Chapter 18

INDOOR AIR POLLUTION FROM HOUSEHOLD USE OF SOLID FUELS

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SUMMARY

This chapter summarizes the methodology used to assess the burden of disease caused by indoor air pollution from household use of solid fuels. Most research into and control of indoor air pollution worldwide has focused on sources of particular concern in developed countries, such as environmental tobacco smoke (ETS), volatile organic compounds from furnishings and radon from soil. Although these pollutants have impacts on health, little is known about their global distribution. Thus, we focus solely on indoor smoke from household use of solid fuels, the most widespread traditional source of indoor air pollution on a global scale.

In order to be consistent with the epidemiological literature, binary classifications of household use of solid fuels (biomass and coal) were used as a practical surrogate for actual exposure to indoor air pollution. Specifically, household solid fuel use was estimated at the national level using binary classifications of exposure to household fuel use, i.e. solid fuel and non-solid fuel (gas, kerosene, electricity). We estimated exposure to smoke from solid fuel by combining a number of national surveys of household fuel use into a regression model that predicts use according to independent, development-related variables, such as income and urbanization. Although this method was necessary owing to the current paucity of quantitative data on exposure, we acknowledge that it overlooks the large variability of exposure within households using solid fuels. As pollution emissions from the use of solid fuel may not always indicate high exposures, we have adjusted exposure estimates by a second term, the ventilation factor, which is based on qualitative measures of ventilation.

Estimates of relative risk obtained from epidemiological studies were combined in meta-analyses for three disease end-points for which there is strong evidence of an association with use of solid fuels: acute lower respiratory infections (ALRI) in children aged <5 years, chronic

obstructive pulmonary disease (COPD) and lung cancer (estimates for lung cancer are only for use of coal).

More than 1.6 million deaths and over 38.5 million disability-adjusted life years (DALYs) were attributable to indoor smoke from solid fuels in 2000. Cooking with solid fuels is thus responsible for a significant proportion, about 3%, of the global burden of disease. Although trends are highly uncertain, attributable risks are likely to be greater than avoidable risks.

Several potentially important health outcomes, including tuberculosis, cardiovascular disease, and adverse pregnancy outcomes, were not included, owing to insufficient epidemiological evidence. In addition, there was insufficient evidence to assess the associated health effects for children aged 5–14 years. The burden of disease caused by use of solid fuel is thus likely to be underestimated.

1. INTRODUCTION

The use of solid fuels for cooking and heating is likely to be the largest source of indoor air pollution on a global scale. Nearly half the world continues to cook with solid fuels such as dung, wood, agricultural residues and coal. When used in simple cooking stoves, these fuels emit substantial amounts of toxic pollutants. These pollutants, called solid-fuel "smoke" in this chapter, include respirable particles, carbon monoxide, oxides of nitrogen and sulfur, benzene, formaldehyde, 1,3-butadiene, and polyaromatic compounds, such as benzo(α)pyrene (Smith 1987). In households with limited ventilation (as is common in many developing countries), exposures experienced by household members, particularly women and young children who spend a large proportion of their time indoors, have been measured to be many times higher than World Health Organization (WHO) guidelines and national standards (Bruce et al. 2000; Smith 1987).

Most research into and control of indoor air pollution worldwide has focused on sources of particular concern in developed countries, such as ETS, volatile organic compounds from furnishings and radon from soil (Table 18.1) (Spengler et al. 2001). Although these pollutants have impacts upon health, little is known about their global distribution.

In an initial attempt to estimate the burden of disease and death caused by indoor sources of air pollution, this chapter focuses solely on the burning of solid fuels. Studies of the health effects of exposure to emissions from the two major sources of energy used for cooking in developed countries, gas and electricity, have been inconsistent, although small but statistically significant increased risks of childhood respiratory disease and other effects associated with use of gas have emerged from meta-analyses (Basu and Samet 1999). This is in contrast to the growing quantity of literature reporting reasonably consistent and strong relationships for a number of health end-points in households burning solid

