Combustion Particles

The World’s Oldest Newest, and Largest Environmental Health Hazard

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Combustion Particles: The Oldest and Newest of Pollutants

• Oldest: first measured and regulated
  – First Royal Air Pollution Commission in history
    • Appointed in 1265, completed its report in 1306
    • (setting the standard for expert committees)
    • Recommended banning coal burning in London
    • Duly taken up 650 years later by the authorities (1956)
    • (setting the standard for policy response)
  – First systematic measurements in London in 1800s:
    on fire stations (dust fall)
  – First exposure response relationships for air pollutants
PM: The Newest Pollutant

- mechanisms of creation and impact are still not clear,
- new health standards being implemented,
- thresholds of effect essentially have disappeared
- new measurement methods being developed,
- even basic metrics in some doubt
- major impacts on regional and global climate now recognized
- difficult tradeoffs now discussed between climate and health goals
Road Map for this Presentation

• What are major sources of exposure to combustion particles?
• How do we calculate the burden of disease from different risk factors in a compatible manner?
• How was this done globally for outdoor and indoor sources of combustion particles?
• How do the results compare with other major risk factors?
• How does this relate to climate change?
Oldest Pollution Source in Human History
By definition
More than 75% of households

50-74% of households

2000 Census
Woodsmoke is natural – how can it hurt you?

Or, since wood is mainly just carbon, hydrogen, and oxygen, doesn’t it just change to CO₂ and H₂O when it is combined with oxygen (burned)?

Reason: the combustion efficiency is far less than 100%
Products of Incomplete Combustion (PIC)

Heat
Energy flows in well-operating traditional Indian woodfired cookstove

PIC = products of incomplete combustion.

Wood: 1 kg
15.33 MJ
Traditional Stove

- Into Pot
  2.76 MJ
  18%

- In PIC
  1.23 MJ
  8%

- Waste Heat
  11.34 MJ
  74%

Smith et al., 2000
<table>
<thead>
<tr>
<th>Solid Fuels</th>
<th>Nominal Combustion Efficiency</th>
<th>Approximate % of Households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>` 99% (98-99.5)</td>
<td>[18%]</td>
</tr>
<tr>
<td>Kerosene</td>
<td>97 (95-98)</td>
<td>[7]</td>
</tr>
<tr>
<td>Wood</td>
<td>89 (81-92)</td>
<td>[53]</td>
</tr>
<tr>
<td>Crop resid</td>
<td>85 (78-91)</td>
<td>[10]</td>
</tr>
<tr>
<td>Dung</td>
<td>84 (81-89)</td>
<td>[10]</td>
</tr>
<tr>
<td>Coal</td>
<td>(variable)</td>
<td>[2]</td>
</tr>
</tbody>
</table>

Carbon Balance:

Eucalyptus in Indian Vented Ceramic Stove

\[ k \text{-factor} = 0.123 \text{ (sum of molar ratios to CO}_2 \text{)} \]

CO\(_2\) Carbon: 295.8 g

TSP Carbon: 1.7 g

PIC Carbon:
- CO: 18.5 g
- CH\(_4\): 2.8 g
- TNMOC: 5.2 g

Char/Ash: 161 g
130 g Carbon

Wood: 1.0 kg
454 g Carbon

Nominal Combustion Efficiency = \( \frac{1}{1+k} \) = 89%

A Toxic Waste Factory!!

Typical biomass cookstoves convert 6-20% of the fuel carbon to toxic substances.
Toxic Pollutants in Biomass Fuel Smoke from Simple (poor) Combustion

• Small particles
• Hydrocarbons
  – 25+ saturated hydrocarbons such as \textit{n-hexane}
  – 40+ unsaturated hydrocarbons such as \textit{1,3 butadiene}
  – 28+ mono-aromatics such as \textit{benzene & styrene}
  – 20+ polycyclic aromatics such as \textit{benzo(\(\alpha\))pyrene}
• Oxygenated organics
  – 20+ aldehydes including \textit{formaldehyde & acrolein}
  – 25+ alcohols and acids such as \textit{methanol}
  – 33+ phenols such as \textit{catechol & cresol}
  – Many quinones such as \textit{hydroquinone}
  – Semi-quinone-type and other radicals
• Chlorinated organics such as \textit{methylen chloride} and \textit{dioxin}

