

## Chapter 7

# Household Air Pollution from Solid Cookfuels and Its Effects on Health

Kirk R. Smith and Ajay Pillarisetti



## INTRODUCTION

Since the earliest human times, humans have used wood as fuel for fires to cook their food. Indeed, learning to control fire is considered the defining moment between the pre-human and human condition (Wrangham 2009). With the agricultural revolution some 10,000 years ago, agricultural residues (including animal dung) were brought to the hearth as well. Around 1,000 years ago, coal became used in areas where it was mined easily—for example, the British Isles and China (Smil 1994). These three fuels—wood, agricultural residues, and coal—constitute the solid cooking fuels used by about 40 percent of humanity today (Bonjour and others 2013). Typically burned in simple cookstoves, these fuels produce smoke that is now understood to cause a large burden of disease (Smith and others 2014).

Cleaner fuels (coal gas, natural gas, liquefied petroleum gas [LPG], and electricity) began to make inroads only in the late nineteenth century. Although today 60 percent of the world's population uses these modern fuels (which are relatively clean in household use, even in simple cookstoves), growth in their use has never kept up with global population growth, primarily because of the persistence of biomass use among the poor. Today, almost 3 billion people use solid cookfuels, which probably is more than at any time in world history (Bonjour and others 2013) and more than the entire world population before 1960.

Household air pollution (HAP) is now understood to be a major risk factor for health. According to the 2013 Global Burden of Disease Study (GBD), HAP is ranked as the single most significant environmental health risk factor globally. In poor countries where many households rely on biomass for cooking (such as in Sub-Saharan Africa), HAP is ranked among the top risk factors examined in the GBD assessments. Depending on which set of estimates is used, some 3 million to 4 million premature deaths are thought to be caused annually by HAP. Between 3 and 5 percent of the GBD in terms of disability-adjusted life years (DALYs) is attributed to it, about one-third in children younger than age five years and the rest divided between adult men and women (for background on DALYs, see Salomon 2014).

This chapter relies on two major reviews published in recent years. One was done as part of the Comparative Risk Assessment (CRA) of the GBD project (Lim and others 2012; Lozano and others 2012; Smith and others 2014), and the other was done as background documentation for the World Health Organization's (WHO) Indoor Air Quality Guidelines (IAQGs) (WHO 2014b). This chapter summarizes what is known about effective and cost-effective interventions to reduce the health effects of exposure to HAP from solid cooking fuels<sup>1</sup> and then explores some of the issues regarding framing, interactions, and viable interventions. The discussion follows the classic environmental health pathway described in box 7.1.

## Box 7.1

### The Environmental Health Pathway

This chapter relies loosely on the classic environmental health pathway for describing and understanding pollution risks (figure B7.1.1), which starts with sources and emissions of pollution, moves to environmental levels, then to human exposures, then to doses within the body, and finally to health impacts (Smith 1987). In the case of household air pollution, a source could be any type of biomass combustion, but we focus here primarily on biomass combustion used in cooking. Different kinds of evidence come to bear at each stage of the pathway, and each stage offers different avenues for control. Because some of the terminology in the pathway is discipline specific, we must briefly clarify what we mean by emissions, concentration, exposure, biomarkers of exposure, and biomarkers of effect.

*Emissions* refer to the rate of release of a pollutant per unit of time or per unit of fuel (the “source” in figure B7.1.1). Measurements of emissions require sampling directly from the source of combustion. Emissions samples often are taken during a cooking cycle—either actual or simulated—and rarely are captured for the entire day. Experience shows that lab measurements or simulated measurements in homes usually underestimate actual emissions in the field (Johnson and others 2008; Johnson and others 2011).

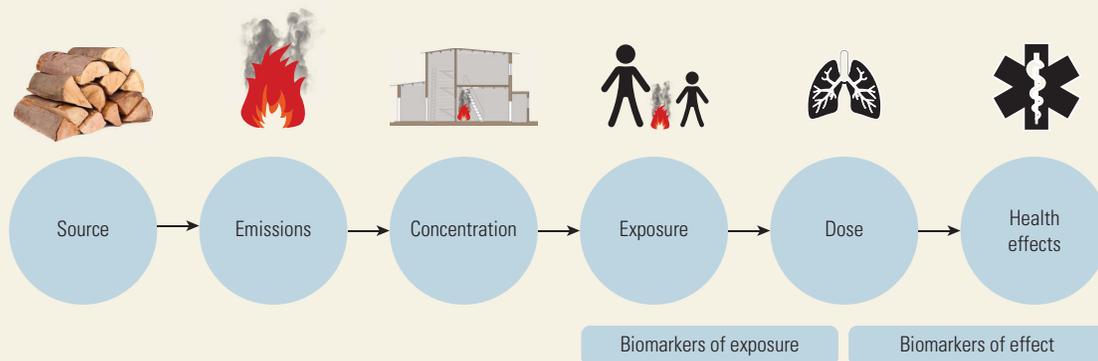
*Concentrations* (generally measured in mass of pollutant per volume of air) are a function of emissions, conditions in the room of interest (such as the room’s ventilation rate), and processes like

deposition and exfiltration of pollutants through openings. Concentrations are not necessarily equivalent to exposures; for example, a monitor that measures pollution in a kitchen (defined here as the built environment around the cooking area, whether indoors or outdoors) for 24 hours does not reflect a person’s exposure to that pollution unless he or she, too, is in the kitchen for 24 hours.

*Exposures* are a result of the spatiotemporal relationship between individuals and the pollution in their immediate surroundings. An individual’s daily exposure is affected by the number, type, and duration of contact with all sources he or she comes into contact with, either directly (for example, one’s own household cooking fire) or indirectly (for example, local traffic sources or a neighbor’s household cooking fire). Exposure can be assessed either through personal measurement, in which an individual wears a monitor, or through exposure reconstruction, in which time-activity information (for example, a diary of time spent in various locations and time spent in proximity to potential sources) is coupled with area monitors measuring concentration in various microenvironments. Personal exposure typically is assessed for 24 or 48 hours.

*Biomarkers of exposure* are measurable metabolites or products of an interaction between an external agent and a target molecule, cell, or organ. Biomarkers of effect are chemical, biological, or physical alterations resulting from an exposure that can be associated with a health endpoint or disease (WHO 1993).

Figure B7.1.1 Classic Environmental Health Pathway



Most of the older literature and even some modern studies refer to the problem as one of indoor air pollution, but the CRA (Lim and others 2012) carefully redefined it as HAP for several reasons (Smith and others 2014):

- Much of the health-relevant exposure to air pollution from cooking fuel occurs in the environment around households, not just indoors.
- Solid cooking fuel is sufficiently polluting to affect widespread ambient (outdoor) air pollution levels appreciably and, thus, to cause ill health far from the source.
- The term *indoor* implies that an effective chimney or other venting would solve the problem entirely, when the basic problem is dirty combustion near people.
- In some parts of the world, incompletely combusted solid fuels are commonly used for space heating or lighting, as well as for cooking, thus confusing the attribution of risk and assessment of appropriate interventions unless the household uses being considered are specified.
- The term *indoor air pollution* overlaps with much research on indoor pollution from other sources (for example, from household furnishings and consumer products). For example, the CRA now separately includes risks from indoor exposure to radon.

This chapter focuses on the evidence base for health effects, because the causality between HAP and ill health is only now being firmly established. This is unlike contaminated water and poor sanitation, for which the connection to ill health was established in the nineteenth century. The causality and scale of the effects from HAP have only recently received recognition in health effects studies, which are now appearing in large numbers. This recent appearance perhaps explains why there are relatively few evaluations of large-scale interventions to date. Initiatives presently under way provide excellent opportunities to do so.

## SOURCES AND EMISSIONS

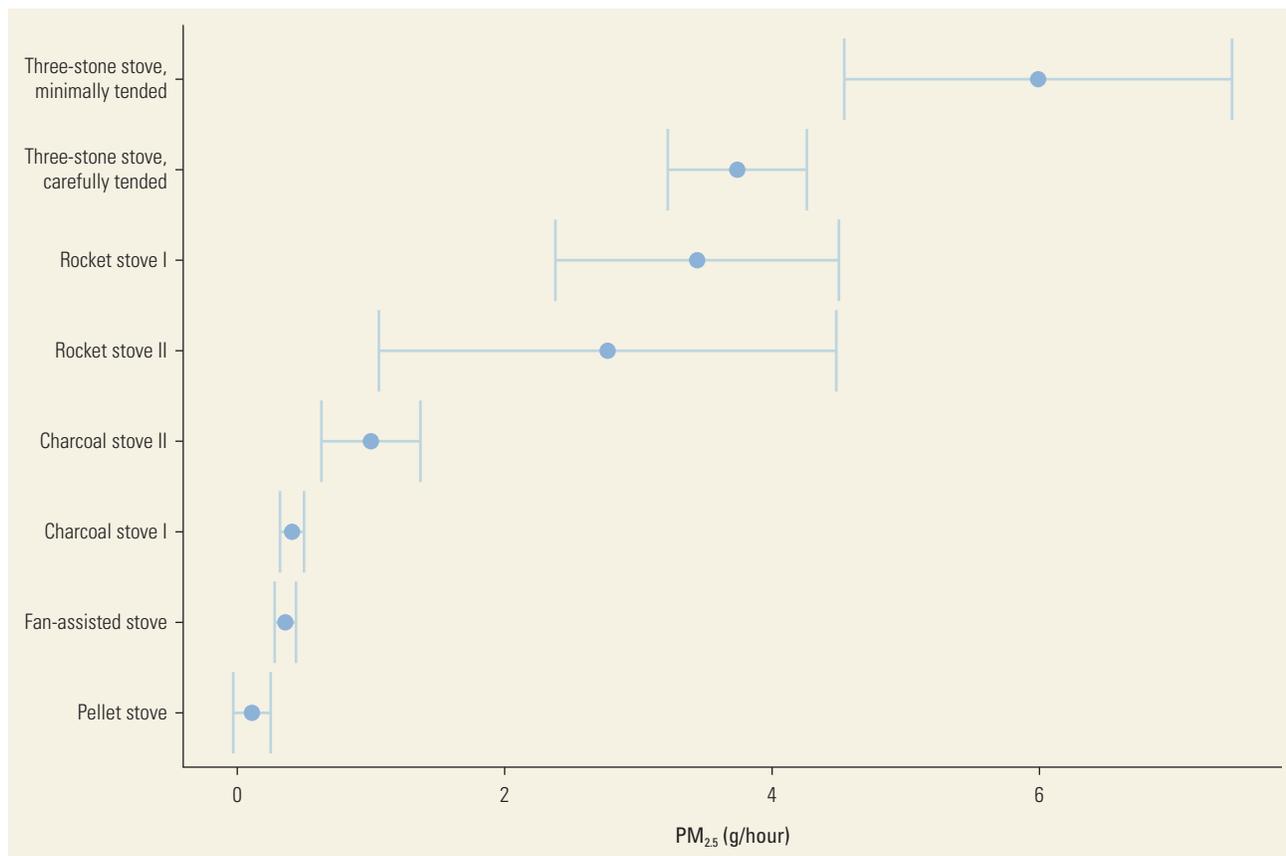
Burning biomass completely in simple stoves is extremely difficult. Even though wood and most other types of biomass have few intrinsic contaminants (unlike coal), substantial fractions of the fuel carbon are not completely oxidized to carbon dioxide; instead, they are converted to a vast range of products of incomplete combustion (PIC). As much as 20 percent of the fuel carbon can be diverted into these products, although

more typical levels are 5–10 percent (Naeher and others 2007; Zhang and others 2000). By mass, the largest PIC component by far is carbon monoxide (CO), but thousands of other compounds have been measured in wood smoke, including nontrivial levels of dozens of well-known toxic chemical species, such as polycyclic aromatic hydrocarbons, benzene, formaldehyde, and even dioxin (Naeher and others 2007; Northcross and others 2012). In broad terms, the mixture is similar to the PIC produced from combustion of the most well-studied form of biomass: tobacco. Indeed, despite their differences, exposures to these two forms of smoke have many similar health effects.