Table 18.1 Major toxic pollutants of indoor air

Pollutant	*Major indoor sources*
Fine particles	Fuel/tobacco combustion, cleaning, fumes from food being cooked, e.g. from cooking oil
Carbon monoxide	Fuel/tobacco combustion
Polycyclic aromatic hydrocarbons	Fuel/tobacco combustion, fumes from food being cooked, e.g. from cooking oil
Nitrogen oxides	Fuel combustion
Sulfur oxides	Coal combustion
Arsenic and fluorine	Coal combustion
Volatile and semi-volatile organic compounds	Fuel/tobacco combustion, consumer products, furnishings, construction materials, fumes from food being cooked, e.g. from cooking oil
Aldehydes	Furnishing, construction materials, cooking
Pesticides	Consumer products, dust from outside
Asbestos	Remodelling/demolition of construction materials
Lead[a]	Remodelling/demolition of painted surfaces
Biological pollutants	Moist areas, ventilation systems, furnishings
Free radicals and other short-lived, highly reactive compounds	Indoor chemistry
Radon	Soil under building, construction materials

[a] Lead-containing dust from deteriorating paint is an important indoor pollutant for occupants of many households, but the most critical exposure pathways are not usually through air. See chapter 19.

Source: Zhang and Smith (2003).

fuels (biomass or coal), particularly those with poorly-vented stoves and homes, which are common throughout developing countries. In many circumstances, it is difficult to distinguish use of solid fuels for cooking from use for heating the home. There may also be effects associated with the use of kerosene, a common cooking fuel in many parts of the world, for which emissions and exposures are intermediate between those for solid and for gaseous fuels (Smith 1987), but on which few studies of health effects seem to have been conducted.

2. ESTIMATING RISK FACTOR LEVELS

2.1 EXPOSURE VARIABLES

One way to determine the health effects of indoor smoke from solid fuels would be to apply the well-established exposure–response relationships from epidemiological studies of outdoor, or ambient, concentrations of the same pollutants (see chapter 17) to the household exposures, called here the "pollutant-based approach" (Smith and Mehta 2003).

There are a number of potential problems with such an approach, however, including:

- *Differences in pollutant mixtures:* Although particles are often used as an indicator pollutant, the composition of particles (size, chemical composition, etc.) as well as that of other pollutants varies from source to source, and also changes with dispersion (Rossi et al. 1999).
- *Differences in exposure patterns:* The daily pattern of indoor air pollution sources varies from that of ambient sources, with large peaks corresponding to cooking and heating schedules (Naeher et al. 2000b).
- *Differences in exposure levels*: Concentrations of particulates from the indoor combustion of biomass have been measured at levels that are 10–50 times greater than in urban areas of developed countries, where the main epidemiology of pollutants has been performed. Extrapolating exposure–response relationships by such a large factor is problematic, particularly as there are indications that the relationship becomes more shallow at higher exposures (Bruce et al. 2000).
- *Relevance of health outcomes addressed:* Most studies of outdoor air pollution have attempted to associate short-term changes in exposure with acute health outcomes. This does not address the long-term impact on chronic health outcomes, nor does it necessarily focus on the health outcomes that are responsible for the bulk of the burden of disease. In particular, ALRI, mostly in the form of pneumonia, are likely to be responsible for the largest burden of disease caused by exposure to indoor air pollution.
- Data on concentrations of particulate matter (PM) in indoor air[1] are sparse. In addition, most measurements have been made for concentrations of total particulates, which are less reliable indicators of risk than smaller particles (PM_{10} or $PM_{2.5}$).

An alternative approach, consistent with that used in most epidemiological studies in developing countries, is to divide the population into categories of people that are exposed or not exposed to smoke from solid fuel, on the basis of fuel use and ventilation. Although necessary here, owing to the current lack of exposure data, this method overlooks the large variability of exposure within each of these groups (Naeher et al. 2000a). Furthermore, the method based on use of fuel is affected by the first of the shortcomings listed above, as the same broad category of fuels may produce different mixtures of pollutants in different settings. We also recognize that exposures from cooking and heating can differ considerably because of different conversion technologies. It was not possible to distinguish between the two end-uses in most cases, however.

To account for differences in other factors (e.g. housing) that would affect levels of pollution (Mehta and Smith 2002), we included a second component in the exposure variable, which we refer to as the "ventilation factor". The final exposure variable in the population was defined as:

$$\begin{gathered}\textit{Household-equivalent solid-fuel exposed population} = \\ (\textit{Population using solid fuel}) \times (\textit{Ventilation factor})\end{gathered}$$

We compiled a database of household use of solid fuel, from which the prevalence of household use of solid fuel was estimated for each subregion.[2] Using known values from this database, a statistical model was developed to predict national use of solid fuel for countries without data. Ventilation factors were assigned on the basis of qualitative evidence, to account for differences in types of cooking and heating appliances and housing.