Best measure of risk \(\sim 0.1\text{-}0.4\%\) of fuel weight

Naehler et al. 2007, JIT
First person in human history to have her exposure measured doing one of the oldest tasks in human history

Kheda District, Gujarat, India
1981

What kind of exposures?
Indoor pollution concentrations from typical woodfired cookstove during cooking

**Indoor Levels**

- Carbon Monoxide: 150 mg/m³
  - Indoor: 10 mg/m³
- Particles: 3.3 mg/m³
  - Indoor: 0.1 mg/m³
- Benzene: 0.8 mg/m³
  - Indoor: 0.002 mg/m³
- 1,3-Butadiene: 0.15 mg/m³
  - Indoor: 0.0003 mg/m³
- Formaldehyde: 0.7 mg/m³
  - Indoor: 0.1 mg/m³

Wood: 1.0 kg Per Hour in 15 ACH 40 m³ kitchen

International Agency for Research on Cancer (IARC) Group I Carcinogens

Typical standards to protect health
Size Distribution of Biomass Smoke Particles

Figure 2.2. Size distribution of woodsmoke and dungsmoke particles. Measurements taken in the East-West Center simulated village house as reported in Smith et al. (1984b). (Figure prepared by Premlata Menon.)

Source: Smith, Apte et al. 1984
Estimated PM10 Concentration in World Cities (pop=100,000+)
Cumulative distribution of urban pollution ($\mu g/m^3$)
How would we answer these questions?

• What is the total impact of disease and injury in the population? -- the overall target for public health interventions?
  – Which diseases are most important for which groups?
  – Are things getting better or worse?

• How do we compare the impacts of different risk factors and potential interventions that affect different populations?
  – For example, what is the burden of disease from particle air pollution?
  – How does the impact of tobacco smoking compare to that from air pollution?
Environmental Health Effects

• Example of results from outdoor particle studies
  – Asthma attacks
  – Missing workdays
  – Missing school days
  – Days with cough
  – Emergency room visits
  – Hospital admissions
  – Physician visits
  – Medication use
  – Daily death rate
  – Lung function
  – Self-reported health status
  – Etc.

• How can these be compared across time, cities, countries, age groups, sectors (e.g., transport versus power plants), etc.?

• Let alone compared with the health impacts from completely different risk factors, such as water pollution, lead exposure, high cholesterol, unsafe sex, etc.?
Ultimate Measure of Ill-health?

- Death is most common
  - Easy to determine
  - Commonly tabulated
- Severe problems as a measure
  - Everyone dies
  - Health never achieved
  - Age is clearly important
- Deaths + Illness = ?
First $C^4$ Database in Health
(Which we have had in many other fields for long periods)

- Combined mortality and morbidity – lost time
- Complete
  - Much of the world unrepresented in past databases
  - Many important disabilities unaccounted
- Consistent definitions of disease states
- Coherent
  - Deaths by disease need to add to total
    - By age and sex
    - Match with demographic stats
  - No natural discipline, i.e. no import stats from the afterlife tabulating how many died of what
Basic Principles

• C4: Combined, complete, consistent, and coherent

• Like is like
  – The only differences in effects is due to age and sex, not to nation, income, race, social class, etc.

• All are equal
  – All people have the potential for the highest life expectancy in the world, there are no intrinsic differences by genetic or other reasons.
<table>
<thead>
<tr>
<th>Code</th>
<th>Cause</th>
<th>Total</th>
<th>8-15</th>
<th>16-29</th>
<th>30-69</th>
<th>70+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>All Causes</td>
<td>14,099,258</td>
<td>1,168,375</td>
<td>2,634,578</td>
<td>8,769,544</td>
<td>422,621</td>
<td>20,094,761</td>
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<tr>
<td>0010</td>
<td>I. Communicable, maternal, perinatal and nutritional conditions</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0020</td>
<td>Infectious and parasitic diseases</td>
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<td>0030</td>
<td>Tuberculosis</td>
<td>247,593,003</td>
<td>83,281</td>
<td>782,431</td>
<td>6,497,044</td>
<td>373,590,993</td>
<td>48,864,419</td>
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<td>0040</td>
<td>Other infectious diseases</td>
<td>1,166,797</td>
<td>10,042</td>
<td>9,042</td>
<td>29,042</td>
<td>30,390</td>
<td>173,590,993</td>
</tr>
<tr>
<td>0050</td>
<td>Schizophrenia, manic-depressive illness and other psychiatric conditions</td>
<td>42,089</td>
<td>10,042</td>
<td>9,042</td>
<td>29,042</td>
<td>30,390</td>
<td>173,590,993</td>
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<td>0060</td>
<td>Mental and behavioral disorders</td>
<td>1,084,567</td>
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<tr>
<td>0100</td>
<td>Malnutrition and nutritional deficiencies</td>
<td>138,701,020</td>
<td>10,042</td>
<td>9,042</td>
<td>29,042</td>
<td>30,390</td>
<td>173,590,993</td>
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Global Burden of Disease Database
World Health Organization

