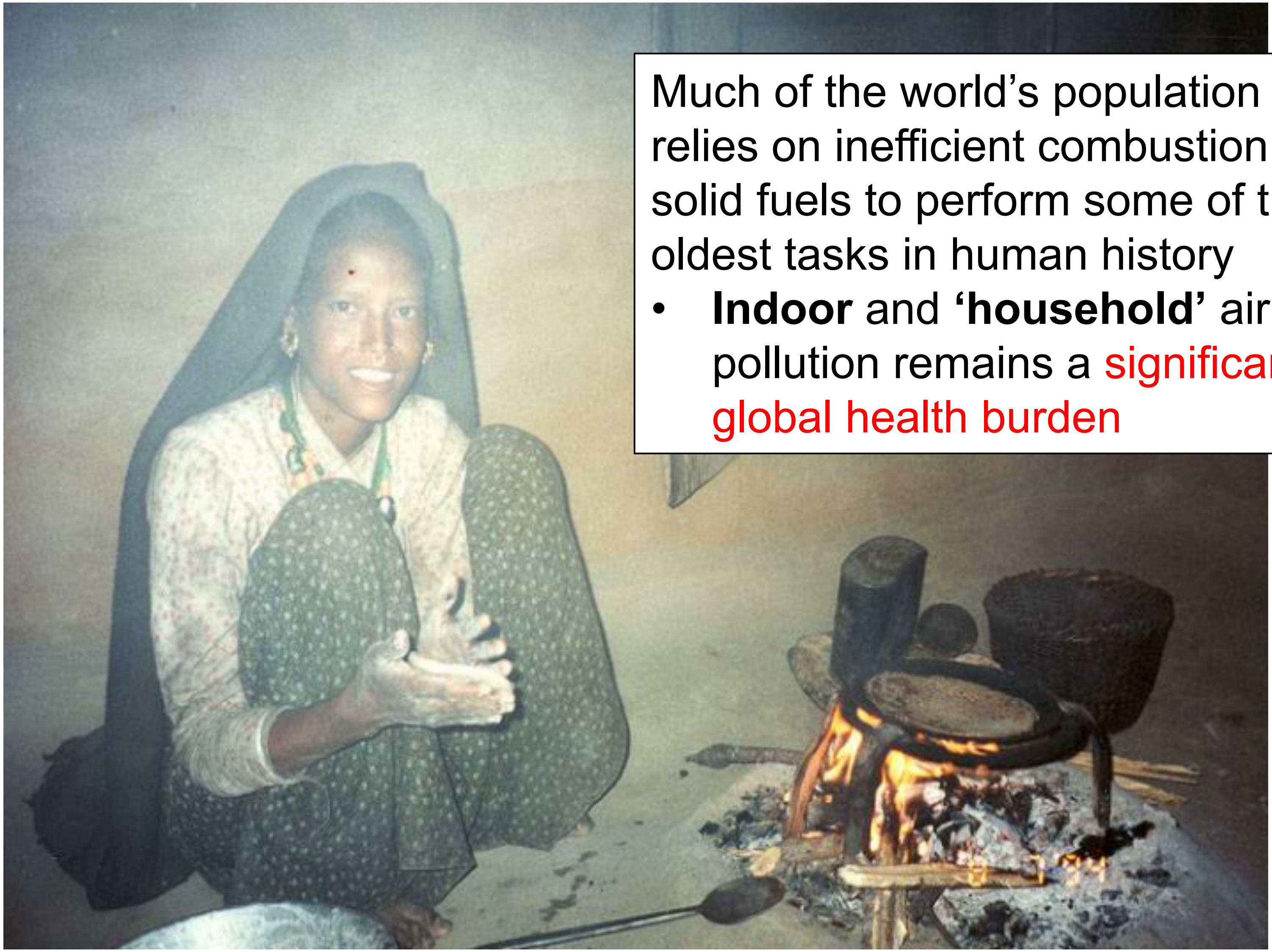
- Last week's guest lecture: Ian Cull
  - How was it?
  - What did he cover?
- Remaining topics I'd like to cover
  - Developing countries (today)
  - Infectious disease transmission (next week)
  - Applications and standards (next week)
  - Final presentations (last class?)
- Not going to have a make-up class from March
  - More time to work on your projects

Exam solutions

Today's lecture

- Indoor air pollution in developing countries
  - We could have an entire class on this topic!

Indoor air pollution in developing regions of the world



Much of the world's population relies on inefficient combustion of solid fuels to perform some of the oldest tasks in human history

- **Indoor** and **'household'** air pollution remains a significant global health burden

Photo: Kirk Smith, UC-Berkeley

Indoor air pollution in developing countries

- Let's start with a video
  - http://www.youtube.com/watch?v=J3Zsj4Lfs_o

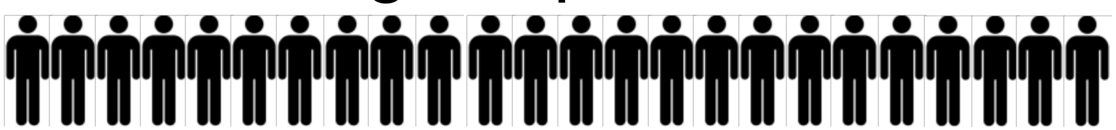
Biomass burning across the world

One-third of the world's population burns biomass for:

Cooking Heating Lighting

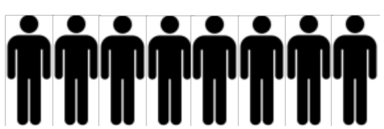
Fuels used include:

Wood, dung, crop residue

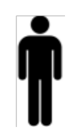


2.4 billion people

Coal



800 million people



= 100 million people

Fullerton et al., 2008 *Trans R Soc Trop Med Hyg*; Bruce et al., 2000 *WHO Bulletin*

Cooking and heating

- Poor ventilation (no flues or hoods)
- Low combustion efficiency
  - High levels of products of incomplete combustion

http://photos.state.gov/libraries/amgov/3234/Week_3/09222010_AP070911056524_300.jpg
http://images.angelpub.com/2010/37/5835/cookstove-2.jpg

Lighting

http://www.vleindia.com/images/thumb/1279793271_slide.jpg

- 1.6 billion people use fuel-based lighting after dark
  - Kerosene, diesel
- Indoor air pollution + substandard luminance + fire

Pollutants emitted from biomass burning

Particulate matter (UFPs, $PM_{2.5}$ and PM_{10})

Carbon monoxide (CO)

Nitrous oxides (NO_x)

Sulfur oxides (SO_x) (coal)

Metals (coal)

Hydrocarbons (HC; e.g. naphthalene)

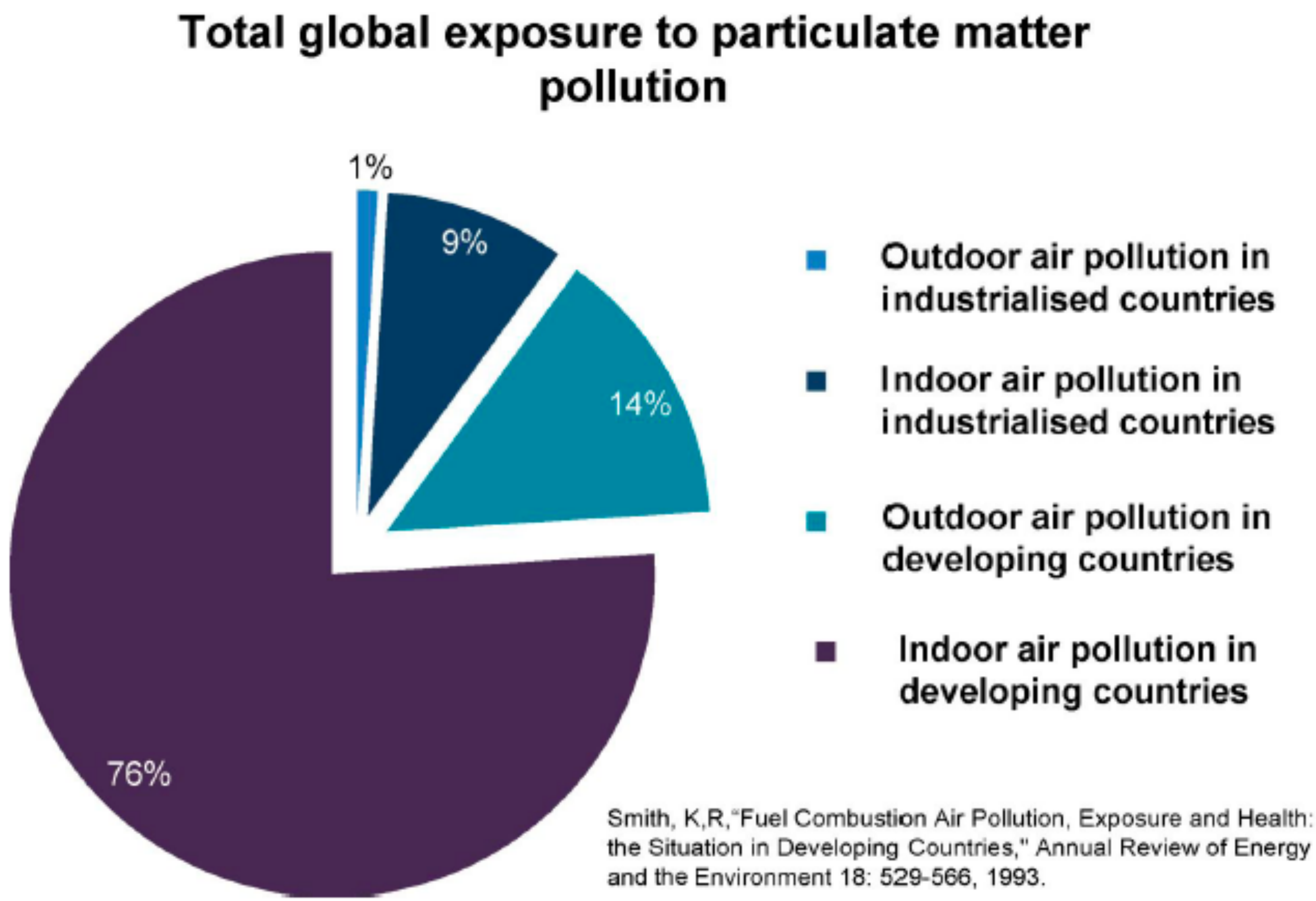
Polycyclic aromatic hydrocarbons (e.g. benzo[a]pyrene)

Oxygenated organics (e.g. formaldehyde) (wood)