2.2 Theoretical-minimum-risk exposure distribution

The theoretical minimum for this risk factor is clearly no use of solid fuels for the production of household energy; this has already been achieved in many populations. In reality, of course, there would still be exposure to pollution from liquid and gaseous fuels, which might be further reduced through a switch to use of electricity or of very well-ventilated cooking conditions.

2.3 A database of household use of solid fuel

A database of households using solid fuel, expressed as a percentage of all households, was compiled for 52 countries in 10 subregions, in order to estimate global household use of solid fuel (see Table 18.2). Although the data were acquired from studies conducted at different times in the past decade, fuel-use patterns are unlikely to have changed drastically within this time frame (International Energy Agency 2002; World Resources Institute 2000). Out of necessity, the data were gathered from various sources using different and, at times, non-validated methodology. We thus had to make many assumptions in order to facilitate subregional comparison and data manipulation associated with solid fuel use. No households were reported to be using solid fuels for cooking in AMR-A, EUR-A, EUR-C and WPR-A, presumably because countries in these subregions have already shifted to cleaner fuels.

In many countries where large proportions of the population cook with solid fuels, data on household energy are widely, although not

Table 18.2 Estimates of data for the database of households using solid fuels

Subregion	*Country*	*Households using solid fuel (%)*	*Type of data source*	*Year*	*Reference*
AFR-D	Algeria	4	National energy statistics	1999	World Resources Institute (2003)
	Angola	100	National energy statistics	1999	International Energy Agency (1999)
	Burkina Faso	97	Household survey	1994/1995	World Bank (2000)
	Chad	95	Household survey	1991	World Bank (1998)
	Gambia	98	Household survey	1992	World Bank (2000)
	Ghana	95	Household survey	1997	World Bank (2000)
	Guinea	99	Household survey	1994/1995	World Bank (2000)
	Guinea-Bissau	95	Household survey	1992	World Bank (2000)
	Madagascar	99	Household survey	1993/1994	World Bank (2000)
	Mali	100	Household survey	1994	World Bank (2000)
	Mauritania	69	Household survey	1995	World Bank (2000)
	Niger	98	Household survey	1995	World Bank (2000)
	Nigeria	67	Household survey and census data	1992	World Bank (2000)
	Senegal	79	Household survey	1994/1995	World Bank (2000)
	Sierra Leone	92	Household survey	1989/1990	World Bank (2000)
AFR-E	Botswana	65	National census	1991	Government of Botswana (1991)
	Central African Republic	99	Household survey	1993	World Bank (2000)
	Congo	67	Household survey	1988	World Bank (1988)
	Côte d'Ivoire	93	Household survey	1995	World Bank (2000)
	Democratic Republic of the Congo	100	National energy statistics	1999	World Resources Institute (2003)
	Ethiopia and Eritrea	97	Household survey and census data	1994	Government of Ethiopia (1998)
	Kenya	85	Household survey	1994	World Bank (2000)
	South Africa	28	Household survey	1993	World Bank (2000)
	Swaziland	88	Household survey	1994	World Bank (2000)
	United Republic of Tanzania	96	Household survey	1993	World Bank (2000)
	Uganda	97	Household survey	1992/1993	World Bank (2000)
	Zambia	87	Household survey	1996	World Bank (2000)
	Zimbabwe	67	National census	1992	Government of Zimbabwe (1992)

AMR-A	—	—	—	—	—
AMR-B	Brazil	27	National census	1991	Government of Brazil (1991)
	Mexico	22	National census	1990	Government of Mexico (1990a)
AMR-D	Ecuador	28	National census	1990	Government of Ecuador (1990a)
EMR-B	Iran (Islamic Republic of)	2	National energy statistics	1999	World Resources Institute (2003)
	Lebanon	0	National energy statistics	1996/1997	World Resources Institute (2003)
	Libyan Arab Jamahiriya	3	National energy statistics	1996/1997	International Energy Agency (1999)
	Tunisia	29	National energy statistics	1999	World Resources Institute (2003)
EMR-D	Afghanistan	98	National energy statistics	1999	World Resources Institute (2003)
	Djibouti	6	Household survey	1996	World Bank (2000)
	Egypt	23	Household survey	1993	World Energy Council (1999)
	Iraq	2	National energy statistics	1999	World Resources Institute (2003)
	Morocco	11	National energy statistics	1999	World Resources Institute (2003)
	Pakistan	76	National energy statistics	1997	Government of Pakistan (1997)
	Sudan	100	National energy statistics	1999	International Energy Agency (1999)
EUR-A	—	—	—	—	—
EUR-B	Turkey	11	National energy statistics	1999	World Resources Institute (2003)
EUR-C	—	—	—	—	—
SEAR-B	Indonesia	63	Personal communication	1995/1996	Government of Indonesia (1996b)
	Thailand	72	National energy statistics	1997	FAO (1997a)
SEAR-D	Bangladesh	96	National energy statistics	1997	FAO (1997a)
	India	81	National census	1991	Government of India (1991a)
	Myanmar	100	National energy statistics	1997	FAO (1997a)
	Nepal	97	National energy statistics	1997	FAO (1997a)
WPR-A	—	—	—	—	—
WPR-B	China	80	National energy statistics	1996	Government of China (1996)
	Philippines	85	National energy statistics	1997	FAO (1997a)
	Viet Nam	98	National energy statistics	1997	FAO (1997a)