Being completely updated 2007-2009
The major disease targets for public health interventions in the world today

Almost all Women & Children

World Lost DALYs
We have a means to answer the first, but what about the second?

• What is the total impact of disease and injury in the population? -- the overall target for public health interventions?
  – Which diseases are most important for which groups?
  – Are things getting better or worse?

• How do we compare the impacts of different risk factors and potential interventions that affect different populations?
  – For example, what is the burden of disease from environmental factors?
  – How does the impact of tobacco smoking compare to that from air pollution?
Comparative Risk Assessment (CRA)
2-year 30-institution project
organized by the World Health Organization

Disease, injury, and death due to 26 major risk factors calculated by age, sex, and 14 global regions.

Fully published in late 2004 in two volumes by WHO
Comparative Risk Assessment Method

Exposure Levels: Past actual and past counterfactual

Exposure-response Relationships (risk)

Disease Burden in 2000 by age, sex, and region

Attributable Burden in 2000 by age, sex, and region
Outdoor Exposure - pollutant for exposure assessment

Criteria
- Index of combustion processes
- Compelling evidence of health effect
- Widely available measure

- Inhalable particles (PM$_{10}$) and fine particles (PM$_{2.5}$)
Two sources of epidemiological evidence

- Chronic exposure studies
  - geographical comparisons

- Short-term exposure studies
  - daily time series analyses

How generalizable is the existing evidence, which is mostly from Western Europe and North America?
Example of Meta-analysis
Cardiovascular mortality and PM10

cardiovascular, all, Opplinger, Pope, 1999
cardiovascular, all, Psomos, Biggert, 2001
cardiovascular, all, Ruhm, Dauponte, 1999
cardiovascular, all, Le Houé, Zeghnoun, 2001
cardiovascular, all, Streeten, Zeghnoun, 2001
cardiovascular, all, Mexico City, Castillejos, 2000
cardiovascular, all, Phoenix, Mar, 2000
cardiovascular, all, Utah Valley, Pope III, 1996
cardiovascular, all, Utah County, Pope, 1992
cardiovascular, all, Rome, Biggert, 2001
cardiovascular, all, Santa Clara County, Fairley, 1999
cardiovascular, all, Provo/Orem, Pope, 1999
cardiovascular, all, Coachella Valley, Olson, 1999
cardiovascular, all, Bangladesh, Olson, 1999
cardiovascular, all, Florence, Biggert, 2001
cardiovascular, all, Incheon, Hong, 1999
cardiovascular, all, Wayne County, Lippmann, 2000
cardiovascular, all, Bologna, Biggert, 2001
cardiovascular, all, Coachella Valley, Olson, 2000
cardiovascular, all, 3 Spanish Cities, Bellister, 2002
cardiovascular, all, Paris, Zeghnoun, 2001
cardiovascular, all, Meath, Galen, 1999
cardiovascular, all, Montreal, Goldberg, 2001
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cardiovascular, all, Erfurt, Wizemann, 2000
cardiovascular, all, Santiago, Olson, 1996
cardiovascular, all, Incheon, Hong, 1999
cardiovascular, all, Torun, Biggert, 2001
cardiovascular, 65+, Krecek, Szemesics, 1999
cardiovascular, 65+, Sao Paulo, Gosavi, 2000
cardiovascular, all, London, Brenner, 1999
cardiovascular, all, West Midlands, Anderson, 2001
cardiovascular, all, Milan, Biggert, 2001
cardiovascular, all, Hong Kong, Wong, 2001
cardiovascular, all, Hong Kong, Wong, 2002
cardiovascular, all, Rotterdam, Huisman, 1999
cardiovascular, all, Rotterdam, Huisman, 2000
cardiovascular, all, Netherlands, Huisman, 2000
cardiovascular, all, Helsinki, Hokka, 1999
cardiovascular, all, Helsinki, Hokka, 1999
cardiovascular, all, Melbourne, Simpson, 2000
cardiovascular, all, Seville, Camaño-Rico, 1999
cardiovascular random effects estimate