As with tobacco smoke, the risks of different diseases resulting from exposure to HAP probably depend in different ways on the landscape of components. However, insufficient evidence exists to pin specific diseases on particular components of wood smoke. Indeed, given the many decades, more controlled conditions, and extensive resources devoted to studying tobacco smoke, still without being able to distinguish differences in detail, the issue of wood smoke mixtures is unlikely to be resolved in the foreseeable future. Therefore, like tobacco researchers, HAP researchers rely on two main indicator pollutants for measurement and risk assessment:  $PM_{2.5}$  (particulate matter with an aerodynamic diameter of less than 2.5 micrometers, called tar in tobacco smoke, the most well-studied component of air pollution correlated with adverse health risk) and CO. Unlike tobacco smoke, smoke from other types of biomass does not contain measurable nicotine. However, smoke resulting from biomass combustion contains a vast range of other components for which  $PM_{2.5}$  and CO are just indicators.<sup>2</sup>

In terms of  $PM_{2.5}$ , a typical wood fuel cookstove used by a single family for cooking household meals produces substantial pollution by any comparison. In laboratory simulations, the wood-fired three-stone stove (the most common stove used worldwide) produces some 6 grams or about 400 cigarettes worth of  $PM_{2.5}$  per hour (figure 7.1) (Jetter and others 2002; Jetter and others 2012). To put it into another context, one year of cooking on a three-stone stove emits particles equivalent to the emissions of 20 diesel trucks driving 50,000 kilometers a year and meeting Euro 6 standards, the standard planned for India in 2020. Considering that 170 million households in India use biomass cooking fuel today, the emissions are roughly equivalent to those of a mixed fleet of 400 million diesel trucks meeting 2010 standards (Euro 4), far more emissions than are expected in India. In practice, field-based measurements of both biomass stoves and diesel trucks likely record even more pollution than is indicated by these numbers (which are based on laboratory evidence).

**Figure 7.1** Emissions of PM<sub>2.5</sub> in Grams per Hour for Common Types of Stoves Showing Range of Reported Lab Measurements



Source: Adapted from the comprehensive stove performance database in Jetter and others 2012; adapted with permission from Jetter, Zhao, Smith, Khan, Yelverton, Decarlo, and Hays. "Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards." *Environmental Science and Technology* 46 (19): 10827–34. Copyright 2012. American Chemical Society.  
 Note: Data displayed are for dry fuel during hot start tests. g/hour = grams per hour; PM<sub>2.5</sub> = particulate matter with an aerodynamic diameter of less than 2.5 micrometers.

Toxicology studies of biomass particulates find some effects on cells and animals to be stronger than those produced by typical ambient air pollution or diesel particles and some to be weaker, with no clear trends (Naeher and others 2007; Zelikoff and others 2002). Growing epidemiological evidence suggests that diesel particles are likely to be more hazardous than average ambient particles or wood smoke particles, but all major assessments to date—for example, those of the WHO (2014b) and the U.S. Environmental Protection Agency—conclude that, at present, insufficient evidence exists to treat PM<sub>2.5</sub> of different origins differently with regard to control priorities.<sup>3</sup>

## CONCENTRATIONS

In indoor kitchens, PM<sub>2.5</sub> concentrations can become extremely high when cooking with solid fuels (Balakrishnan and others 2011), often reaching many

thousands of micrograms per cubic meter of PM<sub>2.5</sub> and causing much eye and throat irritation, particularly in persons unaccustomed to such levels (Diaz and others 2007).<sup>4</sup> The iconic blackening of walls and ceilings in village kitchens using such fuels is testimony to these levels.

Although few systematic survey data are available, including those from the Demographic and Health Survey, the World Health Organization (WHO 2014a), and the World Bank, worldwide only a small fraction of households using biomass for cooking have working chimneys. The exception is China, where most rural kitchens have chimney stoves, partly because of the success of the largest stove dissemination program in history, the National Improved Stove Program (NISP), which operated from the early 1980s to the mid-1990s (Edwards and others 2007; Smith and others 2014; Zhang and Smith 2007). Unlike India's National Program on Improved Chulhas, which operated during roughly the same period (Venkataraman and others 2010), all stoves disseminated under the NISP had chimneys.

Good chimney stoves lower peak levels of indoor pollution, but they lower long-term average exposures only by a factor of two, at most, because even good chimney stoves do not intrinsically reduce emissions; they merely move emissions out of the immediate room and into the surrounding household and village environment, where people also spend time. They further require regular maintenance and proper use to function correctly.

Of course, a chimney does nothing to decrease outdoor air pollution, which is now understood to be heavily influenced by household sources in some countries. In India, for example, an estimated 25–50 percent of population-weighted outdoor  $PM_{2.5}$  exposure results from emissions of primary particles from cookstoves (Chafe and others 2014; Guttikunda 2016; Lelieveld and others 2015). Outdoor  $PM_{2.5}$  levels also include secondary particles from gaseous precursors, such as sulfur oxide, nitrogen oxide, and semivolatile compounds; though not yet well quantified, these compounds also are emitted from households, as well as from vehicles, power plants, and other more traditional sources of outdoor air pollution. If one considers primary particle emissions alone, household cooking is responsible for an estimated 370,000 premature deaths globally from its contribution to general outdoor air pollution on top of the mortality produced from exposure in the household environment itself (Chafe and others 2014).

## EXPOSURE

Household cooking is nearly universally done by women, who often also are responsible for the care of young children. These two groups generally have the highest HAP exposure, because they tend to be near the stove during combustion. As cooking fire smoke permeates the household environment, men and older children also may have significant exposure. However, studies have not characterized these exposures nearly as well. The importance of focusing on exposure (as opposed to just indoor air pollution) is illustrated by the fairly high exposure of women cooking on open fires outdoors.

Because monitors placed in a kitchen or living area cannot capture actual human exposure from a single location (particularly for different family members), the growing practice in epidemiological and other health-oriented research on HAP is to measure personal exposures. This is generally done by asking participants to wear portable monitoring devices for a day or in 24-hour increments for several days (Baumgartner and others 2011; Ni and others 2016; Smith and others 2010; Van Vliet and others 2013), an expensive and somewhat

intrusive exercise given the available technology. Early studies commonly measured exposure only during periods of cooking, when exposure rates often are highest. These levels are hard to interpret, because relative risks and exposure-response relationships typically exist for annual average exposures, not for exposures only during cooking, heating, or other activities.

Evaluation of exposure is made more difficult by high within- and between-household variability (McCracken and others 2009; Pillarisetti and others 2016). Several parameters can influence both concentration and exposure, including (1) the cooking location, with some households cooking indoors, while others cook outdoors, in an open area, or in a separate cooking house; (2) cooking habits and type of cuisine, with some cuisines requiring constant attention during cooking, while others can be left unattended; and (3) the use of multiple fires for cooking. Each of these parameters influences exposure and complicates exposure assessment.

In the past, researchers generally assumed that as long as measurement days were typical of patterns throughout the year, then one or a few days of measurements would provide reasonable estimates of long-term averages. In recent years, however, because of high intrinsic intrahousehold variability, researchers have demonstrated that reliable estimates of long-term averages can be achieved only with multiple days of measurement (McCracken and others 2009; Pillarisetti and others 2016). Although studies have detected effects even with one or a few measurements, investigators risk not being able to do so even when effects exist because of the high degree of exposure misclassification that occurs.

Additional methods of measuring exposure involve measurements of “surrogate” pollutants, such as CO, or reconstruction of exposures using area measurements in multiple microenvironments and time-activity diaries. Exposure surrogates may be chosen because they facilitate more rapid or less difficult measurement of a specific pollutant. However, the decision to measure a surrogate in place of the pollutant of interest requires local, field-based validation of the surrogate as a proxy for the pollutant. Exposure reconstruction using micro-environmental models relies on area measurements of pollutant concentrations in multiple environments in which people spend time (for instance, kitchens, the outdoors, and living quarters), as well as recall or sensor-based data on the time spent in each location. Individual exposures are then estimated by estimating time-weighted average pollutant concentrations (see Balakrishnan and others [2011] for a database of HAP studies using proxy measures and time-activity methods).

## BIOMARKERS AND OTHER SIGNS OF HAP EFFECT

Recent reviews (Smith and others 2014; Tolunay and Chockalingam 2012; WHO 2014b) discuss studies that have found biomarkers of HAP exposure (CO breath, carboxyhemoglobin, urinary metabolites, DNA [deoxyribo-nucleic acid] adducts) and biomarkers of HAP effect (eye opacity, lung function, blood pressure, electrocardiogram ST-segment). These findings are consistent with the disease endpoints documented for HAP and provide support for interpolating between ambient air pollution and smoking exposures for cardiovascular outcomes.

## HEALTH IMPACTS

The health impacts of air pollution exposures of various sorts, including from household fuels, are based on two general categories of evidence:

- Direct epidemiological studies of health impacts in populations exposed to differing categories of exposure
- Interpolation of risks taken from integrated exposure-response (IER) functions derived by combining the results of epidemiological studies of a wide range of air pollution exposures in different situations.

Relying heavily on recent major reviews, this section summarizes the results of both kinds of evidence as they relate to HAP and discusses their relative merits and remaining gaps and uncertainties. The focus is on outcomes ranked as Class I, indicating multiple high-quality epidemiological studies from households in low- and middle-income countries (LMICs), with consistent results and particle exposures at both higher and lower exposures, and using exposure-response data across several particle exposure settings. See Table 7.1, where Class I is defined.

### Direct Epidemiological Studies of HAP Exposures

Most health studies of HAP published to date have relied on simple binary indicators of exposure, such as whether a household's primary cooking fuel is clean versus dirty fuel. Although simplistic, these indicators are more stable over a year than a single measurement of personal exposure or area of concentration. Most of the evaluated studies are cross-sectional in design, which poses the risk of bias by unmeasured confounders (such as socioeconomic status, smoking, and fuel/stove stacking). Many dozens of studies done by different investigators have

found similar ranges of effects for each of various health outcomes in different populations, providing considerable confidence that a degree of effect likely is real. A brief description of each category of disease for which there is epidemiological evidence follows. For a detailed literature review, see Smith and others (2014).