Free radicals

Combustion efficiency is far less than 100%

Global exposure to particulate matter

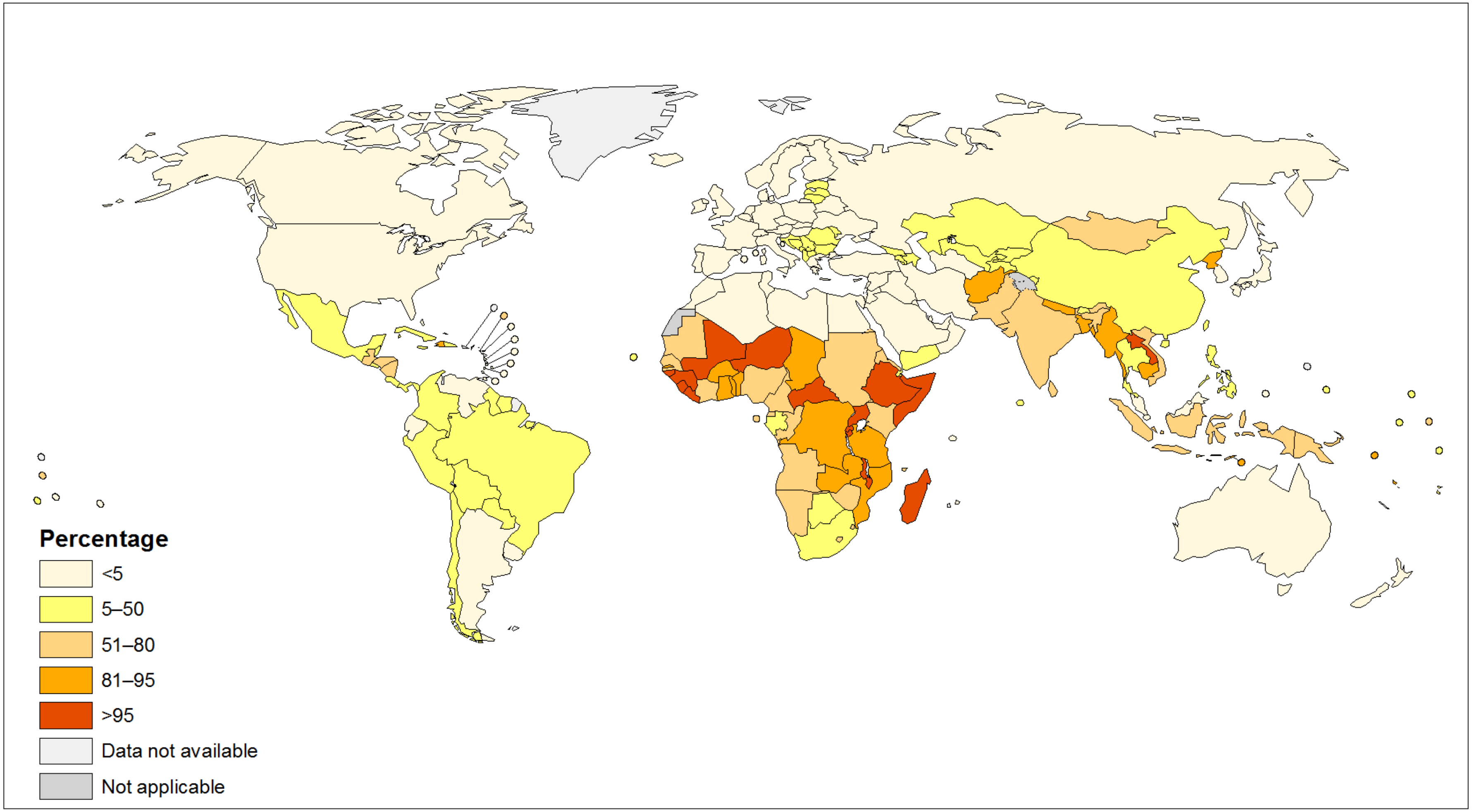


Fullerton et al., 2008 *Trans R Soc Trop Med Hyg*

GLOBAL HEALTH

and indoor air pollution

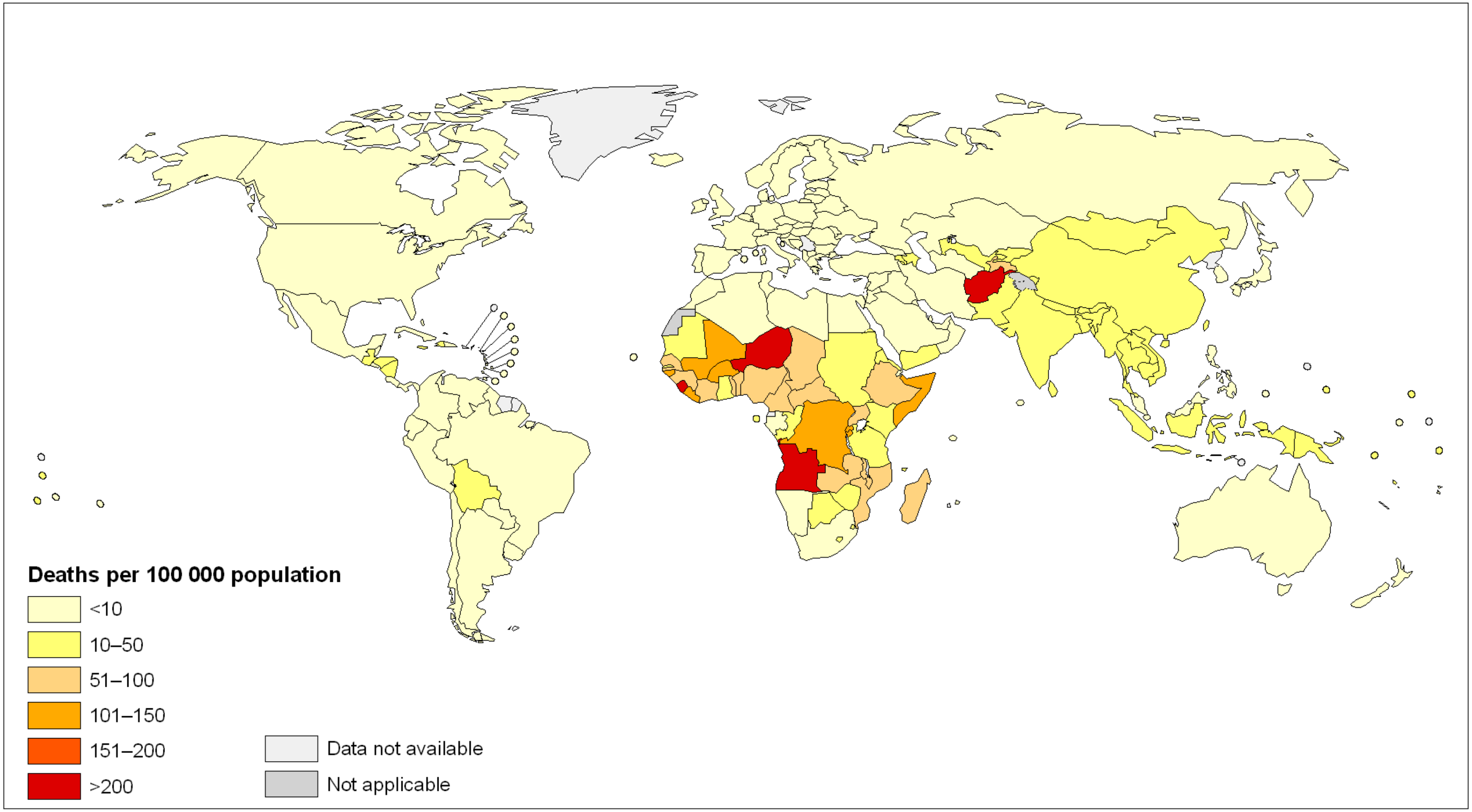
Population using solid fuels (%), 2010
Total



Data Source: World Health Organization
Map Production: Public Health Information and Geographic Information Systems (GIS)
World Health Organization

World Health Organization

Deaths attributable to household air pollution, 2004

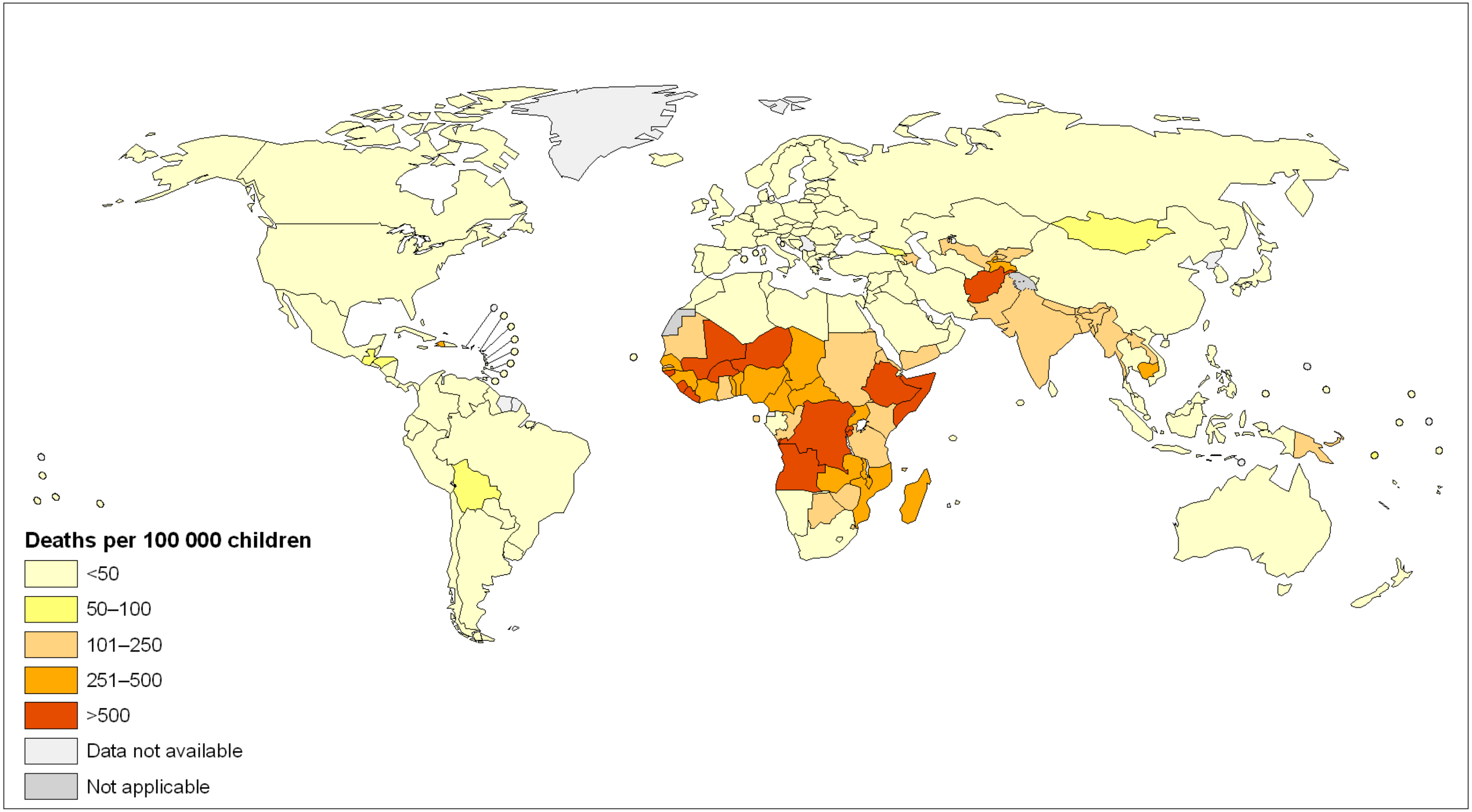


The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement.

Data Source: World Health Organization
Map Production: Public Health Information and Geographic Information Systems (GIS)
World Health Organization

World Health Organization

Deaths attributable to household air pollution in children aged under 5 years, 2004



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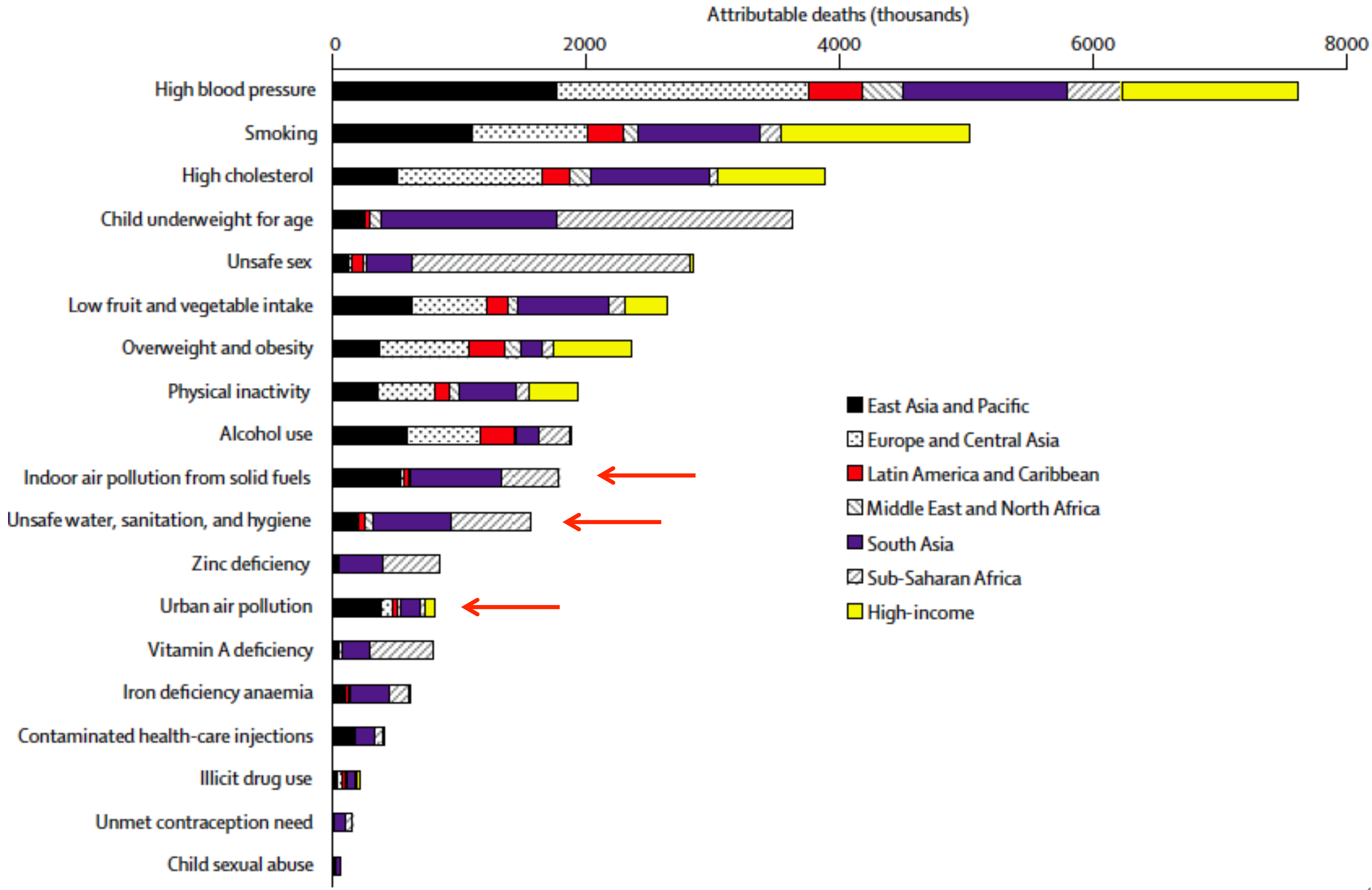
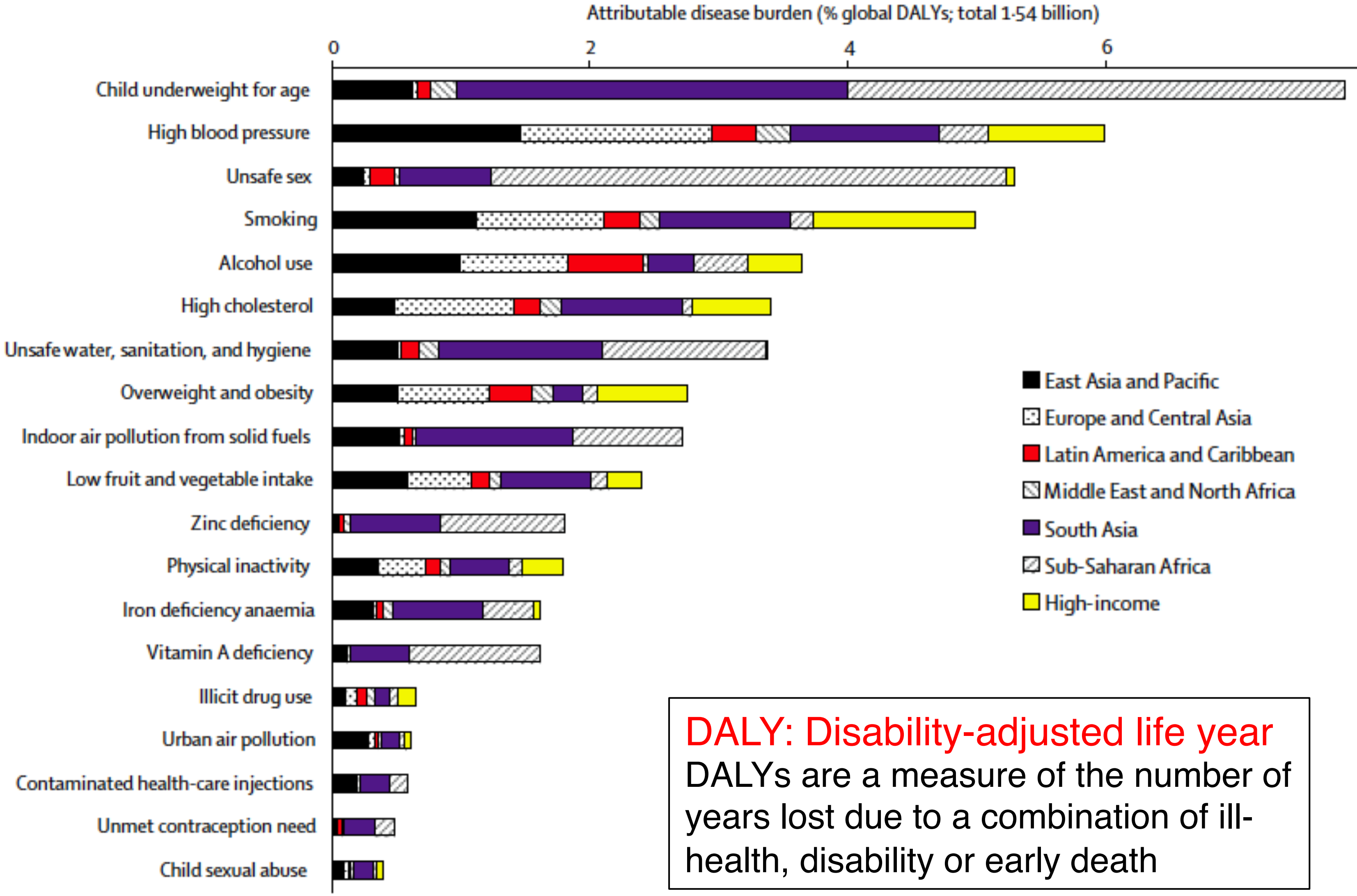
Global risk factors for mortality