cerebrovascular, all, Opplinger, Pope, 1999
cerebrovascular, all, Psomos, Biggert, 2001
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cardiovascular, 65+, Krecek, Szemesics, 1999
cardiovascular, 65+, Sao Paulo, Gosavi, 2000

Combined Estimate
ACS cohort (Pope et al JAMA 2002)  
500,000 adults followed 1982 - 1998

<table>
<thead>
<tr>
<th>Condition</th>
<th>RR (adj)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiopulmonary</td>
<td>1.06</td>
<td>1.02-1.10</td>
</tr>
<tr>
<td>Lung Cancer</td>
<td>1.08</td>
<td>1.01-1.16</td>
</tr>
</tbody>
</table>

Random effects Cox proportional hazards model controlling for age, sex, race, smoking, education, marital status, body mass, alcohol, occupational exposure and diet.
Lost healthy life years (DALYs)

(x1000)

China (world total 6,404,000) India

AfrD AfrE AmrA AmrB AmrD EmlB EmlD EurA EurB EurC SarB SarD WprA WprB

LCA Cardiopulmonary ARI < 5yrs
IAQ Exposure Measure for CRA

- Insufficient measurements of indoor exposures worldwide to use concentration
- Binary metric is possible: use or no use of solid fuels for household cooking and heating: biomass (wood, crop residues, dung) and coal
- Household survey data available for ~100 nations
- Model developed to estimate levels in other ~80 countries.
### The Energy Ladder: Relative Pollutant Emissions Per Meal

<table>
<thead>
<tr>
<th></th>
<th>Biogas</th>
<th>LPG</th>
<th>Kerosene</th>
<th>Wood</th>
<th>Roots</th>
<th>Crop Residues</th>
<th>Dung</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.1</td>
<td>1.0</td>
<td>3</td>
<td>19</td>
<td>22</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>0.3</td>
<td>1.0</td>
<td>4.2</td>
<td>17</td>
<td>18</td>
<td>32</td>
<td>115</td>
</tr>
<tr>
<td>PM</td>
<td>2.5</td>
<td>1.0</td>
<td>1.3</td>
<td>26</td>
<td>30</td>
<td>124</td>
<td>63</td>
</tr>
</tbody>
</table>

Smith, et al., 2005
Diseases for which we have some epidemiological studies

ALRI/Pneumonia (meningitis)

Chronic obstructive lung disease

Only two qualified with sufficient evidence to be included in the CRA
Acute lower respiratory infections (ALRI)

Chief cause of death among the world’s children (~2 million per year). Thus, it is the chief global cause of lost healthy life years.

Child mortality occurs almost entirely in developing countries, and as pneumonia.

Well-accepted risk factors (malnutrition, micro-nutrient deficiencies, other diseases, crowding, chilling) do not account for its scale.
Meta-analysis of studies of ALRI and solid fuels, in children aged <5 years

<table>
<thead>
<tr>
<th>Subgroup analyses of ~14 studies</th>
<th>Odds ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>2.3 (1.9-2.7)</td>
</tr>
<tr>
<td>Use of solid fuel</td>
<td>2.0 (1.4-2.8)</td>
</tr>
<tr>
<td>Duration of time child spent near the cooking fire</td>
<td>2.3 (1.8-2.9)</td>
</tr>
<tr>
<td>Studies adjusting for nutritional status</td>
<td>3.1 (1.8-5.3)</td>
</tr>
<tr>
<td>Studies not adjusting for nutritional status</td>
<td>2.2 (2.0-3.0)</td>
</tr>
<tr>
<td>Children aged &lt;2 years old</td>
<td>2.5 (2.0-3.0)</td>
</tr>
<tr>
<td>Children aged &lt;5 years old</td>
<td>1.8 (1.3-2.5)</td>
</tr>
</tbody>
</table>