— No data.

universally, available. In some cases, the data come directly from national census information or energy use statistics, which state explicitly the number or fraction of households that rely predominantly on solid fuels for their energy needs (Government of Botswana 1991; Government of Brazil 1991; Government of Ecuador 1990b; Government of Ethiopia 1998; Government of India 1991b; Government of Mexico 1990b; Government of Nigeria 1990; Government of Zimbabwe 1992). For example, information on the main fuel used for cooking is collected during the house listing of the census of India each decade (Government of India 1991b). These data, disaggregated into urban and rural sectors, are available at the district level (in India, a district contains about 2 million people).

In some countries, where censuses are infrequent and/or data on residential energy use are not collected, household surveys are an important source of information. Some of these household surveys, such as the widely conducted Demographic Health Surveys are repeated, while others may be conducted only once. For example, primary household energy estimates for 22 countries in Africa, based on household surveys with sample sizes ranging from 1000 to >14 000 households, are included in a database of development indicators for Africa, compiled by the World Bank (2000). In China, data are available in the form of aggregate annual residential fuel consumption at the provincial level, disaggregated by urban and rural areas (Government of China 1996). Cooking and heating energies were distinguished using a simple model that accounted for the average number of "heating days" in each province, based on a 30-year average from 1951–1980 (Lin 1995). A small amount of energy (2 kg-coal equivalent per household per heating day) was considered to be heating fuel and subtracted from the mix of solid fuels in each province. The remaining heating-adjusted cooking fuel was then normalized to "useful energy" using typical conversion efficiencies for each fuel–stove combination reported (Zhang et al. 2000). The proportion of useful cooking energy attributed to each fuel type per household in each province was taken to represent the number of households using that fuel. This analysis was repeated for each of the provinces in China[3] and aggregated to give a national total. It was estimated that in 1996 nearly 80% of the households in China used solid fuels.

Many countries produce national estimates of solid-fuel use, but only a minority collect specific information on fuel use at the household level. Evidence from 10 countries (Bangladesh, Ecuador, Indonesia, Mexico, Myanmar, Nepal, Pakistan, the Philippines, Thailand and Viet Nam) indicates that national and household levels of solid-fuel use are highly correlated ($R^2=0.75$). It should be noted, however, that this relationship holds true when solid fuels are not heavily used in industry. This correlation was used to estimate use of solid fuel by households in nine countries (Afghanistan, Algeria, Egypt, the Islamic Republic of Iran, Lebanon, the Libyan Arab Jamahiriya, Morocco, Tunisia and Turkey) where only information on national use of solid fuel was available. For three countries (Angola, the Democratic Republic of the Congo and the Sudan), in which a large fraction of the total national energy consumed (>70%) comprised biomass fuels (World Resources Institute 2003), household use of solid fuel was assumed to be 100%. In other countries, including Bangladesh, Indonesia, Myanmar, Nepal, the Philippines, Thailand, Viet Nam and Pakistan (FAO 1997a, 1997b; Government of Indonesia 1995, 1996a; Government of Pakistan 1997), aggregate data on annual residential fuel consumption are available. In these cases, the percentage of households using solid fuels was estimated according to the quantity of fuel consumed.

The fraction of the population of each subregion covered by the countries for which some data were available, and the prevalence of solid-fuel use according to these data are given in Table 18.3. Data on specific types of solid fuel (i.e. use of coal vs biomass) are limited to India and China, but this factor is also likely to be important in other countries in which no estimates were made, including South Africa and Pakistan.