Lopez et al., 2006 *The Lancet*

Global disease burden



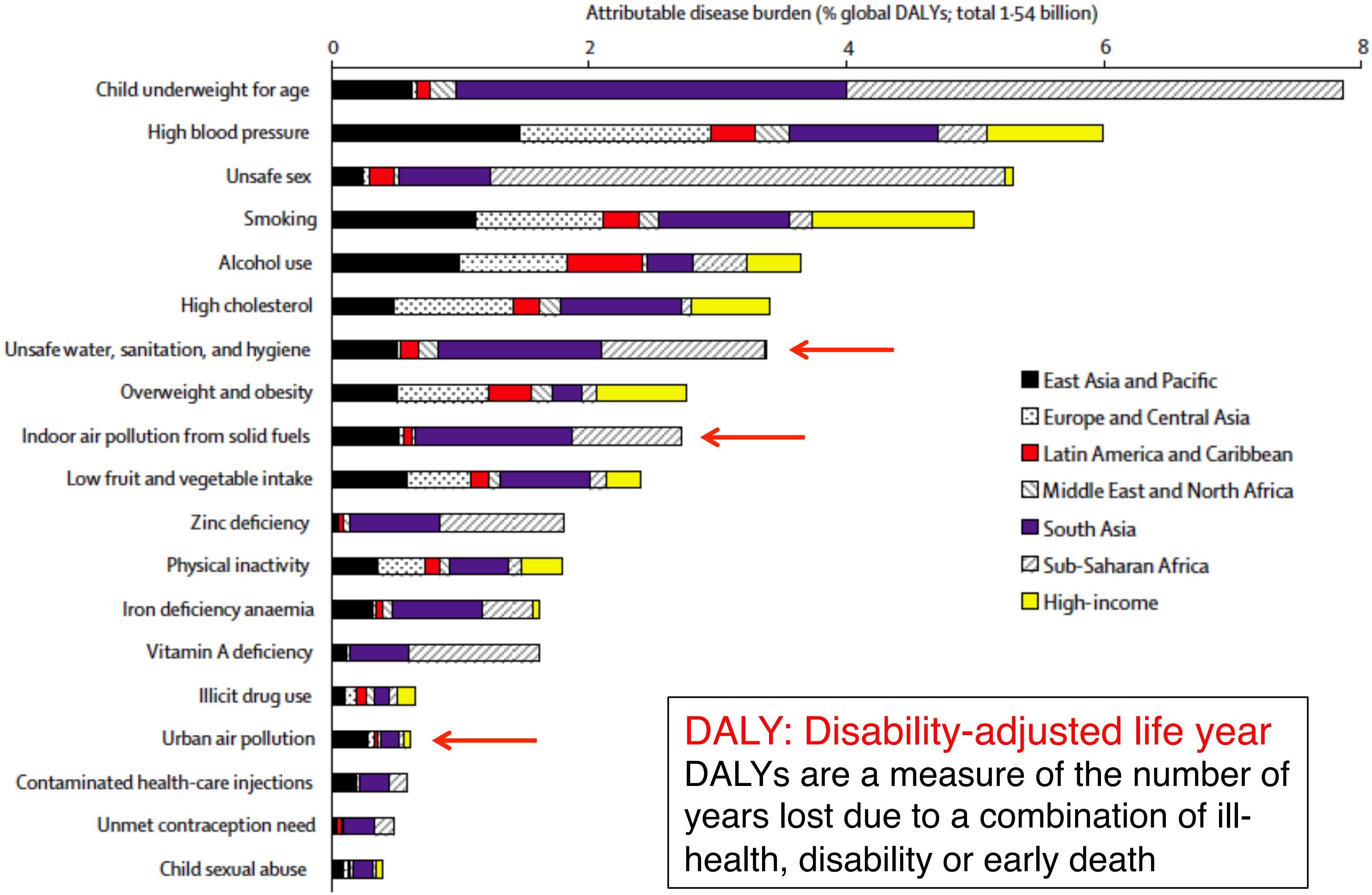
DALY: Disability-adjusted life year
DALYs are a measure of the number of years lost due to a combination of ill-health, disability or early death

Lopez et al., 2006 *The Lancet*

DALY: Disability Adjusted Life Year

- Measure of overall disease burden
  - # of years lost due to illness, disability, or early death
  - Combines mortality and morbidity (existence of ill-health)
  - DALY = YLL + YLD
    - Years of Life Lost + Years Lived with Disability
  - 1 DALY = 1 year of healthy life lost
    - Relative to the longest avg life expectancy in the world
    - Japan, 82.6 years
  - Example: Cancer causes 25 DALYs per 1000 people
    - US population ~307 million → 7.7 million life years

Global disease burden



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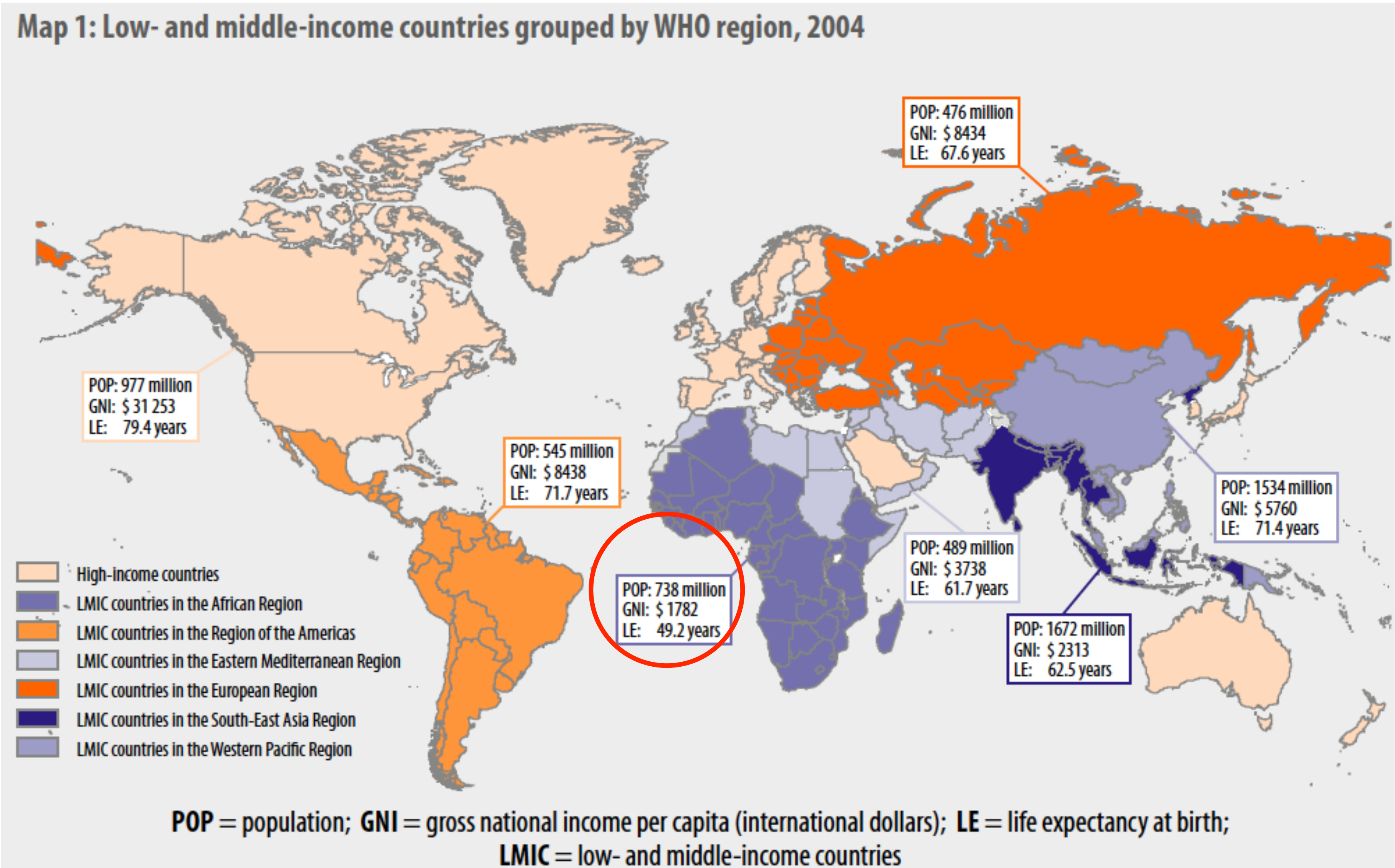
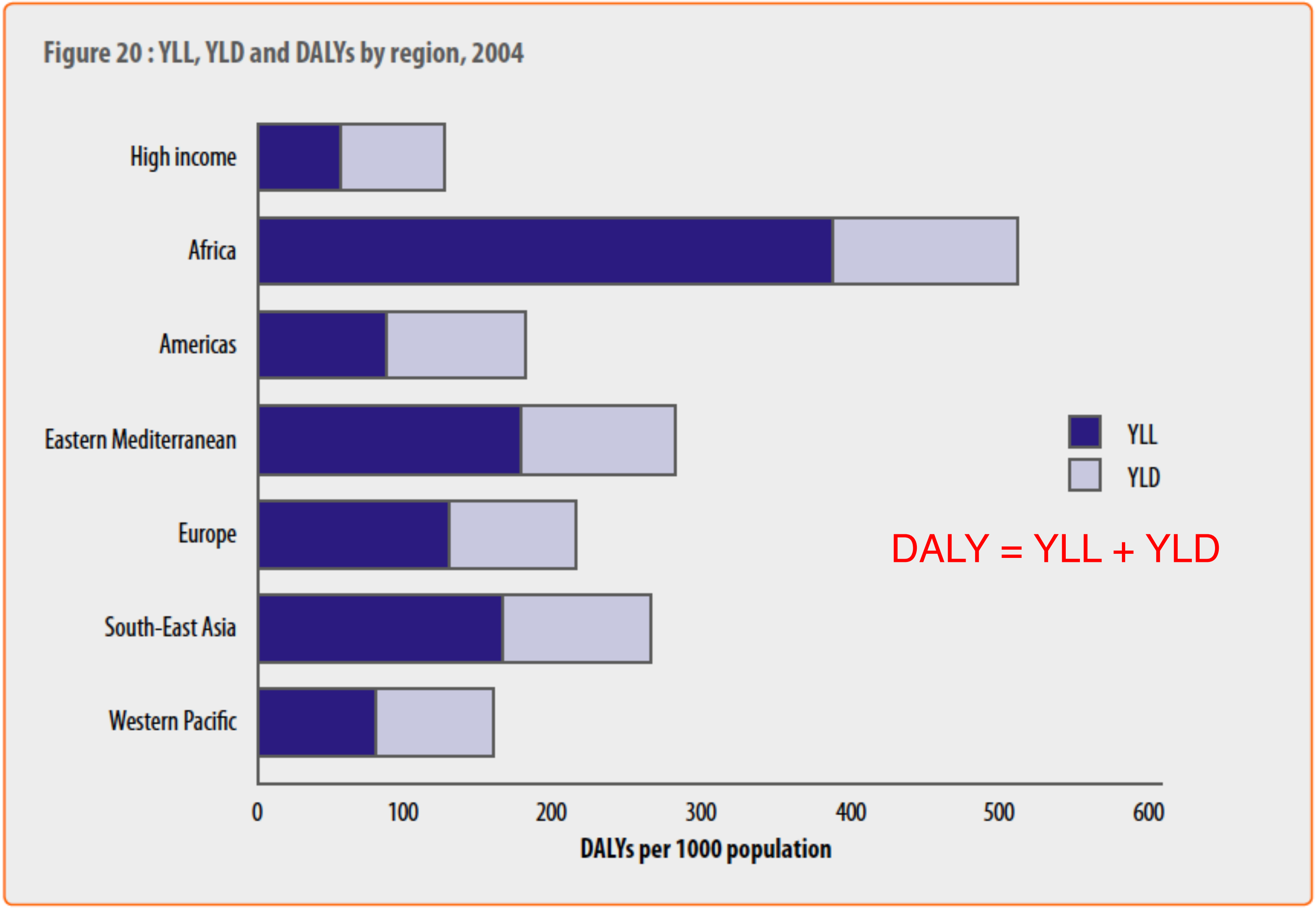
Lopez et al., 2006 *The Lancet*