Children in households using solid fuels have twice the rate of serious ALRI

Smith et al in WHO, Comparative quantification of health risks, 2004
Exposure-response relationship
Results from the First Randomized Trial

Reference point (RR=1) is mean CO in controls

Log linear function provided the best fit
# ALRI-IAP Systematic Review and Meta-Analysis


<table>
<thead>
<tr>
<th>Study</th>
<th>Odds Ratio (random)</th>
<th>Weight %</th>
<th>Odds Ratio (random)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 Intervention Studies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smith (2007)a</td>
<td>5.53</td>
<td>1.18 [0.96, 1.58]</td>
<td></td>
</tr>
<tr>
<td>Smith (2007)b</td>
<td>5.72</td>
<td>1.38 [1.05, 1.79]</td>
<td></td>
</tr>
<tr>
<td>Subtotal (95% CI)</td>
<td></td>
<td>11.26</td>
<td>1.28 [1.06, 1.54]</td>
</tr>
<tr>
<td>Test for heterogeneity: Chi² = 4.48, df = 1 (P = 0.04), I² = 0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test for overall effect: Z = 2.54 (P = 0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| O2 Cohort Studies | | | |
| Armstrong (1991)a | 2.80 | 0.50 [0.20, 1.22] |
| Armstrong (1991)b | 3.65 | 1.50 [0.96, 2.37] |
| Cambeil (1989) | 3.25 | 1.80 [1.39, 5.00] |
| Ezzaral (2001) | 3.42 | 2.32 [1.03, 4.41] |
| Jin (1983) | 5.69 | 0.80 [0.62, 1.03] |
| Pandey (1989)a | 4.34 | 2.45 [1.43, 4.19] |
| Pandey (1989)b | 4.52 | 40.65 [9.70, 150.75] |
| Subtotal (95% CI) | | 25.11 | 2.12 [1.05, 4.27] |
| Test for heterogeneity: Chi² = 54.07, df = 6 (P = 0.00001), I² = 88.9% |
| Test for overall effect: Z = 2.11 (P = 0.03) |

| O3 Case-Control Studies | | | |
| Azzaz (1995) | 3.97 | 1.20 [0.66, 2.21] |
| Broor (2001) | 4.45 | 2.51 [1.51, 4.17] |
| Collings (1980) | 4.58 | 2.16 [1.40, 3.33] |
| De Francisco (1993) | 2.15 | 5.23 [1.72, 15.91] |
| Forrester (1986) | 4.66 | 1.19 [0.71, 1.92] |
| Johnson (1992)a | 0.16 | 0.60 [0.36, 1.07] |
| Kossove (1982) | 1.96 | 4.77 [1.44, 15.74] |
| Kumar (2004) | 2.45 | 3.87 [1.42, 10.57] |
| Mahalakshmi (2002) | 3.63 | 3.97 [2.00, 7.00] |
| Mornie (1992) | 2.41 | 4.86 [1.75, 13.40] |
| O'Dempsey (1996) | 2.59 | 2.55 [1.98, 3.28] |
| Roland (1990)a | 2.95 | 1.40 [0.60, 3.28] |
| Victoria (1994) | 4.00 | 1.10 [0.61, 1.90] |
| Wyverse (2004) | 2.39 | 1.61 [0.61, 1.90] |
| Wesley (1996) | 1.87 | 1.35 [0.39, 4.63] |
| Subtotal (95% CI) | | 40.15 | 1.97 [1.47, 2.64] |
| Test for heterogeneity: Chi² = 32.72, df = 14 (P = 0.003), I² = 57.2% |
| Test for overall effect: Z = 4.53 (P < 0.00001) |

| O4 Cross-sectional Studies | | | |
| Mihara (2003) | 3.83 | 2.20 [1.16, 4.18] |
| Mihara (2005) | 5.87 | 1.58 [1.28, 1.95] |
| Wichmann (2005) | 5.79 | 1.29 [1.02, 1.63] |
| Subtotal (95% CI) | | 16.48 | 1.49 [1.21, 1.95] |
| Test for heterogeneity: Chi² = 3.19, df = 2 (P = 0.20), I² = 37.3% |
| Test for overall effect: Z = 3.74 (P = 0.0002) |