Table 18.3 Estimates of the prevalence of households using solid fuel, by subregion, using the household fuels database

Subregion	*Population covered by available data (000s)*	*Population covered by available data (% of total population of subregion)*	*Households using solid fuel in population covered (%)*
AFR-D	260 515	88.8	72.5
AFR-E	284 784	84.4	84.5
AMR-A	—	—	—
AMR-B	268 997	62.5	24.9
AMR-D	12 646	17.7	28.1
EMR-B	86 174	61.8	5.6
EMR-D	260 797	73.0	66.8
EUR-A	—	—	—
EUR-B	66 591	30.7	10.8
EUR-C	—	—	—
SEAR-B	273 507	93.6	64.9
SEAR-D	1 212 359	97.9	83.8
WPR-A	—	—	—
WPR-B	1 433 356	93.8	81.1

— No data.

2.4 A MODEL TO PREDICT NATIONAL USE OF SOLID FUEL

Using known values from the database of households using solid fuel, a statistical model was built to predict national use of solid fuel according to a number of development parameters. The model was then applied to countries where no data on household fuel use existed. This method also allowed for the estimation of statistical uncertainty (i.e. excluding uncertainty in available data and the validity of model) surrounding each prediction.[4]

As a country develops, households gradually switch from using solid fuels to using cleaner liquid and/or gaseous fuels. Although the picture is often more complex at local and household levels, it is assumed here that this generally holds true over the long term on a subregional scale, a trend well-established by current, albeit cross-sectional, international comparisons. After a certain level of economic growth has been achieved, it is assumed that countries will shift away from cooking entirely with solid fuels. The use of solid fuel for heating may continue, however, especially in areas that are rich in coal and wood.

For countries for which data were not available, a model based on the parameters described in Table 18.4 was used with stepwise linear regression. With a gross national product (GNP) of US$4420 per capita

Table 18.4 Parameters in the fuel use prediction model[a]

Indicator	*Source*
Solid-fuel use (dependent variable)	Table 18.3
Adult female illiteracy, 1998	World Bank (2001)
Average annual growth rate, 1998–1999	World Bank (2001)
Dummy variables for all subregions	NA
Electricity consumption, per capita, 1997 (kilowatt-hours)	World Bank (2001)
Fuel-wood production	UN (1993)
Population in 2000	UN (1998)
Fuel-wood production per capita (kg)	Author calculation
Gini coefficient	World Bank (2001)
GNP per capita, 1999	World Bank (2001)
ln (GNP per capita, 1999)	Author calculation
Petroleum use per capita	UN (1993)
ln (petroleum use per capita)	Author calculation
Rural population, 1999	World Bank (2001)
Traditional fuel use (national), 1993	UN (1993)

NA Not applicable.

[a] Variables already entered were tested for removal at each step, so that variables in the model that became insignificant with inclusion of additional variables were removed. Missing values were replaced with mean values for each variable.

Table 18.5 Models to predict fuel use: GNP per capita vs use of traditional fuel as a predictor variable

Model	*Predictors*[a]	*R*	*R^2*	*Adjusted R^2*
1	Use of traditional fuel, EMR,[b] petroleum use per capita, rural population, constant	0.869	0.756	0.735
2	GNP per capita, EMR, petroleum use per capita, rural population, constant	0.864	0.746	0.724

[a] Dependent variable in both models is the percentage of households using solid fuels.

[b] Each subregional dummy variable was entered separately into the model. EMR was the only subregional dummy variable that was significant in the final model, perhaps because of a combination of low biomass resources and high access to petroleum fuels in some countries in these subregions.

in 1999, Brazil was the richest country in the database to have significant levels of cooking with solid fuels (27% of households). To avoid extrapolating the model to areas where it may be inappropriate, estimates were made only for countries with a GNP of <US$ 5000 per capita in 1999. All countries with a GNP of >US$ 5000 per capita in 1999 were assumed to have made a complete transition to clean household-cooking systems, either with cleaner liquid or gaseous fuels, or electricity or, where solid fuel was still used for cooking or heating, to fully ventilated appliances.

As use of traditional fuel (as a percentage of national energy use) is highly correlated with GNP per capita, stepwise linear regression eliminates GNP per capita when both variables are entered together. If use of traditional fuel is not entered, it is essentially replaced by GNP per capita in the model, with little impact on model fit or standard error (Table 18.5). Two models to predict fuel use were assessed, one employing GNP per capita and the other use of traditional fuel (as a percentage of national energy use) as predictor variables. Use of traditional fuel, which includes use of fuel-wood, bagasse (biomass remaining after processing sugar-cane), charcoal, animal wastes, agricultural residues, and other vegetable biomass wastes, is expressed as a percentage of total fuel use at the national (as opposed to the household) level, on an energy-equivalent basis. Like household use of solid fuel, use of traditional fuel at the national level is highly correlated with GNP per capita (Figures 18.1 and 18.2).