Global life expectancy

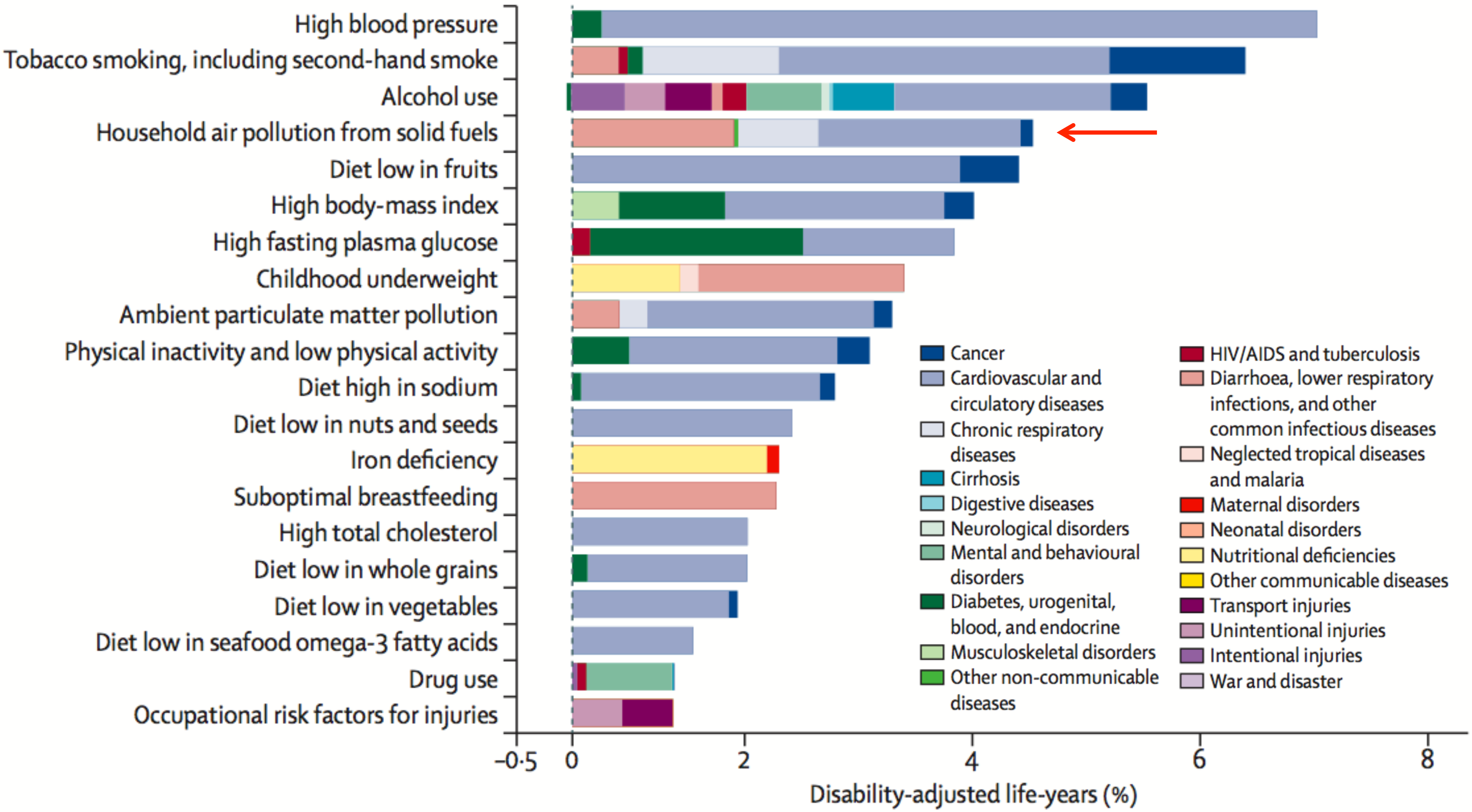


World Health Organization, The global burden of disease: 2004 update

Global DALYs



Global disease burden: 2010 update



Women and young children are especially at risk!

Lim et al., 2013 *The Lancet*

Adverse health effects of biomass burning

Table 3 Respiratory diseases associated with solid fuel use

Health outcome	Meta-analysis RR (95%CI)[19]*
Strong evidence†	
Acute lower respiratory infection (ALRI) in children <5 years of age in developing countries	2.3 (1.9–2.7) 1.78 (1.45–2.18)[23]
Chronic obstructive pulmonary disease (COPD) in women >30 years of age, mainly homemakers residing in rural areas of developing countries	3.2 (2.3–4.8) 2.14 (1.78–2.58)[18]
Lung cancer (coal smoke exposure) in women >30 years of age	1.9 (1.1–3.5)
Moderate evidence‡	
COPD in men >30 years of age	1.8 (1.0–3.2)
Lung cancer (coal-smoke exposure) in men >30 years of age	1.5 (1.0–2.5)
Lung cancer (biomass smoke exposure) in women >30 years of age	1.5 (1.0–2.1)
Asthma in children aged 5–14 years	1.6 (1.0–2.5)
Asthma, >15 years of age	1.2 (1.0–1.5)
Tuberculosis, >15 years of age	1.5 (1.0–2.4)
Insufficient evidence§	
Upper airway cancer	
Low birth weight and perinatal mortality	
Cardiovascular diseases	

*Meta-analysis results from reference 19, unless otherwise stated.
†Strong evidence: Some 15–20 observational studies for each condition, from developing countries. Evidence is consistent (significantly elevated risk in most, although not in all, studies); the effects are sizable, plausible, and supported by evidence from outdoor air pollution and smoking.[19]
‡Small number of studies, not all consistent (especially for asthma, which may reflect variations in definitions and condition by age), but supported by studies of outdoor air pollution, smoking, and laboratory animals.[19]
§Insufficient for quantification based on available evidence.[19]
RR = relative risk; CI = confidence interval.

Perez-Padilla et al., 2010 *Int J Tuberculosis and Lung Disease*

Pollutant-specific adverse health effects

Table 2 Health-damaging pollutants as products of incomplete combustion of solid fuels[11,12,21]

Smoke phases	Characteristics	Mechanism and associated health effects
Particulate	Variety of particulates, different size and composition Respirable size, mean aerodynamic diameter <10 µm (PM_{10}) Fine particles <2.5 µm ($PM_{2.5}$) can be deposited in the lower respiratory tract Organic and inorganic (metals, for example) pollutants can be carried by particulate matter In some cases, carcinogenic pollutants are attached to the particle, for example, higher molecular weight (5-ring and more) polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene	Cause irritation and oxidative stress (additive to other compounds) producing lung and airway inflammation, hyperresponsiveness, and in long-term exposures airway remodeling and emphysema Reduced mucociliary clearance and macrophage response Carcinogenic
Gaseous	Carbon monoxide (CO)	Binds to hemoglobin interfering with transport of oxygen Headache, nausea, dizziness Low birth weight, increase in perinatal deaths. Feto-toxicant, has been associated with poor fetal growth
	Nitrogen oxides (NO_x)	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, longer-term exposure increases susceptibility to infections
	Sulfur dioxide (SO_2), mainly from coal	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, bronchoconstriction
	Hundreds of different hydrocarbons Aldehydes and ketones	Adverse effects are varied, including eye and upper and lower respiratory irritation, systemic effects
	Lower molecular weight (2–4 ring) PAHs	Carcinogenic
	Some of these are classified as carcinogenic: 1,3 butadiene; benzene; styrene, and formaldehyde	

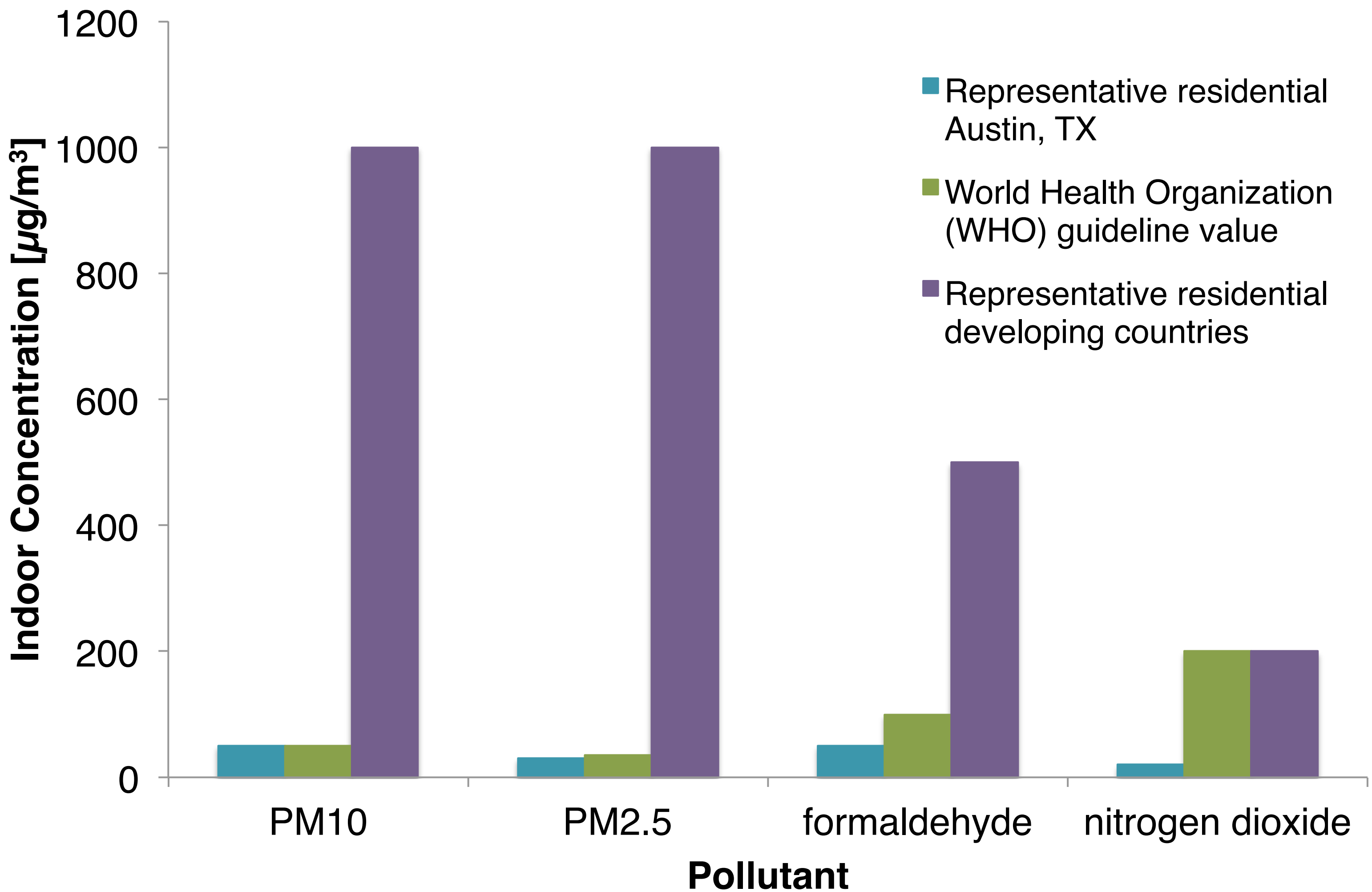
Others possible are arsenic and fluorine from coal combustion.