### Acute Lower Respiratory Infection in Children

Acute lower respiratory infection (ALRI) is a leading killer of children younger than age five years (GBD Risk Factors Collaborators 2015). Smith and others (2014) identified 24 studies that met their inclusion criteria during a systematic review and meta-analysis. Very few of the studies directly measured exposure to HAP, and many used poor-quality proxies of exposure. Furthermore, the case definitions of pneumonia varied among studies. All studies save one randomized control trial (RCT) were observational. The pooled odds ratio (OR) from their study was 1.78 (1.45, 2.18).

Although several trials are near completion, results from just one RCT have been published to date: the RESPIRE study of child ALRI in Guatemala, which compared a wood-fired cookstove with a chimney to the traditional open wood-fired cookstove (Smith and others 2010; Smith and others 2011). Results (summarized in figure 7.2) show a significant effect for severe forms of ALRI, but only marginally significant effects for all cases of ALRI. Of relevance is that the pilot studies justifying the conclusion that this stove would be an effective intervention focused on indoor air quality in the kitchen and not on personal exposures. In the RCT, kitchen concentrations dropped 90 percent, similar to the pilot results, but the actual exposure experienced by women and young children dropped only 50 percent, which was below the power of the study. This is because babies and mothers do not spend all day in the kitchen, and the locations where people spend time during the rest of the day were not appreciably affected by the intervention. The wood-fired cookstove with a chimney moved most of the smoke out of the kitchen and into the surrounding environment, where it still affected people and their exposures. The most important result of the RCT was the exposure-response analysis, enabled by the development of a means to measure infant exposures directly and facilitated by a validated relationship between CO and PM<sub>2.5</sub>.

### Chronic Obstructive Pulmonary Disease

Chronic obstructive pulmonary disease (COPD), the fourth leading cause of death globally (GBD Risk Factors Collaborators 2015), is characterized by persistent airflow limitation associated with chronic inflammation of the airway and lungs in response to exposure to particles and gases (GOLD 2016). A previous

systematic review and meta-analysis evaluating the risk of adult COPD from exposure to HAP identified 24 studies from 12 countries as suitable for inclusion (Smith and others 2014). The majority were cross-sectional (17), 6 were case-control studies, and 1 was a retrospective cohort. All but two studies had positive risk ratios. Stratifying by gender indicated a stronger effect in women (OR, 2.30; 1.73, 2.06) than in men (OR, 1.90; 1.15, 3.13); a subanalysis of duration of exposure indicated a stronger summary effect when comparing the longest to the shortest duration of exposure. All studies used proxy measures of exposure. The pooled OR reported was 1.94 (1.62, 2.33).

### Lung Cancer

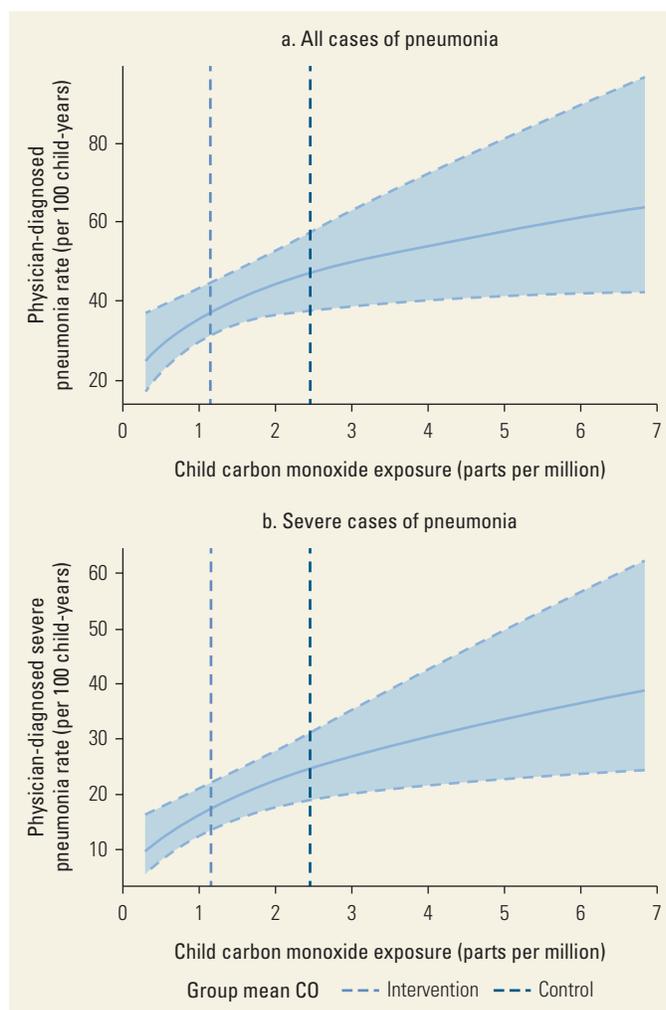
Lung cancer (LC) is the seventh leading cause of death globally (IHME 2016). While the use of coal for heating and cooking is recognized as a group I carcinogen by the International Agency for Research on Cancer, use of biomass for cooking is considered only a probable carcinogen because of weaker epidemiological evidence, even though several chemicals with group I status are found in wood smoke. Smith and others (2014) identified 14 studies, providing 13 individual estimates in a review of the relationship between biomass use for cooking and LC (Bruce and others 2015). Ten studies were focused in Asia, with the remaining four spread across Canada, Europe, and the United States. Exposure assessment relied on survey-based recall of the type of fuel used for cooking or heating, along with the duration and period of life for which biomass was used in a subset. The overall OR was 1.17 (1.01, 1.37) for biomass used for cooking or heating and 1.15 (0.97, 1.37) for cooking only. ORs were 1.21 (1.05, 1.39) and 1.95 (1.16, 3.27) for men and women, respectively, for studies with adequate adjustment and a reference category.

### Cataracts

Cataracts (the clouding of the lens of the eye, preventing the passage of light) are a leading cause of blindness globally and account for approximately 0.12 percent of all DALYs (GBD Risk Factors Collaborators 2015). Toxicological evidence from animal models and epidemiological evidence from smokers indicated a potential relationship between cooking with solid fuels and cataracts. Smith and others (2014) identified seven eligible studies providing eight estimates for review, all from India and Nepal. The pooled OR was 2.64 (1.74, 3.50); however, evidence for men was deemed insufficient for cataracts to be listed as a class I outcome. Therefore, only the estimate for women of 2.47 (1.61, 3.73) was deemed reliable. Table 7.1 summarizes the ORs for primary disease outcomes.

Although not RCTs, a set of retrospective studies of a “natural experiment” in China in which coal stoves with

**Figure 7.2** Relationships between Carbon Monoxide Exposure in Children and Pneumonia and Severe Pneumonia from the RESPIRE Trial in Guatemala



Source: Adapted from Smith and others 2011; reprinted from *The Lancet*, Vol. 378, Smith, McCracken, Weber, Hubbard, Jenny, Thompson, Balmes, Diaz, Arana, and Bruce, “Effect of Reduction in Household Air Pollution on Childhood Pneumonia in Guatemala (RESPIRE): A Randomised Controlled Trial.” 1717–26, 2011, with permission from Elsevier.

Note: CO = carbon monoxide. Shaded areas represent 95% confidence bounds. During the RESPIRE trial, CO was validated for this study population as a surrogate for particulate matter exposure, which is thought to be the best metric of hazard. The dashed lines represent the mean exposure levels.

chimneys were introduced rapidly in areas with no chimneys and in one county starting around 1980 also are an important part of the evidence base (Chapman and others 2005; Seow and others 2014; Shen and others 2009). As they relate to coal smoke, however, their direct relevance to the much more prevalent use of biomass fuel worldwide is not clear, although they do show significant reductions in LC as well as COPD and adult pneumonia. Unfortunately, too little exposure assessment was conducted to include these results in the development of IER functions.

**Table 7.1** Summary of Odds Ratio for Primary Outcomes Derived from the Systematic Review and Meta-Analysis Performed for the 2010 Comparative Risk Assessment of the Global Burden of Disease

Outcome	Group studied <sup>a</sup>	2010 systematic review and meta-analysis estimates	2004 CRA estimates
Acute lower respiratory infection	Children	1.78 (1.45, 2.18)	2.3 (1.9, 2.7)
Chronic obstructive pulmonary disease	Females	2.30 (1.73, 2.06)	3.2 (2.3, 4.8)
	Males	1.90 (1.15, 3.13)	1.8 (1.0, 3.2)
<i>Lung cancer</i>			
Coal	Females	1.98 (1.16, 3.36)	1.94 (1.09, 3.47)
	Males	1.31 (1.05, 1.76)	1.51 (0.97, 2.46)
Biomass	Females	1.95 (1.16, 3.27) <sup>b</sup>	—
	Males	1.21 (1.05, 1.39) <sup>b</sup>	—
Cataracts	Females	2.47 (1.63, 3.73)	—

Note: — = not available; CRA = comparative risk assessment; OR = odds ratio.  
a. Children younger than age five years; females and males ages 15 years and older.  
b. ORs from Bruce and others 2015.

### Interpolation of Risks Using Integrated-Exposure Response Functions

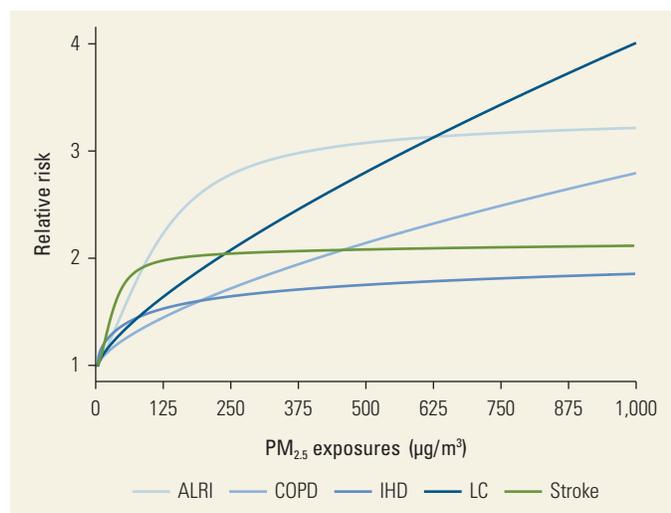
IER functions were created spanning the range of global exposures to PM<sub>2.5</sub> by separately modeling the relationship between exposure from four sources (ambient air pollution, secondhand smoke, HAP, and active tobacco smoking) and five health endpoints (COPD, stroke, heart disease, LC in adults, and ALRI in children younger than age five years) (Burnett and others 2014; Pope and

others 2009). The complete list of data points used to create the model is in Burnett and others (2014, supplementary material table S1).