Information on GNP per capita is more reliable, is updated more routinely, and is available at the national level for nearly all countries. Therefore, we used the model including GNP per capita as a predictor, rather than the model using use of traditional fuel. The final model is shown in Table 18.6 and includes percentage of the rural population, GNP per capita (log-transformed), petroleum use per capita, and location within the EMR subregions (entered as a dummy variable). Other

Figure 18.1 The relationship between use of traditional fuel at the national level (as a fraction of national energy use) and GNP per capita

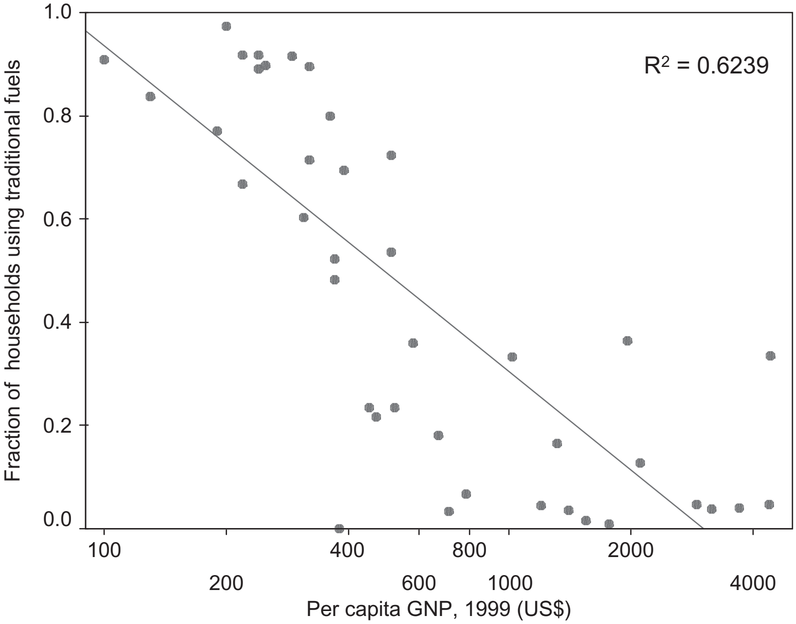
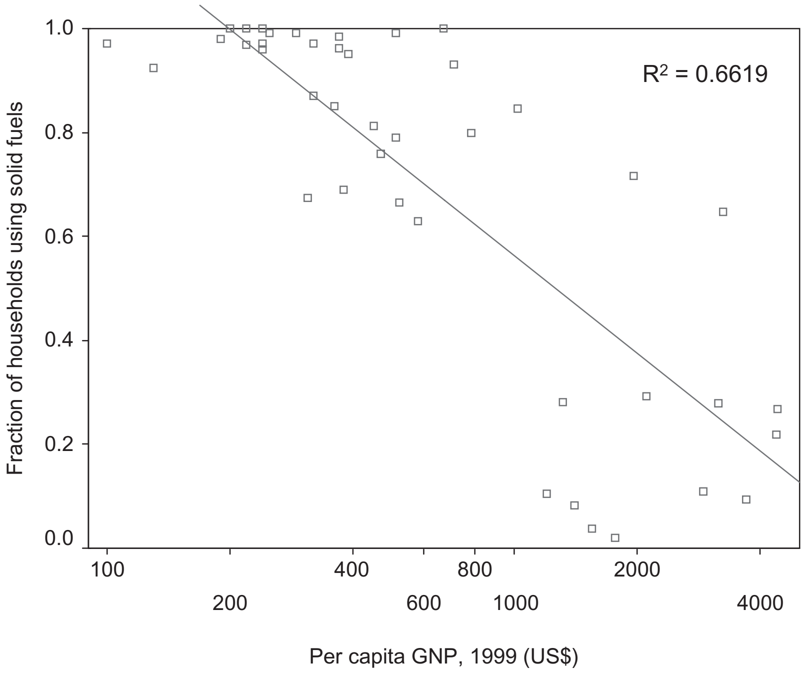


Table 18.6 Final model used to predict household use of solid fuel at the national level[a]

	Unstandardized coefficients	*Standardized coefficients*			
	Beta	*Standard error*	*Beta*	*t*	p
(Constant)	1.12	0.350	NA (0.414–1.82)	3.19	0.0025
Rural	0.661	0.214	0.353 (0.231–1.09)	3.09	0.0033
EMR	–0.248	0.0709	–0.284 (–0.390––0.105)	–3.50	0.0010
GNP(log transformed)	–0.104	0.0405	–0.265 (–0.185––0.0224)	–2.56	0.0136
Per capita petroleum use	–0.0003	0.0001	–0.224 (–0.0006––0.0001)	–2.55	0.0143

[a] Dependent variable is the percentage of households using solid fuels.