Perez-Padilla et al., 2010 *Int J Tuberculosis and Lung Disease*

QUANTIFYING EXPOSURES

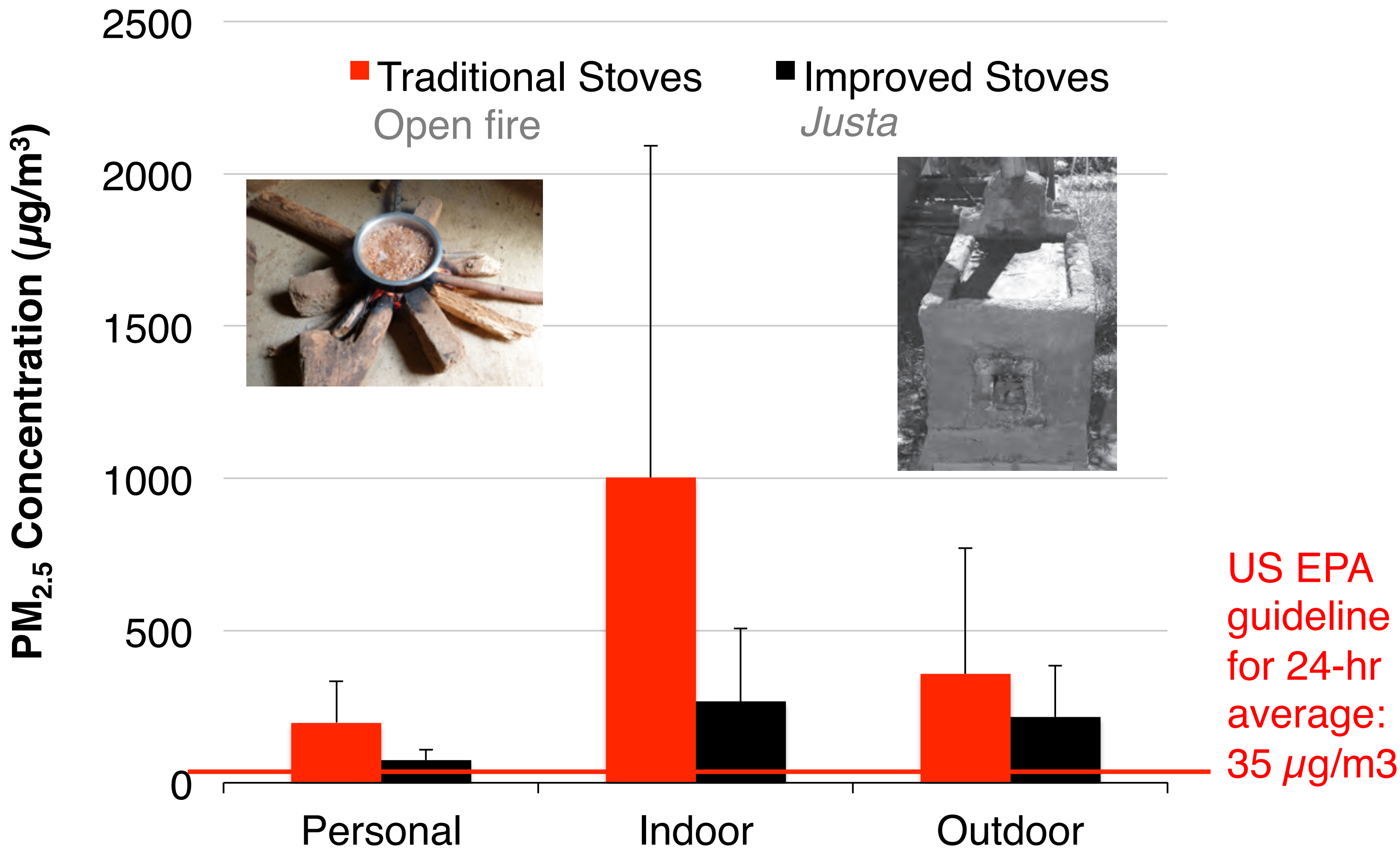
Indoor and household air pollution

Representative pollutant concentrations



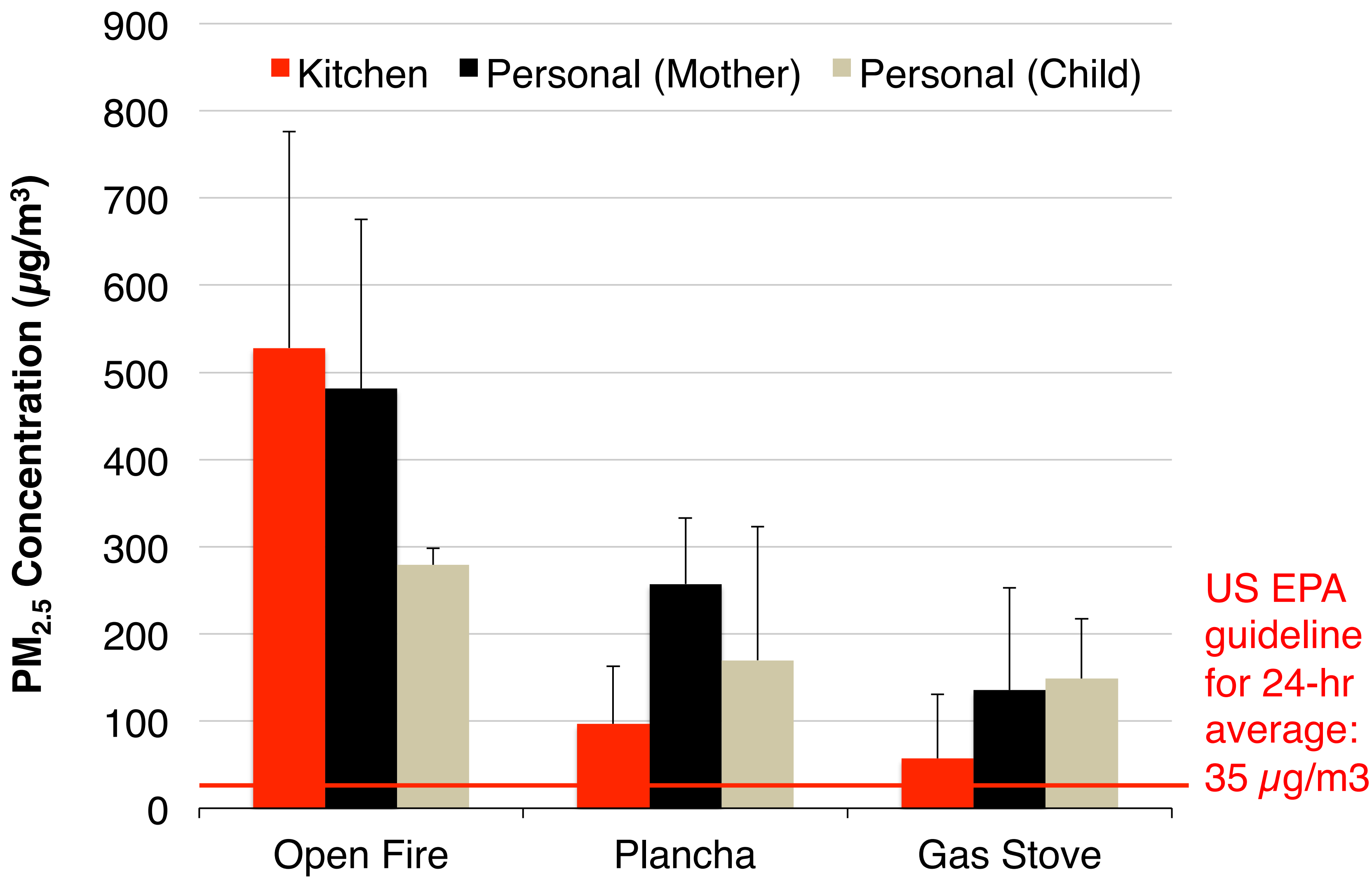
New and old stoves in Honduras: $PM_{2.5}$

~30 homes each group



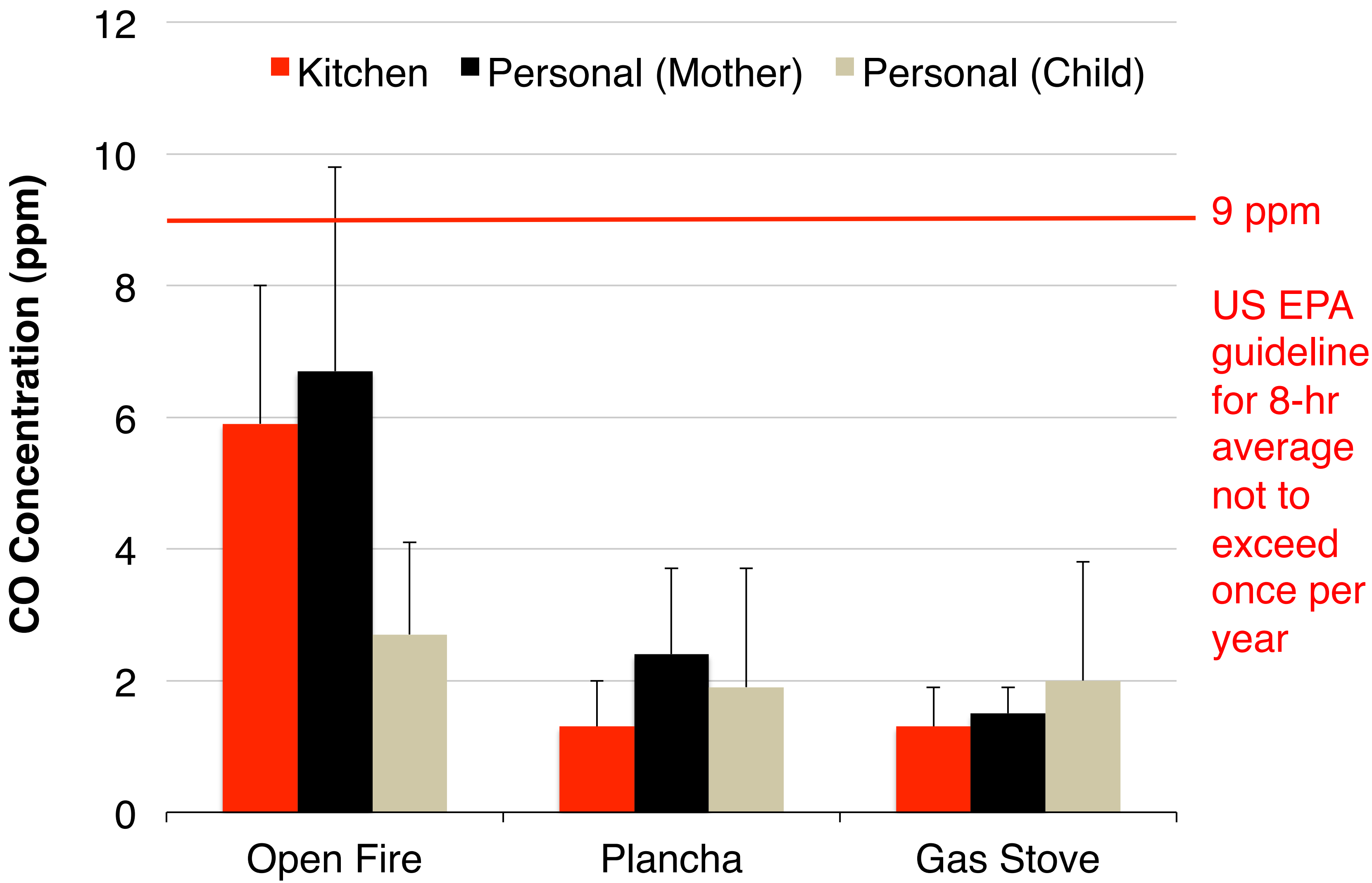
Clark et al., 2010 *Environmental Research*