In using a wide range of concentrations from a variety of sources, the IERs assume that risk associated with these disparate sources is only a function of exposure, not smoke type, enabling the creation of a continuous response function that spans many orders of magnitude and is bounded on the low end by ambient exposure to PM<sub>2.5</sub> and on the high end by active tobacco smoking (Burnett and others 2014; Pope and others 2009). The modeled relative risks are thus a function of PM<sub>2.5</sub> exposures in terms of mass concentration; all PM<sub>2.5</sub> particles are considered equally damaging to health. The resulting functions are highly nonlinear for all outcomes except LC (figure 7.3).

Use of the IERs enabled estimation of the risk associated with exposures at levels common in households that use solid fuel for which there are no or very few HAP studies, but that have intermediate exposures between passive and active smoking. Additionally, it enabled use of the same idealized counterfactual level of approximately 7 micrograms per cubic meter for calculating the burden of disease attributable to HAP and ambient air pollution. Finally, it enabled comparison of IER-modeled risk estimates with estimates backed by evidence based on epidemiological studies (Smith and others 2014). A brief description of the modeled risk estimates for cardiovascular disease (CVD) (including stroke and heart disease) follows, along with a comparison of IER-modeled and epidemiological-study-based estimates for ALRI.

**Figure 7.3** Integrated-Exposure Response Curves Relating Exposure to PM<sub>2.5</sub> to Health Endpoints Associated with Exposure to Air Pollution



Source: Adapted from Burnett and others 2014.

Note: PM<sub>2.5</sub> = particulate matter with an aerodynamic diameter of less than 2.5 micrometers; µg/m<sup>3</sup> = micrograms per cubic meter. Includes ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC) in adults and acute lower respiratory infection (ALRI) in children.

### Cardiovascular Disease

Although evidence exists linking exposure to HAP with biomarkers with known links to cardiovascular outcomes (including blood pressure and heart rate variability), few studies have specifically addressed CVD directly. The strong evidence of impacts at lower (ambient) and higher (active tobacco smoking) levels is good evidence for an effect at the intermediate levels of HAP exposure, however. Figure 7.4 indicates that, for both stroke and ischemic heart disease (IHD), risk flattens as exposure increases, although this effect is more pronounced for stroke.

### Acute Lower Respiratory Infection in Children

Unlike CVD outcomes, both exposure-response and many categorical analyses found that exposure to HAP was associated with child ALRI. The IER for ALRI was informed by studies of ambient air pollution, second-hand smoke, and HAP. Unlike other IERs, the one for ALRI contains directly measured risk and exposure data from RESPIRE, based on repeated measures of child personal exposure to CO, which were then converted to PM (McCracken and others 2013; Smith and others 2010).

Because children do not smoke, the upper bound of exposures in the IER for ALRI are from RESPIRE.

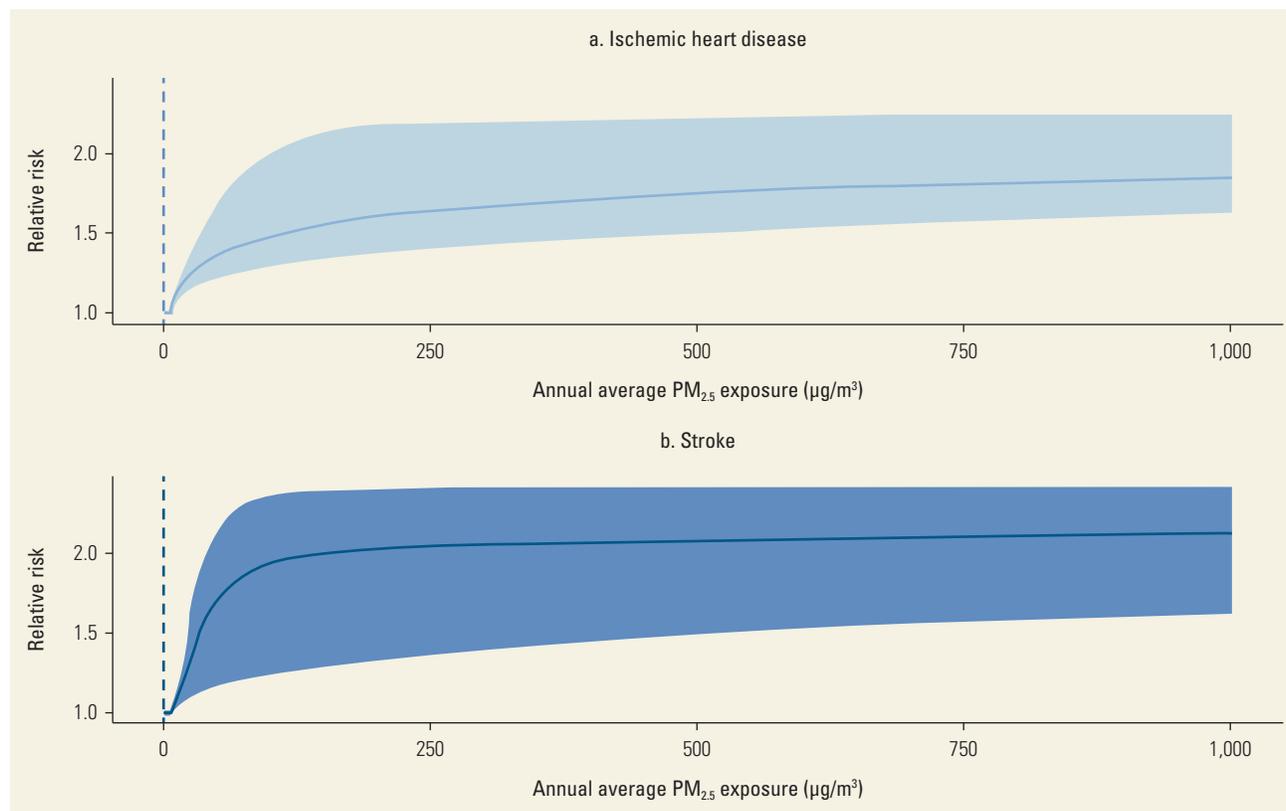
### Uncertainties and Emergent Issues

The health effects literature contains both uncertainties as well as new understandings with regard to exposure patterns that are influencing both research and intervention policies.

### Categories of Evidence: Exposure-Response

RCTs have substantial cachet in international health, and their results are beginning to inform the evidence base for HAP effects as well. However, RCTs are not as valuable or needed for HAP assessments as perhaps they are for other risk factors. Unlike the important risk factors in this volume that otherwise have many conceptual similarities—poor water, sanitation, and hygiene—HAP has a measurable exposure metric linked directly to health. Exposure units in, for example, micrograms per cubic meter annual levels, can thus be translated across populations and interventions. Indeed, this is the concept on which the IAQGs are based (WHO 2014b).

**Figure 7.4** Integrated-Exposure Response Curves for Cardiovascular Outcomes



Source: Adapted from Burnett and others 2014.

Note: PM<sub>2.5</sub> = particulate matter with an aerodynamic diameter of less than 2.5 micrometers; µg/m<sup>3</sup> = micrograms per cubic meter. Shaded areas are model-based uncertainty bounds. Large uncertainties in areas approximating household air pollution exposures (300–1,000 micrograms per cubic meter) indicate a lack of evidence in those exposure ranges.

HAP RCTs alone, however, are idiosyncratic to the local situation and intervention and cannot meet the full requirements of an RCT, particularly the requirement to have placebo controls. Most important, unlike exposure-response relationships, the results do not translate easily to any other population—that is, they do not relate directly to exposure. This is one reason that exposure assessment is so fundamental to environmental health. No RCTs have been done or likely will be done for ambient air pollution, for example, but the effects are known and the benefits of interventions for a place that has never had a health study can be estimated with reasonable confidence if exposures are known. This is because multiple large-scale exposure-response results are available across the world. RCTs are most valuable for establishing causality if it is still in doubt, but they are rather poor at informing policy for HAP. What matters is how clean the fuel has to be to make a difference and how much the clean cooking technology displaces old, polluting technologies; that is, how much does exposure have to be reduced to achieve a meaningful health benefit, which is best informed by exposure-response analysis (Peel and others 2015).

RCTs can greatly improve exposure-response results, however. Although randomizing exposure itself in real populations is essentially impossible, randomizing one important cause of variability lessens the burden of potential confounders, increasing confidence in the results. In addition, the intervention spreads out the exposures more than occurs naturally and thus increases the chance of seeing effects. Exposure-response results have also been improved by the introduction of new means to measure the sources of high intrahousehold variability—in particular, the recent wide-scale introduction of stove use monitors (Pillarisetti and others 2014; Ruiz-Mercado, Canuz, and Smith 2012; Ruiz-Mercado and others 2013). These and other technical advances promise to reduce exposure misclassification further and to enhance the ability to detect effects.

An additional advantage of framing HAP effects in terms of exposure is the ability to combine effects across other major sources of air pollution into IERs. The same effects are found in a monotonically increasing trend with estimated exposure, and this provides a new class of evidence that supports results in all the other categories of exposure (ambient air pollution, secondhand tobacco smoke, and active tobacco smoking), but particularly HAP. Indeed, compared to ambient air pollution and active tobacco smoking, many fewer studies are available for all adult outcomes, and almost none are available for two important CVD outcomes—IHD and stroke. Interpolation along the IER function that is fixed by active tobacco smoking and ambient air pollution at the two

ends of the exposure spectrum and bolstered by results for environmental tobacco smoke thus seems justifiable. It is not credible that exposures that produce CVD effects at both higher and lower levels would not also produce CVD effects at the levels found for HAP. Extrapolation beyond the available data is fraught with potential problems, but a major reason to do graphs is to be able to do interpolation. Direct HAP studies of CVD risk factors, such as blood pressure and heart rate variability, further support the existence of CVD effects, but they do not themselves allow an estimate of the total CVD effect.

Although they are a major advance, the IERs include assumptions and show relationships that still need investigation. Three issues bear mention here. First, although three of the types of pollution are composed almost entirely of combustion particles, and although ambient air pollution typically is composed mostly of combustion particles, different types of combustion, fuels, and mixtures of other pollutants are involved with each. Diesel exhaust is different from tobacco smoke, for example, although both can be measured using  $PM_{2.5}$ . Second, the typical exposure patterns reflecting exposure to these different sources (both daily and over a lifetime) are quite different, even if they can be reduced to a common metric of an annual average. Third, studies use a different measure of exposure for each category of pollution. Ambient air pollution studies use ambient concentrations measured in central locations, such as on the roof of a building in a major metropolitan area. Measured changes of this type are found to reflect changes in actual exposures but are poor representations of absolute exposures. People do not live on top of buildings (where these central site monitors are located), but they do live near small sources that may not affect widespread ambient levels but that do affect individual exposures. Few studies of secondhand tobacco smoke and HAP in adults have measured personal exposure, but some have tried to estimate levels based on fixed monitors or models. Studies of active tobacco smoking use inhaled smoke levels or nominal dose (as measured by smoking machines) to estimate “exposure” per cigarette.