Figure 18.2 Relationship between use of traditional fuel at the household level and GNP per capita



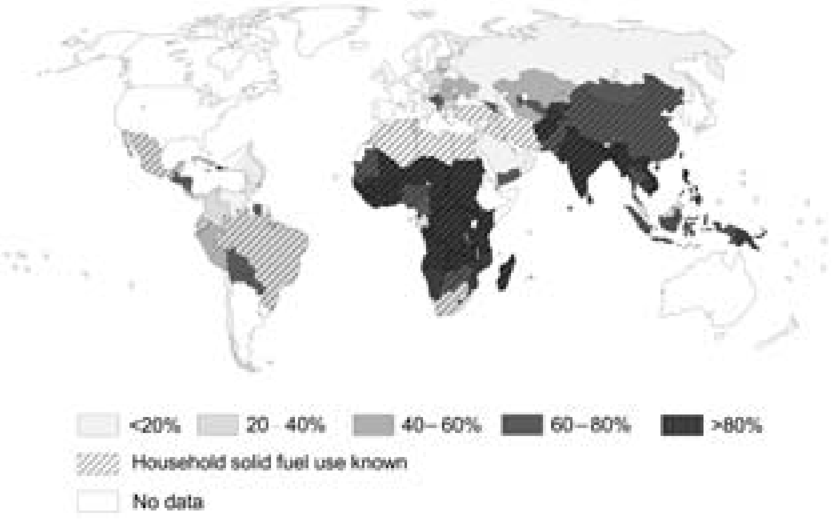
potential variables were dropped from the model in stepwise linear regression.

This model was used to predict percentages of households using solid fuel in all countries where these values were unknown (see Figure 18.3). In order to force the percentage of households using solid fuel to lie between 0% and 100%, estimates for the 23 countries with predicted values of <0 or >100 were converted to 0 and 100, respectively.

Known (for all countries in the household fuel-use database) and predicted estimates of use of solid fuel at the country level were aggregated into subregional estimates of household solid-fuel use (Table 18.7). The subregions with the least coverage are those that have the highest levels of economic development, i.e. those subregions that are least likely to have high proportions of household solid-fuel use because people have, for the most part, already shifted to cleaner fuels and cooking technologies.

We assumed that the fraction of the population exposed is the same as the fraction of households using solid fuel. This assumption is likely

Figure 18.3 Household use of solid fuel, at the national level, 2000



Note: Household solid fuel use estimates are predictions in areas without striations.

Table 18.7 Estimated household use of solid fuel, by subregion

Subregion	Subregional population (000s)	Total population covered by fuel use prediction and by available data		Household use of solid-fuel (% of population)
		n (000s)	%	Point estimate
AFR-D	293 440	292 317	99.6	73.4 (68.1–77.7)
AFR-E	337 547	333 697	98.9	85.8 (80.5–89.2)
AMR-A	320 704	11 201	3.5	1.5 (0.9–2.0)
AMR-B	430 674	388 897	90.3	24.6 (18.8–30.8)
AMR-D	71 318	71 318	100.0	52.9 (42.6–63.2)
EMR-B	139 532	145 137	100.0	6.1 (2.0–12.1)
EMR-D	357 476	278 909	78.0	55.2 (49.8–60.1)
EUR-A	410 714	10 689	2.6	0.2 (0.0–0.5)
EUR-B	216 930	216 930	100.0	41.5 (32.0–50.7)
EUR-C	245 688	245 688	100.0	22.8 (13.9–41.0)
SEAR-B	292 334	292 334	100.0	66.5 (61.1–71.8)
SEAR-D	1 238 808	1 236 398	99.8	83.5 (78.3–88.3)
WPR-A	153 357	328	0.2	0.2 (0.1–0.2)
WPR-B	1 528 144	1 479 669	96.8	78.1 (73.0–82.8)
World	6 036 664	5 003 510	82.9	56.5 (51.7–61.5)

to underestimate exposure since solid-fuel-using households are more likely to be rural and of low socioeconomic status, and are thus likely to have more members than the subregional average.