New and old stoves in Guatemala: $PM_{2.5}$



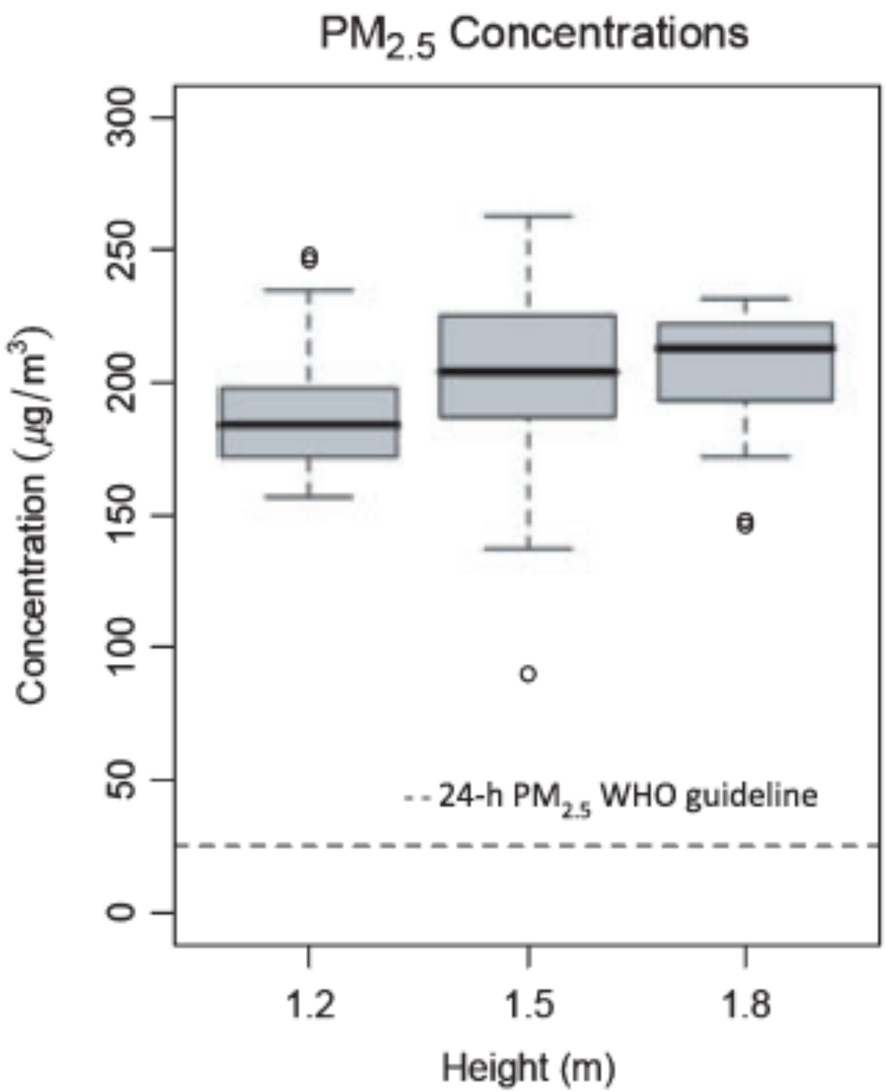
Naeher et al., 2000 *Indoor Air*

New and old stoves in Guatemala: CO



Naeher et al., 2000 *Indoor Air*

Kenya: Fuel-based lighting



Simple wick lamps

Test kiosk

Apple et al., 2010 *Indoor Air*

What pollutants do we measure?

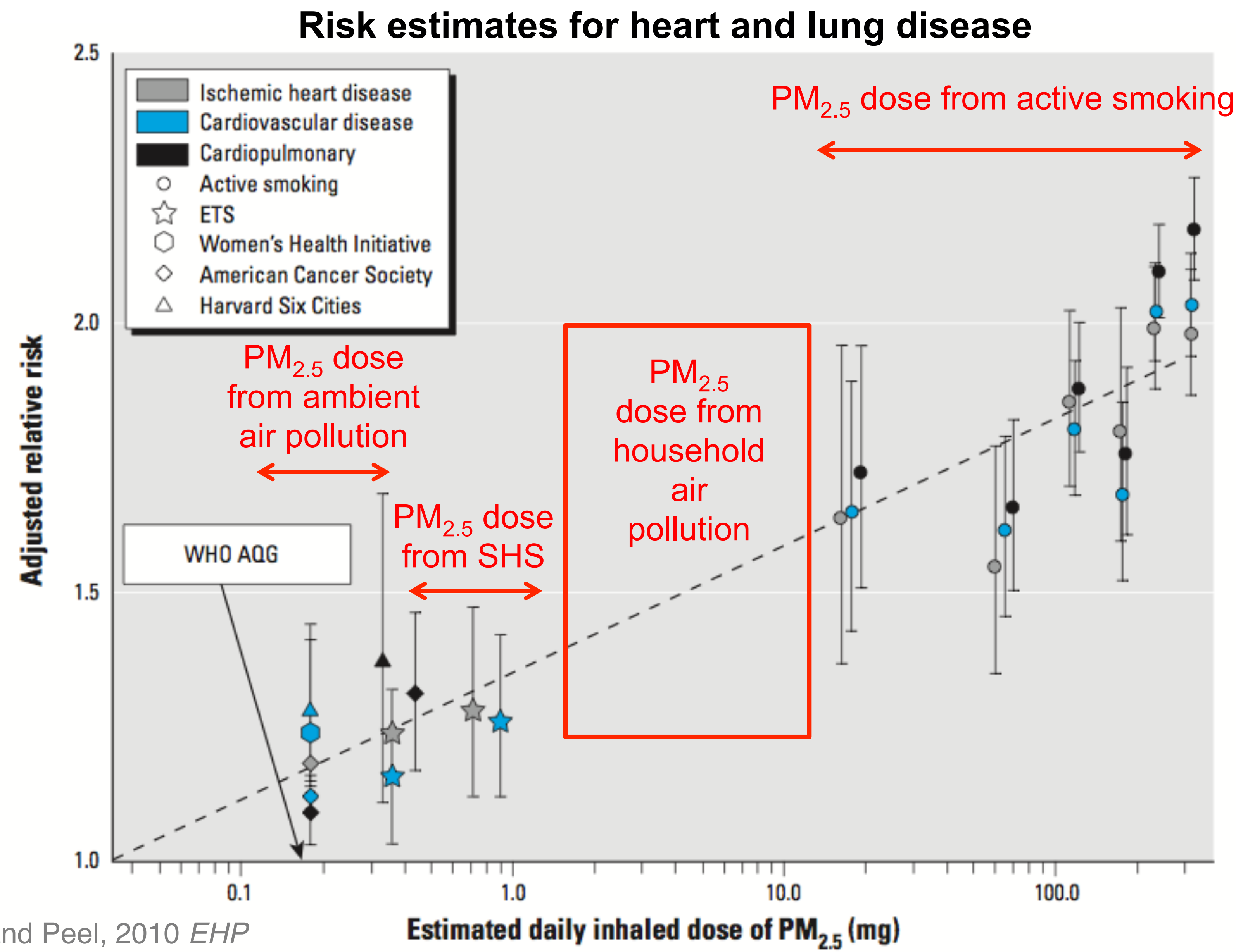
Carbon monoxide and PM

Why mostly only these two?

What are characteristics of desired equipment?

- inexpensive
- reliable
- field calibrated
- have continuous monitoring capacity
- have sufficient data storage

What do these exposures mean for health effects?

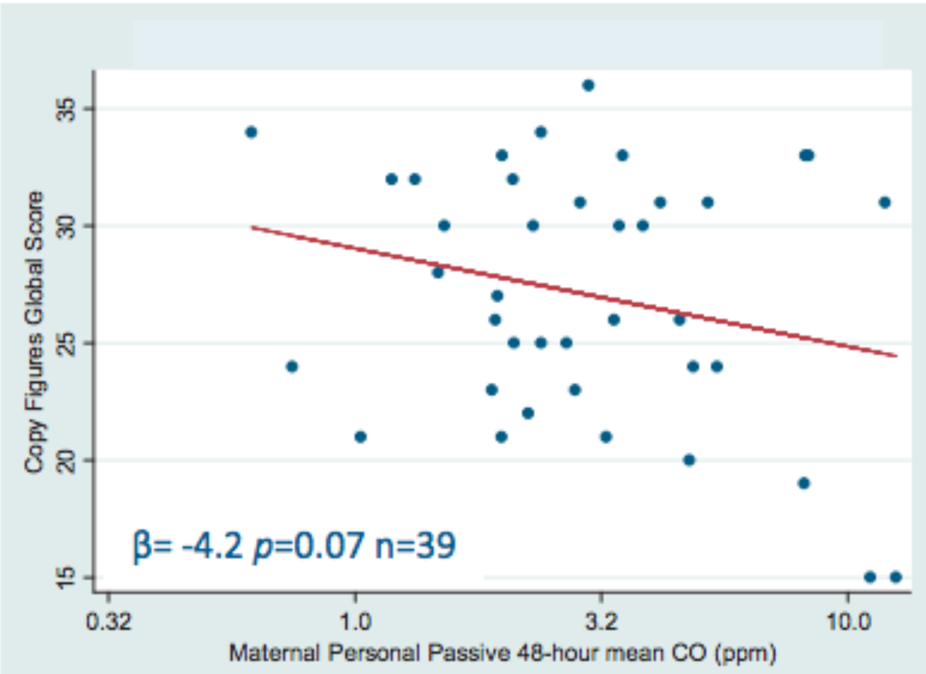


Smith and Peel, 2010 *EHP*

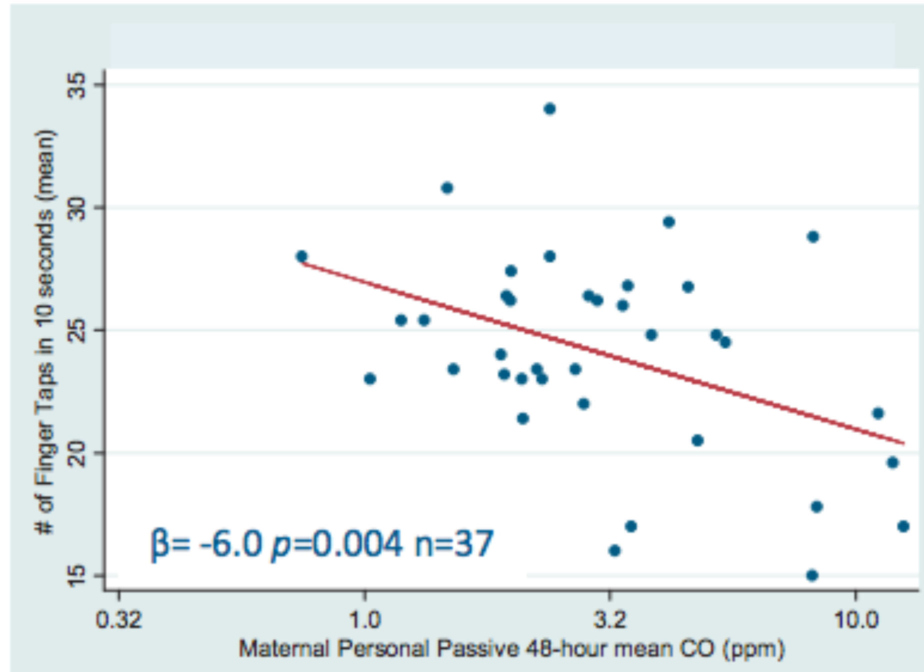
OTHER IMPACTS

Recent evidence of neurological effects

(A) Bender Gestalt-II Copy Figures Phase



(D) Reitan-Indiana Finger Tapping



Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke

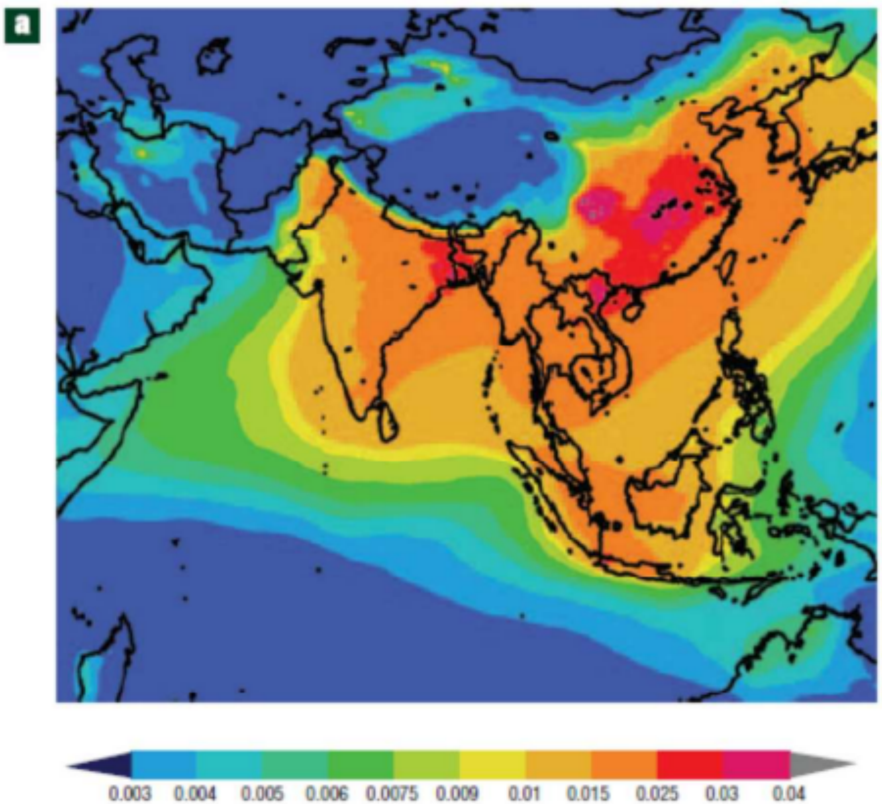
Linda Dix-Cooper [a], Brenda Eskenazi [b], Carolina Romero [c], John Balmes [a,d], Kirk R. Smith [a,*]

