Worldwide Biomass Combustion: Energy, Air Pollution, and Health

Kirk R. Smith
University of California, Berkeley

International Biomass Smoke Health Effects Conference

University of Montana, Missoula
Center for Environmental Health Sciences

August 21-22, 2007
Itinerary Biomass Combustion

• Biomass combustion in the world
  – Fuel and non-fuel
  – Rich and poor

• Air pollution from biomass
  – Emissions
  – Exposures

• Health effects
  – Burden of disease calculations
  – Randomized trial in Guatemala
Oldest Pollution Source in Human History
Typical Household Energy Ladder

Development

Cleanliness, Energy Efficiency, and Capital Costs

The other half
Half the world

Electricity

Kerosene

Wood

Crop Residues

Dung

Global Energy Ladder
(Approximate % of Population)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>% of Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass/ twigs</td>
<td>2</td>
</tr>
<tr>
<td>Dung</td>
<td>4</td>
</tr>
<tr>
<td>Crop Residues</td>
<td>18</td>
</tr>
<tr>
<td>Wood</td>
<td>22</td>
</tr>
<tr>
<td>Charcoal</td>
<td>4</td>
</tr>
<tr>
<td>Coal</td>
<td>6</td>
</tr>
<tr>
<td>Kerosene</td>
<td>10</td>
</tr>
<tr>
<td>Gas</td>
<td>20</td>
</tr>
<tr>
<td>Electricity</td>
<td>14</td>
</tr>
</tbody>
</table>

1% = 60 million people

Coal important in China

Development

Global Energy Ladder

- Wood
- Coal important in China
- Crop Residues
- Kerosene
- Gas
- Electricity
- Half the world
- The other half

Development

Cleanliness, Energy Efficiency, and Capital Costs
How will this look as other poor countries develop in a world with uncertain supplies of oil costing $50/bbl or more?
% Biomass Energy Use & GNP

Source: RWEDP
Energy Use in Thailand by Source

Source: RWEDP
Source: RWEDP
Asia Pacific
shares of 2.31 Gtoe

OECD
shares of 5.33 Gtoe

Approximately equal per capita consumption!

WEA, 2004
More than half the world’s population relies on biomass for most of its energy, a situation that has not changed since the mastery of fire, one million years ago.
Woodsmoke is natural – how can it hurt you?

Or, since wood is mainly just carbon, hydrogen, and oxygen, doesn’t it just change to CO$_2$ and H$_2$O when it is combined with oxygen (burned)?

Reason: the combustion efficiency is far less than 100%
Heat

Products of Incomplete Combustion

PIC

PIC

PRODUC TS OF COMBUSTION

AIR

FLAME

THERMAL FEEDBACK

VOLATILES

CHAR RESIDUE

SOLID FUEL
Indian Cookstoves

Nominal Combustion Efficiency

- Gas: 99% (98-99.5)
- Kerosene: 97 (95-98)
- Solid Fuels
  - Wood: 89 (81-92)
  - Crop resid: 85 (78-91)
  - Dung: 84 (81-89)
  - Coal (variable)

Source: Smith, et al, 2000
Census, 2001
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?
Carbon Balance:

A Toxic Waste Factory!!

Typical biomass cookstoves convert 6-20% of the fuel carbon to toxic substances

- CO2 Carbon: 295.8 g
- PIC Carbon:
  - CO: 18.5 g
  - CH4: 2.8 g
  - TNMOC: 5.2 g
- Char/Ash: 161 g
- TSP Carbon: 1.7 g

Nominal Combustion Efficiency = 1/(1+k) = 89%
Toxic Pollutants in Biomass Fuel Smoke from Simple (poor) Combustion

• Small particles, CO

• 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} & \textit{styrene}
  – 20+ polycyclic aromatics such as \textit{benzo(\(\alpha\))pyrene}

• Oxygenated organics
  – 20+ aldehydes including \textit{formaldehyde} & \textit{acrolein}
  – 25+ alcohols and acids such as \textit{methanol}
  – 33+ phenols such as \textit{catechol} & \textit{cresol}
  – Many quinones such as \textit{hydroquinone}
  – Semi-quinone-type and other radicals