Total (95% CI) | | 100.00 | 1.78 [1.45, 2.18] |

Test for heterogeneity: Chi² = 151.17, df = 26 (P < 0.0001), I² = 74.4% |
Test for overall effect: Z = 5.61 (P < 0.00001)
Global Health Effects of Combustion Particles: Premature Deaths Per Year

- Urban outdoor air pollution: ~800,000
- Household use of solid fuels: ~1,600,000
- Environmental tobacco smoke: ~300,000
- Occupational exposures: ~250,000
- Total ~ 3 million per year
  - With active smoking: ~8 million
- Compare with global totals for
  - Dirty water: 2 million
  - HIV: 3 million
  - All cancer: 7 million
  - Malnutrition: 4 million
Large areas of rural India & China have high ambient air pollution

20-month average ground-level PM2.5 from satellite data
Solid-fuel Using Households: Large Global Exposures to some surprising pollutants – perhaps largest

- Ultrafine particles – fresh and combustion-generated
- Formaldehyde
- Benzene
- PAH
- Dioxin
- Etc.
Biomass smoke – a global concern

- A significant contribution to PM2.5 emissions around the world – more than half in many developed countries (Canada, Denmark, much of USA, etc.)
  - Ag burning a function of ag production, not income - California
  - Wood heating and fireplace use common in many developed countries – Silicon Valley
- Growing because of energy prices
- And climate change
- Not clear whether effects across all major health outcomes are the same as those found in urban studies of PM
  - Chronic and Acute Respiratory
  - Cardiovascular
  - Cancer
- Households in LDCs perhaps only widespread exposure to nearly pure biomass smoke
Energy Use in Thailand by Source

Source: RWEDP
The graph illustrates the relationship between income and various forms of emissions, including biomass, PM, and per capita emissions. The graph shows:

- **Biomass** emissions are positively correlated with income, indicating an increase in emissions as income rises.
- **PM** emissions are negatively correlated with income, suggesting a decrease in emissions as income increases.
- **Per Capita Emissions** have a varying trend; while indoor emissions seem to decrease with income, outdoor emissions show an increase.

The total emissions line also shows a decrease with income, highlighting a trend where overall emissions are reduced as income increases.
California’s 2005 Combustion PM$_{2.5}$ Emissions

- **Residential Fuel**: 24%
- **Off-road vehicles**: 18%
- **On-road vehicles**: 8%
- **Cooking**: 3%
- **Forests and other**: 23%
- **Crops, weeds, rangeland**: 15%
- **Stationary (including power)**: 8%
- **Other**: refining-waste management-structural fires: 1%

**Biomass: 62% of total**

~450 t/day

From CARB database
Warming in 2005 from emissions since 1750

A large part from PIC: products of incomplete combustion

IPCC, 2007
Greenhouse warming commitment per meal for typical Indian wood-fired cookstove

Wood: 1.0 kg
454 g Carbon

CO2 Carbon: 403 g
Methane Carbon: 3.8 g
Other GHG Carbon
Carbon Monoxide: 38 g
Hydrocarbons: 6.3 g
Nitrous Oxide 0.018 g

403 g
86 g
131 g
69 g
4.7 g

Global warming commitments of each of the gases as CO₂ equivalents

Source: Smith, et al., 2000
The semi-gasifier stove customers do not need to buy fuel at present. They only need simply processed fuel. The gasification efficiency can be as high as 60%, and thermal efficiency more than 45%. The most significant character is it doesn’t emit dark smoke, and is friendly to the environment and the farmers’ health.

Lab tests show PIC levels nearly at LPG levels. But can it be reliably achieved in the field?
Co-benefits in China:
~$500/life-year saved
~$6/t-CO$_2$ averted

Smith & Haigler, 2008
Current Cost-effective Region In China

Relative Values ($Int)
- tCO2e offset
- DALYs avoided

Smith & Haigler, 2008
Conclusions

• It is difficult to burn unprocessed solid fuels completely in simple household-scale devices.
• Consequently, a large fraction of the fuel C is diverted to PIC
• Leading to inefficient use of the primary resource
• And, because of the proximity to population, the PIC seem to be responsible for much ill-health in developing countries.
Conclusions (cont.)