Dix-Cooper et al., 2012 *NeuroToxicology*

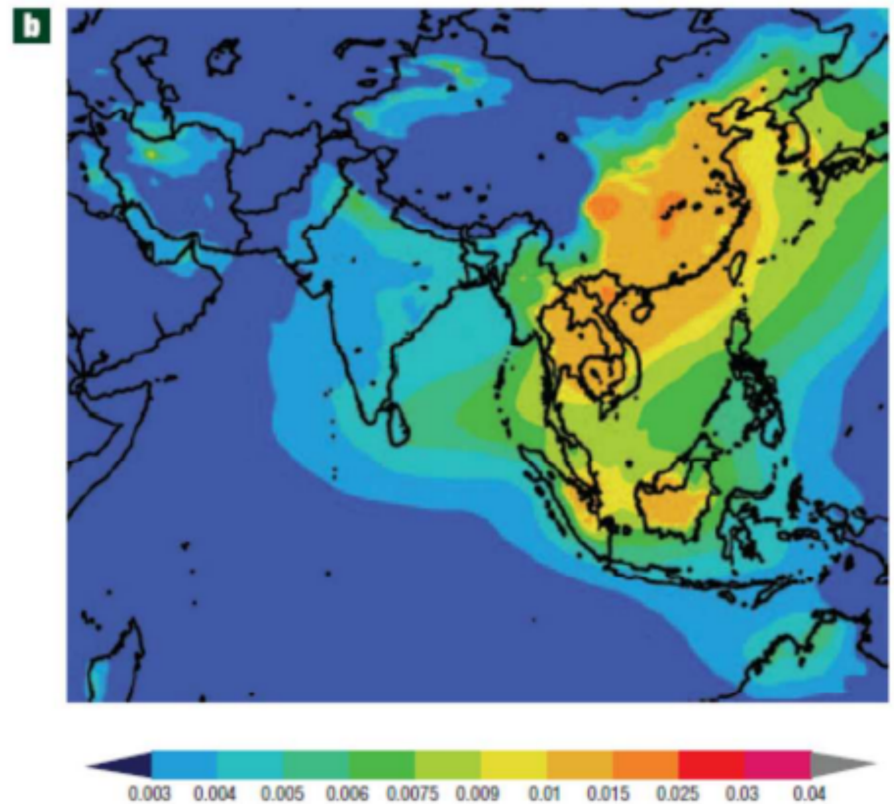
Climate impacts

- Black carbon (BC) with and without cookstove burning:

With cookstoves



Without cookstoves



- BC is a contributor to global warming

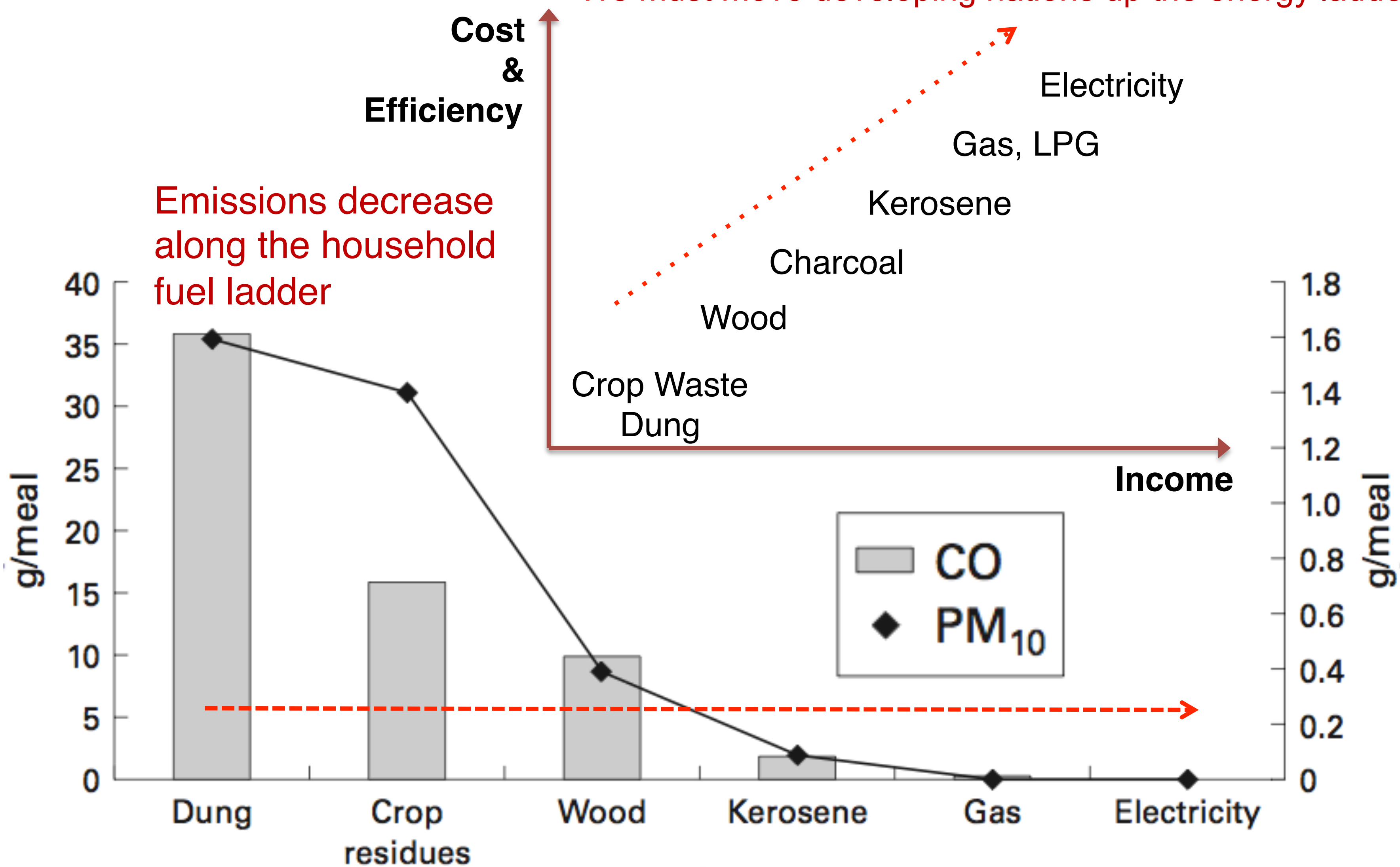
Ramanathan and Carmichael, 2008 *Nature Geoscience*

INTERVENTIONS

Clean cook stove campaigns

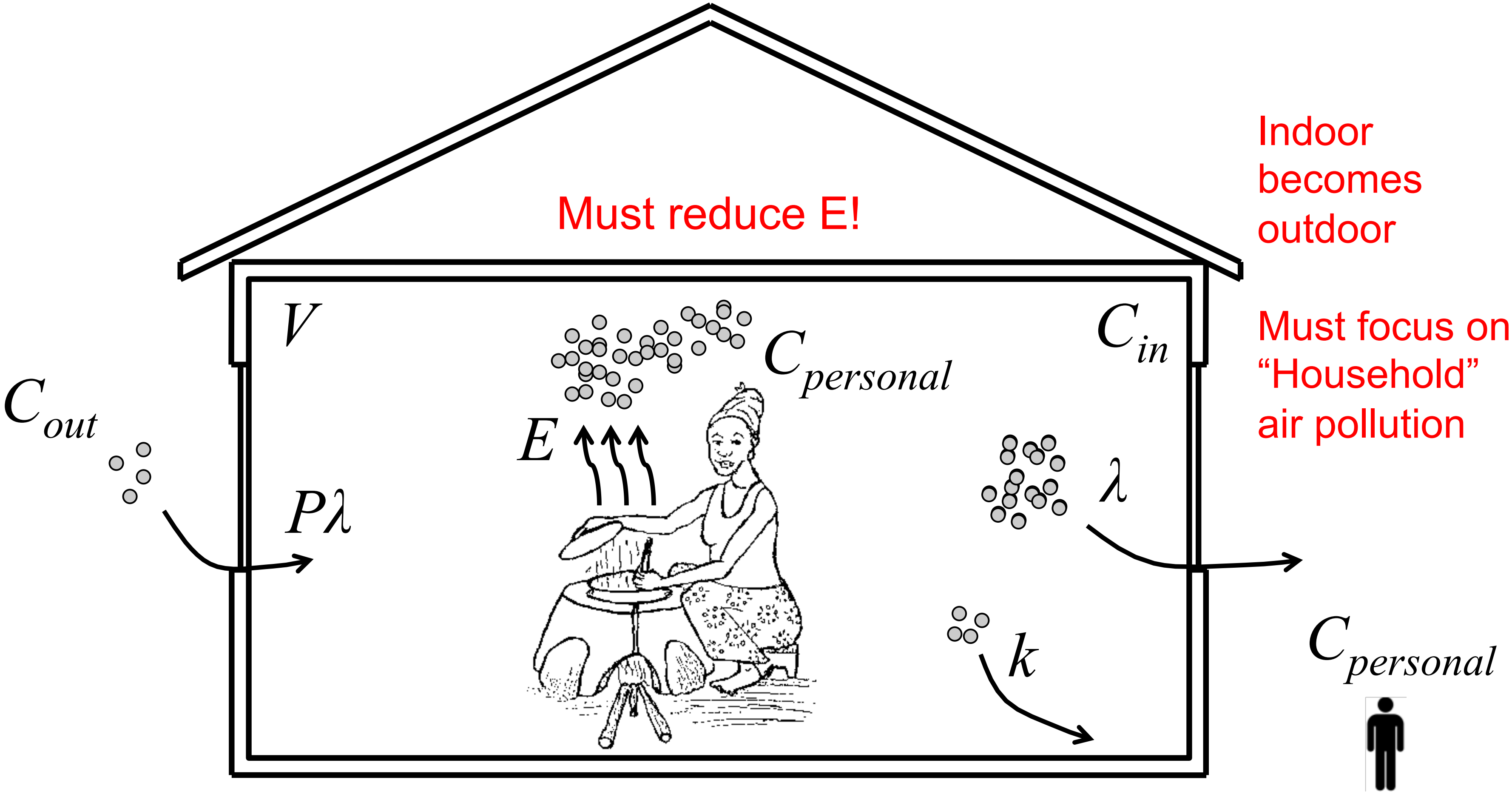
The energy ladder

We must move developing nations up the energy ladder!



Smith et al., 1999, US Environmental Protection Agency

Fundamental parameters driving exposures



C_{in} = Indoor concentration of pollutant C_{out} = Outdoor concentration of pollutant P = Penetration factor (-)
λ = Air exchange rate (hr^{-1}) k = Indoor loss rate (hr^{-1}) V = Volume of home (m^3) E = Emission rate (mg hr^{-1})

Cook stove emissions

$$Emission\ Rate,\ E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Emission Rate, E = mg pollutant per hour
Emission Factor = mg pollutant per kg of fuel
Energy Density = MJ per kg of fuel
Stove Power = MJ per hour
Efficiency = MJ delivered per MJ burned

Johnson et al. (2011) *Atmos Environ*

Calculating emission rates

$$Emission\ Rate,\ E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Typical values | Traditional Stove

- $EF_{PM2.5}$ = 5.2 g kg^{-1}
- Energy density of wood 18 MJ kg^{-1}
- Stove power = 4.9 kJ s^{-1}
  - Cooking energy needed = 11 MJ
  - Thermal efficiency = 14%
  - Cooking time = 4.5 hours

$$E = \frac{5.2\ g\ PM_{2.5}}{kg\ fuel} \times \frac{kg\ fuel}{18\ MJ} \times 4.9\frac{kJ}{s} \times \frac{3600\ s}{hr} \times \frac{MJ}{1000\ kJ} = 5\ \frac{g}{hr}$$

Johnson et al. (2011) *Atmos Environ*

Indoor concentrations

$$C_{ss} = \cancel{PC_{out}} + \frac{E/V}{\lambda + \cancel{k}} = \frac{E}{\lambda V}$$

- AER, λ = 25 hr^{-1}
- Kitchen volume, V = 30 m^3
- $E_{PM2.5}$ = 5 g hr^{-1}
- C_{ss} = 0.0067 g m^{-3} ≈ 7 mg m^{-3} ≈ 7000 µg m^{-3}
- WHO $PM_{2.5}$ standard = 35 µg m^{-3}
- 200 times higher

Johnson et al. (2011) *Atmos Environ*

Cookstoves: What has to change?