• Chlorinated organics such as \textit{methylene chloride} and \textit{dioxin}

Best measure of risk ~ 0.1-0.4% of fuel weight

Naehler et al. 2007, JIT
Size Distribution of Biomass Smoke Particles

Figure 2.2. Size distribution of woodsmoke and dungsme smoke 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
Indoor pollution concentrations from typical woodfired cookstove during cooking

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

All data contribute to an evaluation

### Cancer in humans
- **Sufficient evidence**
- **Limited evidence**
- **Inadequate evidence**
- **Evidence suggesting lack of carcinogenicity**

### Cancer in experimental animals
- **Sufficient evidence**
- **Limited evidence**
- **Inadequate evidence**
- **Evidence suggesting lack of carcinogenicity**

### Mechanistic and other relevant data
For each mechanism:
- **Mechanistic data “weak,” “moderate,” or “strong”**?
- **Mechanism likely to be operative in humans**?

### Overall evaluation
- **Group 1** Carcinogenic to humans
- **Group 2A** Probably carcinogenic to humans
- **Group 2B** Possibly carcinogenic to humans
- **Group 3** Not classifiable as to its carcinogenicity to humans
- **Group 4** Probably not carcinogenic to humans
A tour of IARC’s classifications
— Preamble, Part B, Section 6(d)

<table>
<thead>
<tr>
<th>EVIDENCE IN EXPERIMENTAL ANIMALS</th>
<th>Sufficient</th>
<th>Limited</th>
<th>Inadequate</th>
<th>ESLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVIDENCE IN HUMANS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inadequate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESLC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Group 1 (carcinogenic to humans) whenever there is sufficient evidence in humans**

<table>
<thead>
<tr>
<th>EVIDENCE IN HUMANS</th>
<th>Sufficient</th>
<th>Limited</th>
<th>Inadequate</th>
<th>ESLC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sufficient</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Limited</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Inadequate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ESLC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Group 2A (*probably carcinogenic*) with *limited evidence in humans* and *sufficient evidence in animals*

<table>
<thead>
<tr>
<th>EVIDENCE IN HUMANS</th>
<th>Sufficient</th>
<th>Limited</th>
<th>Inadequate</th>
<th>ESLC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sufficient</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Limited</strong></td>
<td></td>
<td><strong>Group 2A</strong></td>
<td><strong>Woodsmoke</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Inadequate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ESLC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
"Thank God! A panel of experts!"

Courtesy of Ross Anderson
Comparative Risk Assessment

- 26 major risk factors
- Common methods and databases
- Consensual discipline on acceptance of evidence
- Mortality and morbidity by age, sex, and 14 world regions
- Lost healthy life years (DALYs) final metric
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.
Pneumonia Deaths in the United States

Not so long ago, pneumonia was the chief cause of death in developed countries.

The Energy Ladder: Relative Pollutant Emissions Per Meal

CO

Hydrocarbons

PM

Biogas LPG Kerosene Wood Roots Crop Residues Dung

CO 0.1 1.0 3 19 22 60 64
Hydrocarbons 0.3 1.0 4.2 17 18 32 115
PM 2.5 1.0 1.3 26 30 124 63

Smith, et al., 2005

"Clean" "Dirty"
Households Using Biomass Fuels In India

Source: Census of India 1991
National Household Solid Fuel Use, 2000

Based on econometric model and calibration against household surveys in ~50 countries
## 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>
</tbody>
</table>

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

Studies not adjusting for nutritional status | 2.2 (2.0-3.0)

| Children aged <2 years old | 2.5 (2.0-3.0) |
| Children aged <5 years old | 1.8 (1.3-2.5) |

Smith et al in WHO, Comparative quantification of health risks, 2004
Meta-analysis of all studies adjusted for age
Chronic Obstructive Pulmonary Disease (COPD) in women

**OR = 3.2 (95% CI: 2.3-4.8)**

Smith et al., 2004
Global Burden of Disease from Top 10 Risk Factors
plus selected other risk factors