### Other Endpoints

Smith and others (2014) carefully assessed the evidence base for each outcome (disease) associated with HAP. As shown in table 7.2, three classes were established. Diseases in Class I were considered to have sufficient evidence to be included as formal outcomes in the CRA. Class II diseases had a sufficient number of epidemiological studies to conduct meta-analyses, which are found in Smith and others (2014), but the evidence was not considered consistent or otherwise convincing enough to be put forward as part of the formal burden

**Table 7.2 Evidence Classes**

Evidence class	Description	Criteria
Class IA	Quantified primary outcome, based on binary exposures in systematic reviews and meta-analyses	Multiple epidemiological studies of good quality in households in lower-income countries sufficient for meta-analyses; consistent results as well as significant and positive summary estimate; supporting epidemiological studies of other particle exposures, both at higher and lower exposures
Class IB	Quantified primary outcome, continued	Exposure-response data available from several particle exposure settings, allowing development of integrated exposure-response function covering (1) child ALRI, where studies have found that active tobacco smoking does not contribute, but studies have been conducted in the other three exposure settings (outdoor air pollution, secondhand smoke, and household air pollution); (2) CVD outcomes, where studies for outdoor air pollution, secondhand smoke, and active tobacco smoking exist, allowing estimates to be interpolated for HAP
Class II	Quantified secondary outcome	Multiple epidemiological studies in households in lower-income countries sufficient for meta-analyses; unconvincing adjustment for confounding or exposure assessment; inconsistent results or nonsignificant positive result; supporting epidemiological studies from other particle exposures
Class III	Nonquantified secondary outcome	Still thought likely to be causal; weak or insufficient epidemiological studies from households in lower-income countries for meta-analyses; some support from other particle exposure categories

Source: Adapted from Smith and others 2014.

Note: ALRI = acute lower respiratory infection; CVD = cardiovascular disease; HAP = household air pollution. All evidence classes have plausible physiological mechanisms based on toxicology.

of HAP. These included adult ALRI; tuberculosis; nasopharyngeal carcinomas; tumors of the larynx, oropharynx, and hypopharynx; cervical cancer; and still-birth. Diseases in Class III were considered to have suggestive, but insufficient, evidence for quantification. These diseases included asthma and preterm birth.

The CRA Expert Group found sufficient evidence to consider low birth weight as an outcome for HAP exposures, but the GBD project itself removed low birth weight as an outcome, focusing instead on preterm births. However, too few HAP studies had separated preterm birth from low birth weight for these outcomes to be included in the official CRA. (See Smith and others [2014] for a discussion of the available literature.)

A class of impacts not considered in the CRA consists of neurocognitive outcomes in children, although evidence of such effects has been growing, as has evidence of such effects with other pollution exposures (Smith and others 2014). This is an active area of HAP research.

All of the outcomes in Classes I, II, and III are firmly associated with tobacco smoking, a much more thoroughly studied source of exposure to biomass smoke. Thus, the fact that the same diseases that are associated with tobacco smoking have also been found to be associated with HAP exposures (albeit at lower risk levels) is not surprising. Indeed, the IERs provide quantitative evidence of the consistent relationship between HAP

and active smoking risks for the five main diseases associated with each.

## INTERVENTIONS

This section examines the traditional paradigms that have dominated thinking over the past half century regarding how to accelerate the transition to clean cooking technologies in poor populations. It then discusses more recent paradigms.<sup>5</sup>

### Old Paradigms

#### Let Development Take Care of It

Because the rich use clean fuels and the poor use dirty fuels (Bonjour and others 2013), one may be tempted simply to let development take care of the problem. Unfortunately, this has not worked. About the same number of people (almost 3 billion) are using dirty fuels today as 25 years ago, in spite of the considerable development that has occurred in that time. More people are using clean fuels (gas and electricity), but the absolute burden of exposure has not changed appreciably worldwide. However, the trends in the absolute numbers using solid fuels varies by region: going up in Sub-Saharan Africa, going down in East Asia (China), and remaining level in South Asia (Bonjour and others 2013).

### Make the Available Clean

Since the large national stove programs were initiated in China and India in the early 1980s, perhaps a dozen other national efforts and hundreds (if not thousands) of community and nongovernmental organization (NGO) programs, small and large, have been initiated worldwide to promote better stoves using the same local fuels (mainly different forms of biomass).<sup>6</sup> Although initially focused on fuel efficiency, many of these programs are also attempting to lower smoke levels—that is, to make the available fuels clean through better combustion, chimneys, and others approaches. As described in WHO (2014b), this improvement has been extremely elusive, and finding interventions that have reduced health-related exposures substantially and sustainably for a large population is difficult. Nevertheless, much progress has been made, and investments are needed to continue upgrading the engineering, business, and social marketing required to reach this goal.

One promising development is the parallel work of the International Standards Organization and the WHO to develop standards and guidelines for promoting only the cleanest devices in the future. Quantitative guidelines

were made possible only by development of the IERs. Now a base of epidemiological evidence exists to support standards that quantify what emissions level is clean enough for good health (WHO 2014b). As mentioned, emissions reductions alone do not guarantee exposure reductions; rather, interventions must be adopted, maintained, and used regularly to achieve meaningful exposure reductions to protect health.

As part of the evidence review for the IAQGs (WHO 2014b), systematic reviews and meta-analyses were performed of the international literature on interventions (Dherani and others 2014). The methods and results are summarized in box 7.2. This review found that solid-fuel stoves with chimneys delivered the largest reductions in PM and CO concentrations, with CO levels often reaching WHO air quality guidelines. However, none achieved PM levels close to the guidelines. One key issue is the degree of heterogeneity between studies. For this reason, referring to the circumstances and results of individual stove and fuel evaluations is important for appropriate interpretation of these results. Continued efforts are needed to standardize the methods used for field evaluation.

### Box 7.2

#### Assessment of Improved Biomass Stove Interventions

To assess the potential health benefits that can be expected following the introduction of improved solid-fuel stoves, one must examine the reductions in HAP and personal exposure—and the absolute levels achieved—when these interventions are in everyday use. Although the results of laboratory emissions tests provide valuable information on the potential reductions in exposure, field evaluations provide a more realistic assessment of exposure when such interventions are adopted and used at scale. The key questions for the review were as follows:

- Are improved solid-fuel stoves in everyday use (compared to traditional solid-fuel stoves) effective for reducing average concentrations of, or exposure to, PM and CO in households in LMICs?
- By what amount (in absolute and relative terms) do the interventions reduce PM and CO, and how

do postintervention (in-use) levels compare with the WHO air quality guidelines?

**Methods.** A search was conducted of electronic databases and specialist websites. Eligible studies included randomized trials, quasi-experimental and before-and-after studies, as well as observational designs and reported daily mean (24- or 48-hour) small PM (most reported PM<sub>2.5</sub>, but two studies reported PM<sub>4</sub>) or CO, with standard deviations or 95 percent confidence intervals. Interventions were categorized as standard combustion solid-fuel stoves with and without chimneys, advanced combustion solid-fuel stoves, clean fuels (LPG, biogas, ethanol, electricity, solar), and mixed interventions. Studies were selected, extracted, and assessed using standardized procedures and forms. Baseline and postintervention values, differences, and percentage changes from baseline were tabulated for each study, and weighted average values were calculated

*box continues next page*

### Box 7.2 (continued)

for all studies contributing data to each category of stove or fuel intervention. Subject to sufficient studies, meta-analysis of absolute changes in the two pollutants for each category of solid-fuel stove and clean fuel was carried out using the generic inverse-variance method, and publication bias was assessed. Narrative summaries were provided for intervention categories with very few eligible studies.

**Results.** A total of 38 eligible studies, some with multiple estimates, was included: 27 studies that provided data on kitchen PM, 3 on personal PM, 26 on kitchen CO, and 5 on personal CO. Only one or two studies were available for each intervention (LPG, electricity, charcoal, mixed). Baseline levels of PM and CO were variable, but all exceeded the annual WHO guideline for PM<sub>2.5</sub> of 35 micrograms per cubic meter by a factor of 10–100 times, and CO varied from just below to 6 times greater than the 24-hour air quality guideline for CO of 7 milligrams per cubic meter (5.68 parts per million). After intervention, reductions in pollutants were reported for almost all individual studies; when grouped, large reductions in the range of 38–82 percent were found for kitchen PM and CO levels, with the largest reductions for solid-fuel stoves with chimneys and the lowest for solid-fuel stoves without chimneys. Studies reporting impacts on personal exposure were identified only for solid-fuel chimney stoves, but reductions in the range of 47–76 percent were found.

Despite these large percentage reductions, post-intervention levels of PM remained well above the WHO guidelines for group-weighted means at around 400 micrograms per cubic meter, although the few personal exposure studies had a considerably lower weighted mean of 70 micrograms per cubic meter. In contrast, many interventions reduced CO to levels below the WHO 24-hour air quality guideline, with weighted mean values of 4–5 parts per million for stoves with chimneys, but almost 7 parts per million for stoves without chimneys. Postintervention personal exposure in the set of chimney-stove studies was 1.7 parts per million. Sensitivity analyses (conducted where the number of estimates was sufficient), including by study design, analytic approach (that is, comparing controls with only stoves in actual use or with all stoves allocated), and duration of use, did not find strong effects. Among the larger sets of studies, clear evidence of publication bias existed. Evidence from studies of improved wood stoves in high-income rural settings found, as expected, PM<sub>2.5</sub> levels much lower than those of improved wood stoves in developing countries (ranging from 13 to 54 micrograms per cubic meter) and an association between improved solid-fuel stoves (all of which were vented with some having advanced emissions control technology) and emissions reductions in a majority of households.

*Source:* Based directly on Dherani and others (2014), which also contains lengthy tables describing the published studies to date.

### New Paradigms

Based on the new evidence that exposures must be brought to low levels to achieve major health benefits, and the poor performance of “improved” biomass stoves to date, new paradigms are emerging in the field, although they have been operating on their own in the modern energy sector all along.

#### Make the Clean Available

How one achieves clean cooking is no mystery. Gas and electricity are used by 60 percent of humanity, and these fuels cook every cuisine without problem (although with taste changes compared to traditional methods for some foods). Unlike typical biomass stoves, gas and electric stoves cannot be made dirty at the household level (even with nonoptimal use), and they do not require any special attention or training. They also are aspirational, with

attractive modern cooking appliances being an important sales advantage in most settings. They are not available to the populations using biomass, however, not only because of their cost but also because of unreliable or unavailable public and private infrastructure. Any kind of gas burns cleanly, including biogas and natural gas, but LPG is usually the first to reach rural areas. Rather than simply waiting passively for people to shift to clean fuels, there is clear need to find ways to promote these fuels to poor households in a more systematic and aggressive manner.

Several large and innovative initiatives for promoting LPG began in India in 2015. Although initiated by the Ministry of Petroleum and Natural Gas in collaboration with the three national oil companies that market LPG, these initiatives were driven by a desire to reduce the health impacts of solid fuel use for cooking. As of March 2016, more than US\$1 billion had been committed

to expand LPG to 50 million low-income households in three years, reaching perhaps 300 million people (Ministry of Finance 2016). This ambitious initiative has several innovative features designed to target LPG subsidies much more precisely to poor households and away from middle- and upper-class and commercial consumers. These features involve the use of modern digital technology, including bank accounts, cell phones, and biometric identification cards. In addition, widespread integrated use of formal and social media to promote the effort exists, including text messages, billboards, television and radio, Internet, and athletic events.