- Everything!

$$Emission\ Rate, E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Stoves must get better
Fuels must get better

Can't just add a chimney

Cookstoves are major sources of outdoor pollution

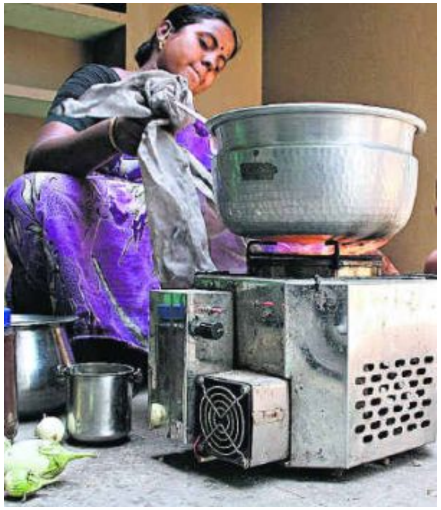
31-44% of primary $PM_{2.5}$ emissions in China
50-56% in India

Chafe et al., 2011 Indoor Air, Austin, TX

Enter: clean cook stoves

What is a clean cook stove?

1. Meets social, resource, income, and behavior needs
2. Improved performance relative to baseline conditions
   - Pollutant emissions and energy efficiency
3. Scalable through markets or other mechanisms


http://cleancookstoves.org/overview/what-is-a-clean-cookstove/

Example stoves

Traditional biomass *chulha*	Traditional coal *chulha*	Improved *chulha*	Kerosene

Biogas	Commercial biomass *bhati*	Commercial coal *bhati*	LPG stove

Sahu et al., 2011, ES&T

Example stoves

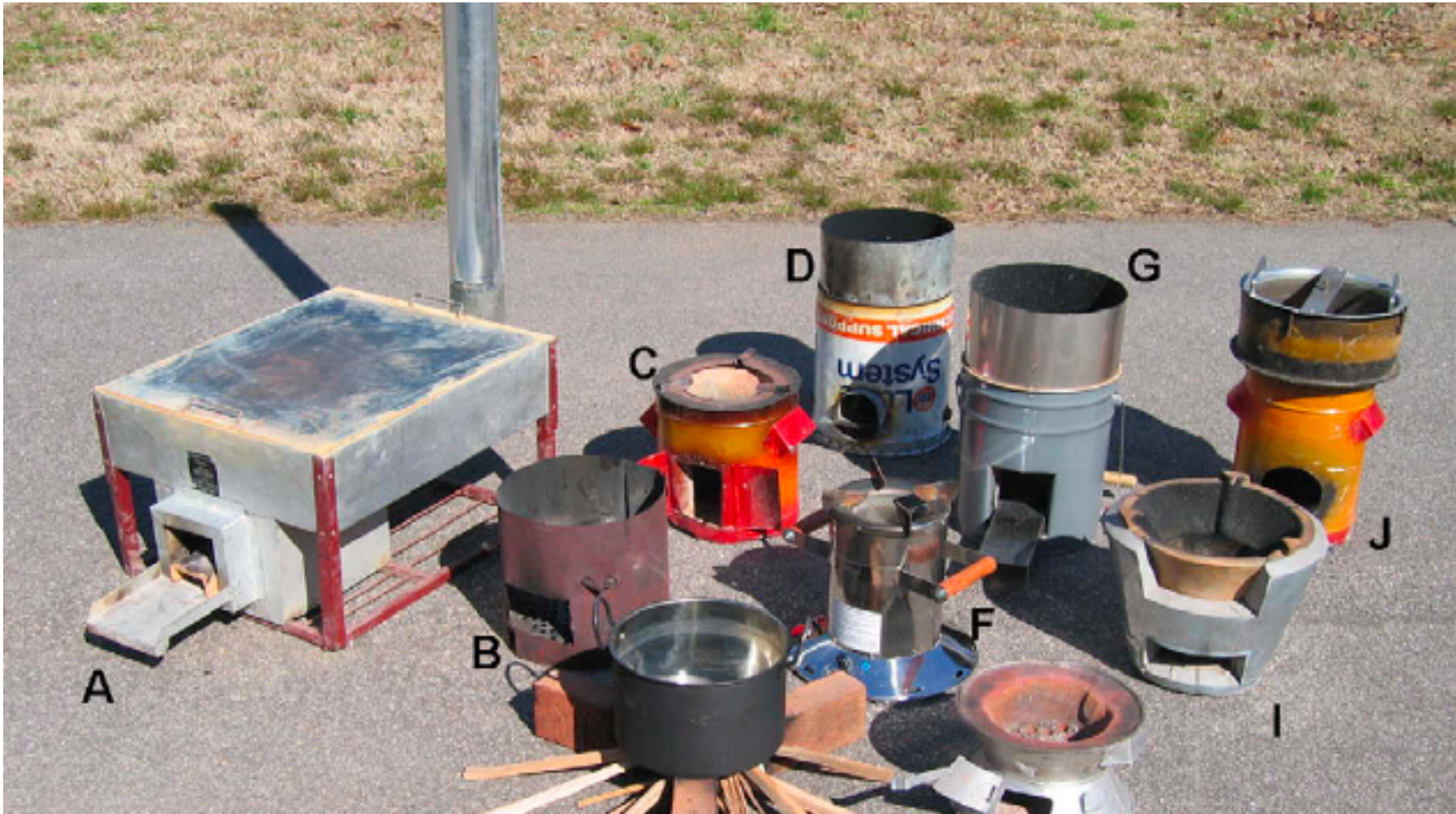


Fig. 1 – Stoves tested: A. Ecostove, B. VITA, C. UCODEA charcoal, D. WFP rocket, E. 3-stone fire, F. Philips, G. 6-brick rocket, H. Lakech charcoal, I. NLS, J. UCODEA rocket.

Jetter and Kariher, 2009 Biomass and Bioenergy

Ongoing research

- Emissions tests continue to be improved and conducted on more stoves
  - Often stark contrasts between laboratory and field test results
  - Some have turned to modeling efforts in stove design
- Exposure measurement studies continue to be conducted
  - Often coupled with health outcome studies
  - These take time, effort, and $$$ to do it right (i.e., randomized trials)
- The elephant in the room: cook stove adoption

Barriers to widespread adoption

- Previous reports have shown that stove implementation campaigns have been costly
  - And often result in poor adoption
- People often prefer their old inefficient stoves
  - Tradition or cooking preference
- People often use a mix of old and new stoves
  - “Stove stacking”
- People often alter their new stoves, diminishing effectiveness
- New stoves have had excessive costs
- Failures to integrate women in the stove design process

Social and behavioral aspects

- Stove adoption in El Fortin, Nicaragua
  - Problems with “culturally unfamiliar” stoves
  - Unfamiliar fuel types
- Surveyed 124 cooks in semi-rural Nicaragua
  - 1 year after introduction of improved cookstoves
- 48% still used their traditional open fire stoves
  - Often mixed
- Almost all preferred the new stove overall
- Many made adjustments to new stoves
  - Removing the plancha (griddle surface)
  - Leaving edges unsealed

Davis et al., Indoor Air 2011, Austin, TX

For more information

Indoor Air Pollution in Developing Countries: Research and Implementation Needs for Improvements in Global Public Health

Elliott T. Gall, MSE, Ellison M. Carter, MSE, C. Matt Earnest, MSE, and Brent Stephens, PhD

American Journal of PUBLIC HEALTH

Barriers and research and implementation needs

- Costs of improved cook stove programs have been too high
  - Costs must come down
- Research and implementation agencies need to integrate
  - Lab testing, field testing, and implementation together
- Mixed successes with stove adoption
  - Wide array of researchers need to work to understand adoption
- Indoor (and household) concentrations are still too high after new stoves
  - Engineers need to continue to develop cleaner and more efficient stoves
- Health assessments remain limited to draw robust conclusions
  - Need to standardize measurements/metrics to conduct larger scale intervention studies
- Instrumentation is a significant barrier to exposure studies
  - Need to develop low-cost reliable sensors

http://built-envi.com/wp-content/uploads/2013/03/gall_etal_ajph_2013.pdf

GET INVOLVED

Partnership for Clean Indoor Air

http://www.pciaonline.org/

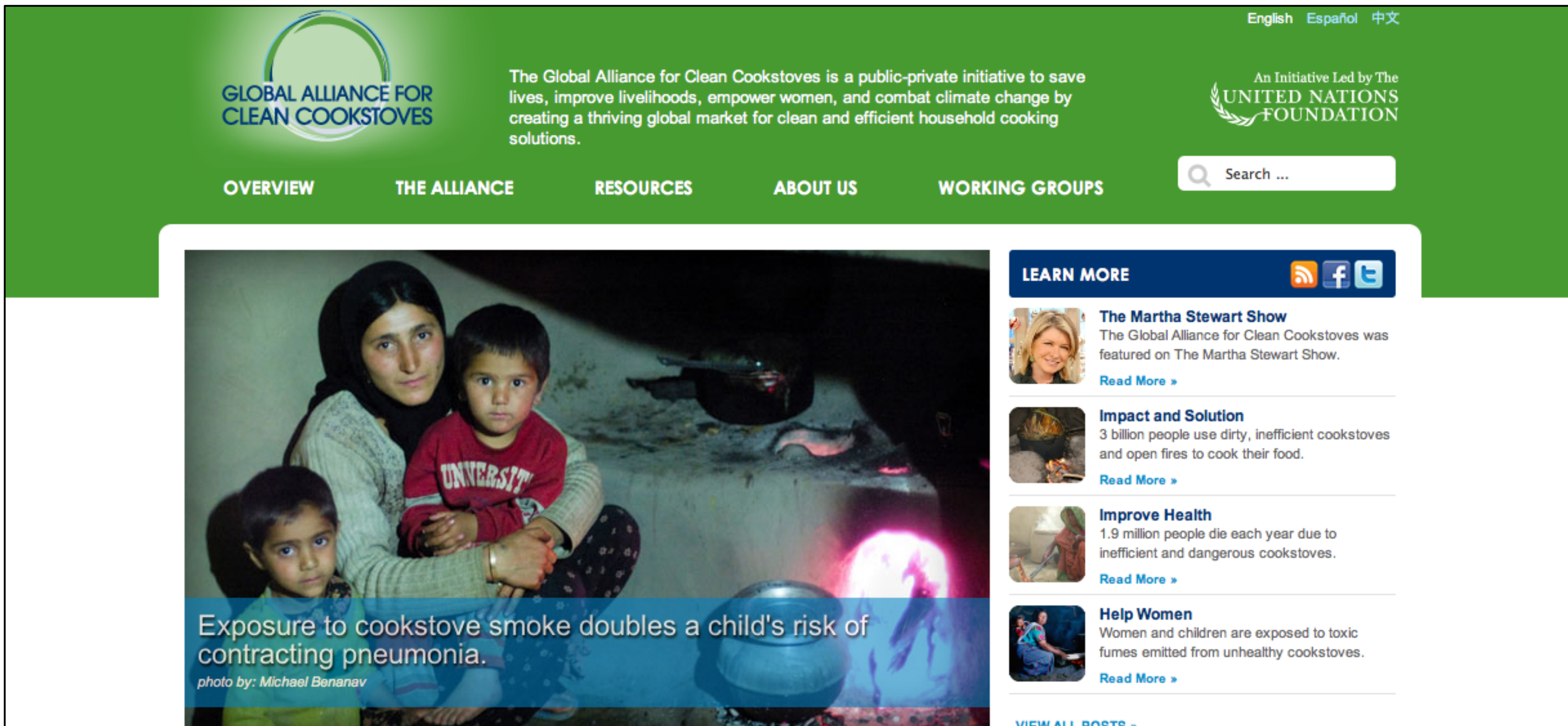
537 partner organizations contributing resources and expertise to reduce pollutant exposure from cooking and heating practices in households around the world.

Essential elements of effective, sustainable household energy and health programs:

1. Meeting the needs of local communities for clean, efficient, affordable and safe cooking and heating options
2. Improved cooking technologies, fuels and practices for reducing indoor air pollution
3. Developing commercial markets for clean and efficient technologies and fuels
4. Monitoring and evaluating the health, social, economic and environmental impact of household energy interventions

Global Alliance for Clean Cookstoves

The Global Alliance for Clean Cookstoves is a new public-private partnership to save lives, improve livelihoods, empower women, and combat climate change by creating a thriving global market for clean and efficient household cooking solutions. The Alliance's 100 by '20 goal calls for 100 million homes to adopt clean and efficient stoves and fuels by 2020.



http://cleancookstoves.org/

Resources for getting involved

- Some EWB resources
  - GA Tech: http://ewb-gt.org/?page_id=1568
  - Michigan Tech: http://ewb.students.mtu.edu/
- Some important academic groups in this field
  - Kirk Smith, UC-Berkeley: http://ehs.sph.berkeley.edu/krsmith/
  - Ashok Gadgil, LBL: http://cookstoves.lbl.gov/
  - Tami bond, UIUC: http://www.hiwater.org/
  - CSU Engines Lab: http://www.eecl.colostate.edu/research/household.php
  - Modi group, Columbia: http://modi.mech.columbia.edu/
  - Duke: http://sites.duke.edu/cookstove/
- Other important groups
  - Berkeley Air Monitoring Group: http://www.berkeleyair.com/
  - Trees, Water, People: http://www.treeswaterpeople.org/
  - Aprovecho: http://www.aprovecho.org
  - Bioenergylists: http://www.stoves.bioenergylists.org/