- Underweight
- Unsafe sex
- Blood pressure
- Tobacco
- Alcohol
- Unsafe water/sanitation
- Child cluster vaccination*
- Cholesterol
- Lack of Malaria control*
- Indoor smoke from solid fuels
- Overweight
- Occupational hazards (5 kinds)
- Road traffic accidents*
- Physical inactivity
- Lead (Pb) pollution
- Urban outdoor air pollution
- Climate change

Percent of All DALYs in 2000

4.9 million deaths/y
1.6 million deaths/y (+/- 50%)
0.8 million death/y

Smith et al.
2005
Need for Stronger Evidence

- Problem with observational data
- Randomized control trials (RCTs) are coin of realm in international health
- Decided to do RCT in 1984
- Received funding in 2001
- Publications coming out in 2007
First Randomized Trial in Air Pollution History*

After a worldwide search, a site in the Guatemalan Highlands was chosen.

* In normal populations
Setting

• Rural highlands of San Marcos, western Guatemala
• Population nearly all indigenous Mayan Indians
• Nearly all depend on wood for cooking and heating
• Traditional stove is the 3-stone fire – no venting to outside
• Very poor, high IMR, pneumonia, diarrhoea and stunting common
• Poor health service uptake - culture, language, transport, time
• Intervention is a stove with chimney that is well-accepted by community
RESPIRE: Randomized Exposure Study of Pollution Indoors and Respiratory Effects

Highland Guatemala

Traditional 3-stone open fire

Plancha chimney wood stove
Need for fast, cheap, and easy monitoring for particles so that widespread temporal and spatial measurements can be done easily in many places
Combined Optical and Ionization Measurement Techniques for Inexpensive Characterization of Micrometer and Submicrometer Aerosols

An Inexpensive Dual-Chamber Particle Monitor: Laboratory Characterization

Rufus Edwards
School of Social Ec
University of Calif

Kirk R. Smith
School of Public Hi

Brent Kirby
Chemistry Departm

Tracy Allen
Electronically Monit

Charles D. Litton
Pittsburgh Researci
Disease Control an

Susanne Hering
Aerosol Dynamics,

An inexpensive light-scattering particle monitor: field validation

Zohir Chowdhury, Rufus Edwards, Michael Johnson, Kyra Naumoff Shields, Tracy Allen, Eduardo Canuz and Kirk R. Smith

Received/Acceptance Data: Forthcoming 2007

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 PM_{2.5} 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 (r²>0.99). Moreover, the UCB can consistently estimate PM_{2.5} mass concentrations in wood-burning kitchens (Pearson r²= 0.885; N=99), with good agreement between duplicate measures (Pearson r² = 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)
Overview of study design

- 530 eligible households: open fire, woman pregnant or child less than 4 months
- Baseline survey and exposure assessment

Randomize

Keep open fire

Plancha

Follow up till aged 18 months
- Surveillance for ALRI, diarrhoea, &c
- Detailed exposure monitoring

Compare incidence and exposure in 2 groups
Plancha offered to ‘controls’

Year 1
5500 Households total

Years 1-3

Years 3-4
Overview of child health outcomes assessment

Follow-up at weekly visit

Home

Weekly visit
- Well
- Mild illness
- Referral to study doctor

Community centre

Study doctor examines
- Pulse oximetry
- If pneumonia, RSV* test and refer for CXR
- Refer if very ill

Hospital

Assessed by duty doctor
Study team obtain CXR and inpatient data and diagnosis

Health outcome definitions

Child dies

Verbal autopsy

* Respiratory syncitial virus
Results for MD-diagnosed Severe Pneumonia:

**RSV+, hypoxic**

<table>
<thead>
<tr>
<th>OR (SE)</th>
<th>p</th>
<th>95%CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.93 (0.25)</td>
<td>0.79</td>
<td>0.55 – 1.57</td>
</tr>
</tbody>
</table>