The most well-known of the programs is the Give It Up scheme, through which middle- and upper-income consumers are asked to give up their LPG subsidy to households below the poverty line. Households who give up their subsidy are listed on a Scroll of Honor on the website and can see which family benefited from their contribution.<sup>7</sup> Some 30,000 households a day were doing so at the height of the program. As a result, the government was able to focus new resources on providing the up-front costs (stove and cylinder) to enable poor households to take on LPG, and oil companies were incentivized to expand fuel access substantially and to improve the reliability of supply. In addition, new modes of distributing LPG are being tried, including promotion and sales by women's groups. Importantly, the government has specified that all new LPG connections since early 2016 are to be in the name of the woman of the house wherever possible, a significant movement toward improving gender engagement. Because shifting the subsidy from one income group to another does not entail additional government expenditure, the cost-effectiveness of this effort depends only on the additional expenditures for up-front costs.<sup>8</sup>

Another approach is to promote clean fuels that have not been widely adopted in high-income countries and thus have no established operational viability. The most prominent of these is biogas; although attractively clean and made renewably from animal dung, biogas is limited in scope by climate, capital cost, and the need for at least two large animals in each household. Second is ethanol, which burns cleanly and can be made renewably from several crops, including sugarcane and sorghum. Unknown, however, is whether large-scale production would trigger demand in other sectors (for example, as a petroleum enhancer or beverage) that would dominate its availability and price as a fuel.

The review described in box 7.2 also examined available studies for clean fuel interventions. It found none for electric cooking and too few for LPG or biogas to make an assessment. However, it found several for ethanol that indicated a reduction in overall exposure, but not enough to reach WHO air quality guidelines (WHO 2014b).

One major reason that clean fuel interventions do not show greater reductions is the remaining use of polluting fuels either in the same household or nearby, which has not been monitored well in past studies. More and better-designed studies are needed for all kinds of clean fuel interventions, as well as new intervention modes that promote usage and initial adoption.

### **Embrace Leap-Frog Technologies**

Highly advanced, electronic devices are now available for cooking. Depending on the task, electric induction stoves are 50 percent more efficient and 50 percent faster (as well as safer and longer-lived) than old-style electric stoves. They are so different as to provide a new entry into the cookstove landscape. Sales are booming in Asia, and prices are dropping, reaching as low as US\$10 each in some markets. Most of the sales growth is occurring among customers now using gas, as cooking with induction stoves is sometimes cheaper than cooking with subsidized LPG. How far might induction stoves be pushed into rural areas when electricity supply becomes more reliable? Ecuador, for example, is replacing every stove in the country with an induction stove, and other countries with excess hydropower are considering taking such an approach. Could induction stoves be linked to local power made from renewable energy sources? This is an exciting prospect. Even when linked to coal power, induction stoves create substantially less pollution exposure and only minor increases in greenhouse gases (Smith 2014).

Synthetic liquid or gaseous fuels such as the bio-ethanol discussed earlier and synthetic LPG made from coal, which are clean at the household, also show promise but require additional study and evaluation of system requirements. Synthetic natural gas from coal is also being promoted in China and Mongolia but requires extensive pipeline infrastructure that makes it cost-prohibitive in most rural areas.

### **Target the Community Level**

Ongoing research and modeling show that, in many circumstances, changing one household in a village to clean fuels reduces exposure less than one might expect (Desai 2016; Smith 1987). This is because of a coverage or community effect—that is, even if you cook using LPG (or do not cook at all), you are affected by all of your neighbors who still cook on biomass stoves. Although varying by geography and meteorology, most of humanity lives in fairly close quarters, whether in cities or villages, and the community effect is common. For this reason, the most effective interventions are likely to occur at the community level. This has two other advantages: providing fuels, stoves, and service at the community scale usually is more efficient, lowering costs and increasing reliability,

and it is possible to unleash social pressure to change social norms—for example, creating a smokeless village designation to encourage neighbors to work together (put pressure on each other) to avoid producing smoke in their village. Indeed, these other benefits of community interventions are likely to be the most critical.

The LPG initiatives in India are promoting “smokeless villages” designed to develop LPG connections by village rather than by household. As of mid-2016, at least 4,000 smokeless villages (defined as 100 percent of households being connected) had been certified, with thousands more being planned.

As with much of the rapid changes in the “make the clean available” agenda, however, evaluation of smokeless villages and other modes of LPG expansion have not yet been subjected to high-quality evaluation, something clearly needed.

### Recent Innovations

New ways of thinking have emerged from the literature but have not yet been well integrated into interventions. Among these is growing recognition of the following.

#### Impact on Outdoor Pollution

A major reason that the field has moved away from the term *indoor* to *household* air pollution is the realization that, although pollution may start in the kitchen, it moves throughout the household, then into the community environment outside, where it adds to general ambient air pollution. The degree to which this matters depends on the situation; in India, for instance, as noted, an estimated 25–50 percent of primary ambient PM<sub>2.5</sub> comes from household cooking. Estimates are similar for China, although household use of solid fuel for heat is also seasonally important in much of the country (Liu and others 2016). Cleaning up household fuels clearly is a necessary step in dealing with outdoor pollution. Because outdoor air pollution has become a serious policy and public concern in many countries that still have significant household use of solid fuel, this connection provides a potential impetus for control programs and a framework for evaluation.

In late 2015, India’s Ministry of Health and Family Welfare released a white paper proposing a pioneering approach to air pollution (Ministry of Health and Family Welfare 2015). It was the first ministry of health in the world to consider air pollution in the context of other health priorities, with the idea of using the health sector’s unique assets to address it (air pollution generally has been handled by environmental agencies, which have a different agenda). India’s Ministry of Health and Family Welfare is also the first government agency in the

world to address household and ambient air pollution together by proposing a program to manage exposure, not concentrations, in particular locations (Sagar and others 2016). If implemented, this approach would focus more on pollution sources that are in close proximity to people (stoves and vehicles) and less on sources that are far from people (power plants and industries).

#### Household Air Pollution as a Health Problem

Part of the poor progress of previous attempts to reduce HAP may be due to their origins in the technology sector rather than the health sector and the heavy emphasis the technology sector places on simple local technologies and community groups or NGOs. In contrast, the health sector taps the very best advanced scientific, technological, and manufacturing techniques to develop effective vaccines, antibiotics, and surgery tools; then, after those techniques have been proved worthwhile in highly structured field trials, the health sector makes them available through prepurchase, royalty agreements, and mass manufacture to reduce the cost. It then uses NGOs and other community groups to bring the vaccines to vulnerable populations. Unlike the technology sector, the health sector treats everyone the same; it does not promote less effective antibiotics in rural areas because the people there are poor. Unequal treatment may be satisfactory when addressing fuel efficiency or meeting local labor and materials goals, which are important issues in their own right. The technology sector is less effective at achieving health goals, and its priorities raise disquieting ethical issues.

One reason that often is given for continued cooking on open fires is the taste of the food, but the health sector would ask, is taste worth nearly one million lives a year in India? The health sector does not stop its programs because people like the taste of tobacco or dislike wearing seatbelts or dislike using condoms. It recognizes the importance of personal preferences, however, and brings social pressure to bear in an effort to change those tastes. The health sector has already recognized the importance of various kinds of “herd” effects—for example, with sanitation and mosquito protection. First is effectiveness on a large scale, which has often been promoted in biomass stove programs. Next is the household business model, which may come later. Finally, the health sector is not afraid of subsidies but provides the evidence needed to prove that expenditures on the health of the poor are cost-effective social investments.

#### Common Challenges with Interventions

Although many relatively small-scale, low-cost interventions (such as the provision of better-burning biomass stoves) will continue, efforts to reach households at a

large scale using existing infrastructure in the petroleum and power sectors are growing, but in ways that better focus on health. India is leading the way, but other countries have programs or are planning them.<sup>9</sup>

With LPG or electricity, little HAP concern exists, because the appliances that use these cooking fuels can stand up to variations in user behavior, and the appliances' performance is well known, with billions in use over many decades. Even with the most advanced biomass stoves, however, good field performance is difficult to maintain, even when the stoves are used regularly. Two common difficulties remain, however, with both approaches: cost and continued use of traditional polluting cookstoves.

### Cost and Subsidy

An advanced biomass stove with a chimney and blower (characteristics likely to be required for good health) is not cheap by low-income-country standards. The cost of the stove alone is likely to be more than US\$100 and probably closer to US\$200, as seen in successful chimney stove programs in China and Mexico, for example. The costs of dissemination, maintenance, repair, and replacement add to this. In addition, to date, only biomass pellet stoves are reliably clean enough to come close to the IAQGs for emissions. Pellet stoves require users to forfeit the greatest advantage of today's biomass fuel, which is that it can be gathered at no direct financial cost. Financing the stoves and pelletizing infrastructure in ways that are sustainable for poor populations is a major challenge.

The same is true of providing LPG or electric power reliably and sustainably. Electrification offers a way to spread costs, given its many social and other benefits in addition to health. Up-front costs are substantially lower than for nearly equivalently clean biomass stoves, but electricity entails recurring costs and access issues.

The very poor are unlikely to be able to afford any truly clean cooking technology. If significant progress is to occur, some form of public support likely will be needed for some years. This is not unusual: public support is accepted for many health-protective interventions for the poor, including vaccines, antenatal care, and basic antibiotics. The term *subsidy* often is applied to public support for fuels, usually in a pejorative way. However, subsidies for nuclear power, the coal industry, and the solar industry are not intended to target health protection for the poor, unlike support for HAP-reducing technologies such as LPG and advanced biomass stoves. Thus, if public expenditures can be shown to be as well targeted and effective as other expenditures on health-protective interventions, they may be considered social investments rather than subsidies, with a substantially different political and developmental connotation.

### Compliance and Stacking

The second issue is *stacking*, which refers to the common observation that people often do not switch to a new technology immediately, even if it is better in many ways and eventually takes over. In the case of cooking, people often continue to use their traditional fuel stove even if they also use an advanced biomass stove or LPG. It may take years, in the case of LPG, before they switch entirely, a process that has a generational component—young women often do not continue what their mothers find hard to give up.

As a result, with a new clean fuel alternative in the home, all of the HAP exposure is due to continued use of the traditional stove, and the exposure can be substantial. This is a familiar situation in health interventions: simply providing access and affordability does not guarantee high compliance (for example, in using bed nets, condoms, latrines, tuberculosis drugs, low-salt foods, and nicotine substitutes). In most of these examples, as with HAP, a high rate of compliance is needed to reduce risk adequately (seemingly more than 90 percent in the case of latrines and bed nets, for example). Accordingly, as with every other health intervention that must be accompanied by behavioral change, incentives must be found and implemented to enhance compliance (Fernald, Gertler, and Neufeld 2009; Fernald, Hou, and Gertler 2008; Lim and others 2010) or, in stove parlance, to reduce the degree and duration of stacking.