• Because the average Global Warming Potential of PIC carbon is greater than CO$_2$, there is significant global warming commitment per unit energy use for household devices, even when the biomass is harvested renewably.

• To be greenhouse-gas neutral, therefore, a biomass fuel cycle must not only be based on renewable harvesting, but it also must have good combustion efficiency, i.e., produce little PIC
Conclusions (cont.)

• Careful improvements/reductions in solid household fuel use offer multiple benefits in energy, health, and global warming.
• Probably requires coordinated improvement of fuel and stove
• Cost-effectiveness compares well with other interventions:
• Significant engineering challenge to reliably produce high combustion and overall efficiencies cheaply with simple solid fuels
Summary: The Hazards of Combustion Mismanagement

• Sticking burning stuff in your mouth
• In your home
• In your workplace
• In your community
• On your planet
• Letting it burn down your house
<table>
<thead>
<tr>
<th>Combustion Risk Factor</th>
<th>Million Deaths</th>
<th>Percent of Global Deaths</th>
<th>Percent of Disease Burden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobacco</td>
<td>4.9</td>
<td>8.7%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Indoor smoke from household solid fuel</td>
<td>1.6</td>
<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td>ETS and Workplace</td>
<td>0.5</td>
<td>0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Urban outdoor air pollution</td>
<td>0.80</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Climate change</td>
<td>0.15</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Fires</td>
<td>0.24</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Adjusted totals</td>
<td>~ 8</td>
<td>~ 14%</td>
<td>~ 10%</td>
</tr>
</tbody>
</table>
Combustion Mismanagement

An ancient but still large source of death and disease around the world

One out of seven deaths each year occurs prematurely because of combustion mismanagement, mostly from small particles.

And growing!
Laws of Carbon-thermodynamics

I. Keep all fossil and forest carbon out of the atmosphere

II. If you cannot do so, the least-damaging form to release is carbon dioxide because all other forms are worse for climate and health.

III. Even renewable (non-fossil) carbon is damaging for climate and health if not released as carbon dioxide.
Laws of Particle Health

• Don’t release combustion particles into the air – they are all bad for health
• If you must, do so far from people
• If you cannot avoid doing so, do it outside not inside
• Whatever you do, don’t stick burning stuff in your mouth
Need for fast, cheap, and easy PM monitoring techniques: something the aerosol community can help with
Combined Optical and Ionization Measurement Techniques for Inexpensive Characterization of Micrometer and Submicrometer Aerosols

Technique Paper

An Inexpensive Dual-Chamber Particle Monitor: Laboratory Characterization

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An inexpensive light-scattering particle monitor: field validation

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Received/Acceptance Data: Forthcoming 2007

Publication data
DOI: 10.1039/b000000x

We have developed a small, light, passive, inexpensive, datalogging particle monitor called the “UCB” (University of California Berkeley Particle Monitor). Following previously published laboratory assessments, we present here results of tests of its performance in field settings. We demonstrate the mass sensitivity of the UCB in relation to gravimetric filter-based PM2.5 mass estimates as well as commercial light-scattering instruments co-located in field chamber tests and in kitchens of wood-burning households. Although requiring adjustment for differences in sensitivity, Inter-monitor performance was consistently high ($r^2>0.99$). Moreover, the UCB can consistently estimate PM2.5 mass concentrations in wood-burning kitchens (Pearson $r^2$ = 0.885; $N=99$), with good agreement between duplicate measures (Pearson $r^2$ = 0.940; $N=88$). In addition, with appropriate cleaning of the sensing chamber, UCB mass sensitivity does not decrease with time when used intensively in open woodfire kitchens, demonstrating the significant potential of this monitor.
Guatemala house with open fire
DustTrak vs UCB particle monitor

Co-location June 15 2004

Time (hrs:min)
Mass (mg/m³)
Most the papers and other publications from which these data were taken are available at http://ehs.sph.berkeley.edu/krsmith

Thank you