**Non-RSV, hypoxic**

<table>
<thead>
<tr>
<th>OR (SE)</th>
<th>p</th>
<th>95%CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.59 (0.15)</td>
<td>0.031</td>
<td>0.36 – 0.95</td>
</tr>
</tbody>
</table>

Interpretation: Children in households with open woodfires seem to have ~ two-thirds (1/0.60) more serious non-RSV pneumonia than those in households with well-operating woodstoves with chimneys.
2-3 million ALRI Deaths In Children Under 5

- Poor case-management: 50%
- Underweight: 40%
- Lack of breastfeeding: 10%
- Diarrhea: 20%
- Measles: 10%
- Zn Deficiency: 15%
- No vaccines: 25-50%
- Genetic Susceptibility: 25-50%

Poor Housing: 40%
Lack of chimneys: 20%
Lack of clean fuel: 30%
Household solid-fuel burning: 20%
Outdoor air pollution: ?
Lack of breast feeding: ?

Attributable Fractions do not add to 100%

Rough estimates only
Chimney Stove Intervention to Reduce Long-term Woodsmoke Exposure Lowers Blood Pressure among Guatemalan Women

John P. McCracken,
Kirk R. Smith, Murray A. Mittleman, Anaité Díaz, Joel Schwartz

(Published in Environmental Health Perspectives, July 2007)
Background

- Ambient particles associated with increased blood pressure (BP) (e.g. Linn, 1999; Zanobetti, 2004)
- Elevated BP predicts increased cardiovascular risk
- No studies of long-term air pollution exposures and BP
- Effects of biomass smoke have not been studied
Objectives

Goal: To evaluate the effect of long-term reductions in woodsmoke exposure on systolic (SBP) and diastolic blood pressure (DBP).

Specific hypotheses:
1. Personal fine particle (PM$_{2.5}$) exposures will be lower among women using chimney stoves to cook.
2. Chimney stove intervention will be associated with lower SBP and DBP.
Study Design

• Study population
  – Eligible: Women ≥ 38 years, cooking daily
  – Excluded: pregnant, breastfeeding

• Two follow-up periods
  – Trial period (7/03-12/04)
  – Echo-intervention period (3/04-3/05)

Personal PM$_{2.5}$  SBP and DBP
### Measures by Group and Period

#### Subjects (Measures)

<table>
<thead>
<tr>
<th></th>
<th>Trial Period</th>
<th>Echo-Intervention Period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intervention Group</strong></td>
<td>49 (115)</td>
<td></td>
</tr>
<tr>
<td><strong>Control Group</strong></td>
<td>71 (111)</td>
<td>55 (65)</td>
</tr>
</tbody>
</table>
### Between-Groups Results

<table>
<thead>
<tr>
<th>Number of subjects (measures)</th>
<th>Adjusted mean difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control group</td>
</tr>
<tr>
<td>SBP</td>
<td>71 (111)</td>
</tr>
<tr>
<td>DBP</td>
<td>71 (111)</td>
</tr>
</tbody>
</table>

* Adjusted for age, body mass index, daily temperature, season, day of the week, time of day, use of wood-fired sauna, household electricity, an asset index, ever smoking, and secondhand tobacco smoke exposure
<table>
<thead>
<tr>
<th></th>
<th>Number of subjects (measures)</th>
<th>Adjusted mean difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial period</td>
<td>Echo-intervention</td>
</tr>
<tr>
<td>SBP</td>
<td>55 (88)</td>
<td>55 (65)</td>
</tr>
<tr>
<td>DBP</td>
<td>55 (88)</td>
<td>55 (65)</td>
</tr>
</tbody>
</table>

* Adjusted for age, body mass index, daily temperature, season, day of the week, time of day, use of wood-fired sauna, household electricity, an asset index, ever smoking, and secondhand tobacco smoke exposure
Total

Energy Per Capita

Biomass

Income
PM Emissions Per Capita

Total

Biomass

Income
California’s 2005 Combustion PM$_{2.5}$ Emissions

- **Biomass:** 62% of total
  - ~450 t/day

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

From CARB database
Thank you