Additional research is needed to find ways to promote reduced use of the old and increased adoption and use of the new. Recent systematic reviews of adoption and barriers to adoption of clean stoves (Puzzolo and others 2016) and of clean fuels and electricity (Rehfuess and others 2014) highlight this need. They also challenge dissemination approaches that only market the new, as might be adequate for economic sustainability. Imagining a business model for eliminating the old polluting stove, however, is difficult, a phenomenon that is not uncommon with household or individual health interventions.

Approaches for triggering community pressure (for example, conditional cash transfers and cell phone messaging) have been applied successfully in other situations and could successfully reduce HAP as well. In addition, some innovations show promise even if they have never been applied—for example, linking the use of HAP-reducing cooking technology, such as LPG, to national life insurance and rural employment schemes, as is being considered in India.

## CONCLUSIONS

The health impacts of HAP have been suspected for decades, beginning with a few isolated studies more than a half century ago (Padmavati and Pathak 1959); only

recently, sufficient evidence has been marshaled to make a systematic case for HAP's ill health effects across a range of diseases. This evidence is substantiated best in the two detailed reviews used so extensively in this chapter (Smith and others 2014; WHO 2014b). The conceptual and empirical connection between active and passive tobacco smoking and ambient air pollution provided by the IERs gives rise to a completely different and in itself compelling set of arguments for HAP's ill health effects, in addition to the growing base of epidemiological and toxicological evidence. Although the evidence is insufficient to pin down a precise risk for all diseases now attributed to HAP exposures or to establish a firm base for diseases that have some, but insufficient, evidence to include on the list, it seems likely that HAP will remain on the list of severe health risks affecting the world's poorest populations.

HAP will continue to constitute a major risk factor as long as billions of households worldwide use solid fuels. However, simply believing it to be a major risk is not sufficient to bring solutions. As noted in the introduction, fecal matter in the household environment was confirmed as a major risk factor for ill health in the late 1800s, but it still kills millions today in spite of considerable efforts to reduce this health burden. Both of these risk factors share uncomfortable similarities: they are significant, operate in poor populations, and require behavioral and engineering innovations and interventions. They both also seem to be refractory to cheap solutions. How can we be sure then that HAP (which only passed the threshold of acceptability in 2010 or so, and even still perhaps not as completely as fecal contamination) is not still killing millions a century from now?

Although basic epidemiological, toxicological, and exposure research continues, HAP's threshold of acceptability has been passed, and serious research is needed to determine what works on a large scale. Regarding poor sanitation, the failure to move in this direction is perhaps partly responsible for the long delay between recognition of the problem and its solution. Considering the question of scale—at the household level and the institutional level, in terms of the agencies and organizations that can operate on a large scale and perform careful monitoring and evaluation of natural interventions—is another way to frame this effort. This mode of thinking is particularly salient for those efforts now under way with clean fuels (such as LPG and electricity) in India, Bhutan, Paraguay, Ecuador, and elsewhere. As HAP has the advantage of a measurable exposure metric, much of this research can proceed more quickly and with less cost because exposure outcomes can be used as endpoints. If, in parallel, exposure-response is emphasized in the

health research, the two together can help to find ways to provide the world with clean household environments effectively and steadily.

Providing empirical evidence of the cost-effectiveness of alternative interventions is difficult, although there is movement in this direction (Newcombe and others 2016; Pillarisetti, Mehta, and Smith 2016). The long-term solution is clear: clean fuels (although they will not be available for the very poorest populations for some years). Until then, however, the evident popularity of such fuels could be a model for how improved biomass stoves are designed and disseminated.<sup>10</sup> Only now are we beginning to understand how to bring clean fuels to the poor (but not the poorest) populations much faster than development alone has brought, while simultaneously accelerating the movement away from traditional practices during the transition.

## NOTES

World Bank Income Classifications as of July 2014 are as follows, based on estimates of gross national income (GNI) per capita for 2013:

- Low-income countries (LICs) = US\$1,045 or less
- Middle-income countries (MICs) are subdivided:
  - a) lower-middle-income = US\$1,046 to US\$4,125
  - b) upper-middle-income (UMICs) = US\$4,126 to US\$12,745
- High-income countries (HICs) = US\$12,746 or more.

1. This chapter focuses almost entirely on wood fuel, which dominates world use and research. Agricultural residues, including animal dung, are far less consistent and less well characterized. Coal pollution is even more difficult to summarize because of wide variations in the quality of coal around the world, including the content of toxic species, such as sulfur, arsenic, lead, mercury, ash, and others. For a good discussion, see WHO (2014b).
2. Few studies have been conducted on the impact of chronic CO exposures on health, and CO in wood smoke rarely causes acutely toxic exposures because of the warning of extreme irritation from other wood smoke components. Therefore, this chapter does not explore CO exposure further, though we note observed links between exposure to CO during pregnancy and adverse outcomes. However, low-volatile solid fuels, particularly charcoal and some coals, can produce acutely hazardous CO exposures. Indeed, despite the dearth of systematic assessments, thousands of deaths likely occur globally each year (some even in high-income countries) as a result of CO exposure (for example, from charcoal grills used indoors).
3. Kerosene, another middle distillate like diesel, is still used for household cooking in some countries and is widely used for lighting in hundreds of millions of households

without adequate electricity. Growing evidence suggests that, by mass, PM<sub>2.5</sub> from kerosene combustion is more toxic than PM<sub>2.5</sub> from biomass combustion. To date, however, the WHO has been unable to do more than recommend that kerosene be discouraged as a household fuel. (See WHO 2014b.)

4. The WHO guideline for annual average PM<sub>2.5</sub> concentrations is 10 micrograms per cubic meter (WHO 2014b).
5. This section draws on Smith and Sagar (2014) and Smith (2015), as well as on WHO (2014b).
6. See <http://cleancookstoves.org/>.
7. See <http://mylpg.in/>.
8. In 2016, the Give It Up program was folded into an even larger program to promote a total of 50 million LPG connections in India in three years.
9. See <http://www.cooking-for-life.org/>.
10. IAQGs has a section on the needs of the very poor in the transition to clean fuels for all.

## REFERENCES

- Balakrishnan, K., G. Thangavel, S. Ghosh, S. Sambandam, K. Mukhopadhyay, and others. 2011. *The Global Household Air Pollution Measurement Database*. Geneva: World Health Organization. [http://www.who.int/indoorair/health\\_impacts/databases/en/](http://www.who.int/indoorair/health_impacts/databases/en/).
- Baumgartner, J., J. J. Schauer, M. Ezzati, L. Lu, C. Cheng, and others. 2011. "Patterns and Predictors of Personal Exposure to Indoor Air Pollution from Biomass Combustion among Women and Children in Rural China." *Indoor Air* 21 (6): 479–88.
- Bonjour, S., H. Adair-Rohani, J. Wolf, N. G. Bruce, S. Mehta, and others. 2013. "Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980–2010." *Environmental Health Perspectives* 121 (7): 784–90.
- Bruce, N., M. Dherani, R. Liu, H. D. Hosgood III, A. Sapkota, and others. 2015. "Does Household Use of Biomass Fuel Cause Lung Cancer? A Systematic Review and Evaluation of the Evidence for the GBD 2010 Study." *Thorax* 70 (5): 433–41.
- Burnett, R. T., C. A. Pope III, M. Ezzati, C. Olives, S. S. Lim, and others. 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environmental Health Perspectives* 122 (4): 397–403.
- Chafe, Z. A., M. Brauer, Z. Klimont, R. Van Dingenen, S. Mehta, and others. 2014. "Household Cooking with Solid Fuels Contributes to Ambient PM<sub>2.5</sub> Air Pollution and the Burden of Disease." *Environmental Health Perspectives* 122 (12): 1314–20.
- Chapman, R. S., X. He, A. E. Blair, and Q. Lan. 2005. "Improvement in Household Stoves and Risk of Chronic Obstructive Pulmonary Disease in Xuanwei, China: Retrospective Cohort Study." *BMJ* 331 (7524): 1050.
- Desai, M. A. 2016. "Model of Postulated Coverage Effect from Clean Cooking Interventions." In *Multiscale Drivers of Global Environmental Health*. Doctoral dissertation submitted to the Environmental Health Sciences Graduate Group, University of California, Berkeley, 88–147.
- Dherani, M., K. Jagoe, L. P. Naeher, and C. Noonan. 2014. "Review 6: Impacts of Interventions on Household Air Pollution Concentrations and Personal Exposure." In *WHO Indoor Air Quality Guidelines: Household Fuel Combustion*, edited by E. Rehfuess, D. Pope, and N. Bruce. Geneva: World Health Organization.
- Diaz, E., T. Smith-Sivertsen, D. Pope, R. T. Lie, A. Diaz, and others. 2007. "Eye Discomfort, Headache, and Back Pain among Mayan Guatemalan Women Taking Part in a Randomised Stove Intervention Trial." *Journal of Epidemiology and Community Health* 61 (1): 74–79.
- Edwards, R. D., Y. Liu, G. He, Z. Yin, J. Sinton, and others. 2007. "Household CO and PM Measured as Part of a Review of China's National Improved Stove Program." *Indoor Air* 17 (3): 189–203.
- Fernald, L. C., P. J. Gertler, and L. M. Neufeld. 2009. "10-Year Effect of Oportunidades, Mexico's Conditional Cash Transfer Programme, on Child Growth, Cognition, Language, and Behaviour: A Longitudinal Follow-Up Study." *The Lancet* 374 (9706): 1997–2005.
- Fernald, L. C., X. Hou, and P. J. Gertler. 2008. "Oportunidades Program Participation and Body Mass Index, Blood Pressure, and Self-Reported Health in Mexican Adults." *Preventing Chronic Disease* 5 (3): A81.
- GBD Risk Factors Collaborators. 2015. "Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental, Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990–2013: A Systematic Analysis for the Global Burden of Disease Study 2013." *The Lancet* 386 (10010): 2287–323.
- GOLD (Global Initiative for Chronic Obstructive Lung Disease). 2016. *Global Strategy for the Diagnosis, Management and Prevention of COPD*. GOLD. <http://www.goldcopd.org/>.
- Guttikunda, S. 2016. *Urban Emissions*. <http://www.urbanemissions.info/>.
- IHME (Institute for Health Metrics and Evaluation). 2016. "GBD Compare Data Visualization." IHME, University of Washington, Seattle. <http://vizhub.healthdata.org/gbd-comparevizhub.healthdata.org/gbd-compare>.
- Jetter, J. J., Z. Guo, J. A. McBrien, and M. R. Flynn. 2002. "Characterization of Emissions from Burning Incense." *Science of the Total Environment* 295 (1–3): 51–67.
- Jetter, J., Y. Zhao, K. R. Smith, B. Khan, T. Yelverton, and others. 2012. "Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards." *Environmental Science and Technology* 46 (19): 10827–34.
- Johnson, M., T. Bond, N. Lam, C. Weyant, Y. Chen, and others. 2011. "In-Home Assessment of Greenhouse Gas and Aerosol Emissions from Biomass Cookstoves in Developing Countries." In *Greenhouse Gas Strategies in a Changing Climate Conference 2011*, 530–42. Pittsburgh: Air and Waste Management Association.

- Johnson, M., R. Edwards, C. A. Frenk, and O. Masera. 2008. "In-Field Greenhouse Gas Emissions from Cookstoves in Rural Mexican Households." *Atmospheric Environment* 42 (6): 1206–22.
- Lelieveld, J., J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer. 2015. "The Contribution of Outdoor Air Pollution Sources to Premature Mortality on a Global Scale." *Nature* 525 (7569): 367–71.
- Lim, S. S., L. Dandona, J. A. Hoisington, S. L. James, M. C. Hogan, and others. 2010. "India's Janani Suraksha Yojana, A Conditional Cash Transfer Programme to Increase Births in Health Facilities: An Impact Evaluation." *The Lancet* 375 (9730): 2009–23.
- Lim, S. S., T. Vos, A. D. Flaxman, G. Danaei, K. Shibuya, and others. 2012. "A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010." *The Lancet* 380 (9859): 2224–60.
- Liu, J., D. L. Mauzerall, Q. Chen, Q. Zhang, Y. Song, and others. 2016. "Air Pollutant Emissions from Chinese Households: A Major and Underappreciated Ambient Pollution Source." *Proceedings of the National Academy of Sciences* 113 (28): 7756–61. <http://www.pnas.org/cgi/doi/10.1073/pnas.1604537113>.
- Lozano, R., M. Naghavi, K. Foreman, S. Lim, K. Shibuya, and others. 2012. "Global and Regional Mortality from 235 Causes of Death for 20 Age Groups in 1990 and 2010: A Systematic Analysis for the Global Burden of Disease Study 2010." *The Lancet* 380 (9859): 2095–128.
- McCracken, J. P., J. Schwartz, N. Bruce, M. Mittleman, L. M. Ryan, and others. 2009. "Combining Individual- and Group-Level Exposure Information: Child Carbon Monoxide in the Guatemala Woodstove Randomized Control Trial." *Epidemiology* 20 (1): 127–36.
- McCracken, J. P., J. Schwartz, A. Diaz, N. Bruce, and K. R. Smith. 2013. "Longitudinal Relationship between Personal CO and Personal PM<sub>2.5</sub> among Women Cooking with Woodfired Cookstoves in Guatemala." *PLoS One* 8 (2): e55670.
- Ministry of Finance. 2016. *Union Budget 2016–2017*. New Delhi: Ministry of Finance, Government of India.
- Ministry of Health and Family Welfare. 2015. *Report of the Steering Committee on Air Pollution and Health-Related Issues*. New Delhi: Ministry of Health and Family Welfare, Government of India.
- Naeher, L. P., M. Brauer, M. Lipsett, J. T. Zelikoff, C. D. Simpson, and others. 2007. "Woodsmoke Health Effects: A Review." *Inhalation Toxicology* 19 (1): 67–106.
- Newcombe, K., T. Ramanathan, N. Ramanathan, and E. Ross. 2016. "Innovations in Payments for Health Benefits of Improved Cookstoves." In *Broken Pumps and Promises: Incentivizing Impact in Environmental Health*, edited by E. A. Thomas, 171–79. Cham, Switzerland: Springer International Publishing AG.
- Ni, K., E. Carter, J. J. Schauer, M. Ezzati, Y. Zhang, and others. 2016. "Seasonal Variation in Outdoor, Indoor, and Personal Air Pollution Exposures of Women Using Wood Stoves in the Tibetan Plateau: Baseline Assessment for an Energy Intervention Study." *Environment International* 94: 449–57. doi:10.1016/j.envint.2016.05.029.
- Northcross, A. L., S. K. Hammond, E. Canuz, and K. R. Smith. 2012. "Dioxin Inhalation Doses from Wood Combustion in Indoor Cookfires." *Atmospheric Environment* 49 (March): 415–18.
- Padmavati, S., and S. N. Pathak. 1959. "Chronic Cor Pulmonale in Delhi: A Study of 127 Cases." *Circulation* 20 (3): 343–52.
- Peel, J. L., J. Baumgartner, G. A. Wellenius, M. L. Clark, and K. R. Smith. 2015. "Are Randomized Trials Necessary to Advance Epidemiologic Research on Household Air Pollution?" *Current Epidemiology Reports* 2 (4): 263–70.
- Pillarisetti, A., L. W. H. Alnes, J. P. McCracken, E. Canuz, and K. R. Smith. 2016. "Long-Term PM<sub>2.5</sub> in Kitchens Cooking with Wood: Implications for Measurement Strategies." *Environmental Science and Technology* 48: 14525–533.
- Pillarisetti, A., S. Mehta, and K. R. Smith. 2016. "HAPIT, the Household Air Pollution Intervention Tool, to Evaluate the Health Benefits and Cost-Effectiveness of Clean Cooking Interventions." In *Broken Pumps and Promises: Incentivizing Impact in Environmental Health*, edited by E. A. Thomas, 147–70. Cham, Switzerland: Springer International Publishing AG.
- Pillarisetti, A., M. Vaswani, D. Jack, K. Balakrishnan, M. N. Bates, and others. 2014. "Patterns of Stove Usage after Introduction of an Advanced Cookstove: The Long-Term Application of Household Sensors." *Environmental Science and Technology* 48 (24): 14525–33.
- Pope, C. A. III, R. T. Burnett, D. Krewski, M. Jerrett, Y. Shi, and others. 2009. "Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke: Shape of the Exposure-Response Relationship." *Circulation* 120 (11): 941–48.
- Puzzolo, E., D. Pope, D. Stanistreet, E. Rehfuess, and N. G. Bruce. 2016. "Clean Fuels for Resource-Poor Settings: A Systematic Review of Barriers and Enablers to Adoption and Sustained Use." *Environmental Research* 146 (April): 218–34.
- Rehfuess, E. A., E. Puzzolo, D. Stanistreet, D. Pope, and N. G. Bruce. 2014. "Enablers and Barriers to Large-Scale Uptake of Improved Solid Fuel Stoves: A Systematic Review." *Environmental Health Perspectives* 122 (2): 120–30.
- Ruiz-Mercado, I., E. Canuz, and K. R. Smith. 2012. "Temperature Dataloggers as Stove Use Monitors (SUMs): Field Methods and Signal Analysis." *Biomass and Bioenergy* 47 (December): 459–68.
- Ruiz-Mercado, I., E. Canuz, J. L. Walker, and K. R. Smith. 2013. "Quantitative Metrics of Stove Adoption Using Stove Use Monitors (SUMs)." *Biomass and Bioenergy* 57 (October): 136–48.
- Sagar, A. D., K. Balakrishnan, S. Guttikunda, A. Roychowdhury, and K. R. Smith. 2016. "India Leads the Way: A Health-Centered Strategy for Air Pollution." *Environmental Health Perspectives* 124 (7): A116–17.
- Salomon, J. 2014. "Disability Adjusted Life Years." In *Encyclopedia of Health Economics*, edited by A. J. Cuyler, 200–03. San Diego, CA: Elsevier.

- Seow, W. J., W. Hu, R. Vermeulen, H. D. Hosgood III, G. S. Downward, and others. 2014. "Household Air Pollution and Lung Cancer in China: A Review of Studies in Xuanwei." *Chinese Journal of Cancer* 33 (10): 471–75.
- Shen, M., R. S. Chapman, R. Vermeulen, L. Tian, T. Zheng, and others. 2009. "Coal Use, Stove Improvement, and Adult Pneumonia Mortality in Xuanwei, China: A Retrospective Cohort Study." *Environmental Health Perspectives* 117 (2): 261–66.
- Smil, V. 1994. *Energy and World History*. Boulder, CO: Westview Press.
- Smith, K. R. 1987. *Biofuels, Air Pollution, and Health: A Global Review*. New York: Plenum Publishing.
- . 2014. "In Praise of Power." *Science* 345 (6197): 603.
- . 2015. "Changing Paradigms in Clean Cooking." *EcoHealth* 12 (1): 196–99.
- Smith, K. R., N. Bruce, K. Balakrishnan, H. Adair-Rohani, J. Balmes, and others. 2014. "Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution." *Annual Review of Public Health* 35: 185–206.
- Smith, K. R., J. P. McCracken, L. Thompson, R. Edwards, K. N. Shields, and others. 2010. "Personal Child and Mother Carbon Monoxide Exposures and Kitchen Levels: Methods and Results from a Randomized Trial of Woodfired Chimney Cookstoves in Guatemala (RESPIRE)." *Journal of Exposure Science and Environmental Epidemiology* 20 (5): 406–16.
- Smith, K. R., J. P. McCracken, M. W. Weber, A. Hubbard, A. Jenny, and others. 2011. "Effect of Reduction in Household Air Pollution on Childhood Pneumonia in Guatemala (RESPIRE): A Randomised Controlled Trial." *The Lancet* 378 (9804): 1717–26.
- Smith, K. R., and A. Sagar. 2014. "Making the Clean Available: Escaping India's Chulha Trap." *Energy Policy* 75 (December): 410–14.
- Tolunay, H. E., and A. Chockalingam. 2012. "Indoor and Outdoor Air Pollution and Cardiovascular Health." *Global Heart* 7 (2): 87–196.
- Van Vliet, E. D. S., K. Asante, D. W. Jack, P. L. Kinney, R. M. Whyatt, and others. 2013. "Personal Exposures to Fine Particulate Matter and Black Carbon in Households Cooking with Biomass Fuels in Rural Ghana." *Environmental Research* 127 (November): 40–48.
- Venkataraman, C., A. D. Sagar, G. Habib, N. Lam, and K. R. Smith. 2010. "The Indian National Initiative for Advanced Biomass Cookstoves: The Benefits of Clean Combustion." *Energy for Sustainable Development* 14 (2): 63–72.
- WHO (World Health Organization). 1993. *Biomarkers and Risk Assessment: Concepts and Principles, Environmental Health Criteria*. Geneva: WHO, International Programme on Chemical Safety.
- . 2014a. Global Health Observatory (database): Population Using Solid Fuels, by Country. WHO, Geneva. <http://apps.who.int/gho/data/node.main.135?lang=en>.
- . 2014b. *WHO Indoor Air Quality Guidelines: Household Fuel Combustion*. Geneva: WHO
- Wrangham, R. W. 2009. *Catching Fire: How Cooking Made Us Human*. New York: Basic Books.
- Zelikoff, J. T., L. C. Chen, M. D. Cohen, and R. B. Schlesinger. 2002. "The Toxicology of Inhaled Woodsmoke." *Journal of Toxicology and Environmental Health, Part B: Critical Reviews* 5 (3): 269–82.
- Zhang, J. J., and K. R. Smith. 2007. "Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions." *Environmental Health Perspectives* 115 (6): 848–55.
- Zhang J. J., K. R. Smith, Y. Ma, F. Jiang, W. Qi, and others. 2000. "Greenhouse Gases and Other Airborne Pollutants from Household Stoves in China: A Database for Emission Factors." *Atmospheric Environment* 34 (26): 4537–49.