2.5 Assigning ventilation factors

Since people in different parts of the world use different cooking and heating appliances and have different types of housing, ventilation must also be taken into account when estimating exposure. Here, the term "ventilation" encompasses both ventilation-related characteristics of the stove (such as the presence of a chimney that vents to the outside of the house) and characteristics of the kitchen (building material, architectural features that influence indoor air quality, location of the kitchen with relation to living area, etc.).

Although we had no data on ventilation conditions according to subregion, we hypothesized that ventilation was a function of climate and development (UNCHS 1996). As described above, countries with a GNP per capita of >US$ 5000 were essentially assigned an estimated exposure of 0, that is, any use of solid fuel in the household was assumed to be undertaken in fully-vented appliances, with no re-entry of the pollution into the household. In the absence of further information (as described below), all other countries were assigned a ventilation factor of 1.0.

In countries of eastern Europe and the former Soviet Union, a long history of household use of solid fuel under cold climatic conditions and relatively high standards of living, before the recent economic decline, led to the development of energy technologies with far fewer indoor emissions and, consequently, less exposure per unit of solid fuel burned. Therefore, we set the ventilation factor at 0.2 for EUR-B and EUR-C.

In China, the widespread national improved-stove programme has disseminated cooking stoves with chimneys to three-quarters of rural households using solid fuel since 1981 (Goldemberg et al. 2000; Smith et al. 1993), resulting in decreased effective exposure. The ventilation factor for China was set at 0.25 for child health outcomes, because even well-operating, improved biomass stoves with chimneys are still responsible for some exposure (Sinton et al. 1995). We set China's ventilation factor at 0.5 for adult health outcomes, as current disease patterns for adults partly reflect exposure before the introduction of improved stoves. India, the only other country with a long-term national stove-improvement programme, has had only mixed success, with relatively low stove lifetimes and national coverage (NCAER 2002). The ventilation factor was therefore maintained at 1.0 for India.

Tables 18.8 and 18.9 detail estimated exposures as defined above for children aged <5 years and for adults. Separate estimates of exposure resulting from use of coal are presented in Table 18.10 for adults only, as adults are affected by chronic health outcomes (see section 3).

Table 18.8 Exposure of children (aged <5 years) to indoor smoke from solid fuels

Subregion	*Household solid-fuel use (%)*	*Ventilation factor*	*Exposure (% population) Point estimate (95% CI)*
AFR-D	73.4	1.00	73.4 (68.1–77.7)
AFR-E	85.8	1.00	85.8 (80.5–89.2)
AMR-A	1.5	1.00	1.5 (0.9–2.0)
AMR-B	24.6	1.00	24.6 (18.8–30.8)
AMR-D	52.9	1.00	52.9 (42.6–63.2)
EMR-B	6.1	1.00	6.1 (2.0–12.1)
EMR-D	55.2	1.00	55.2 (49.8–60.1)
EUR-A	0.2	0.97	0.0 (0.0–0.5)
EUR-B	41.5	0.65	26.0 (20.6–31.1)
EUR-C	22.8	0.25	7.2 (5.0–11.3)
SEAR-B	66.5	1.00	66.5 (61.1–71.8)
SEAR-D	83.5	1.00	83.5 (78.3–88.3)
WPR-A	0.2	1.00	0.2 (0.1–0.2)
WPR-B	78.1	0.37	28.0 (26.1–29.6)

Table 18.9 Exposure of adults (aged ≥15 years) to indoor smoke from solid fuels

Subregion	*Household solid-fuel use (%)*	*Ventilation factor*	*Exposure (%) Point estimate (95% CI)*
AFR-D	73.4	1.00	73.4 (68.1–77.7)
AFR-E	85.8	1.00	85.8 (80.5–89.2)
AMR-A	1.5	1.00	1.5 (0.9–2.0)
AMR-B	24.6	1.00	24.6 (18.8–30.8)
AMR-D	52.9	1.00	52.9 (42.6–63.2)
EMR-B	6.1	1.00	6.1 (2.0–12.1)
EMR-D	55.2	1.00	41.4 (37.4–45.1)
EUR-A	0.2	0.97	0.0 (0.0–0.5)
EUR-B	41.5	0.65	26.0 (20.6–31.1)
EUR-C	22.8	0.25	7.2 (5.0–11.3)
SEAR-B	66.5	1.00	66.5 (61.1–71.8)
SEAR-D	83.5	1.00	83.5 (78.3–88.3)
WPR-A	0.2	1.00	0.2 (0.1–0.2)
WPR-B	78.1	0.58	44.7 (41.7–47.4)

Table 18.10 Exposure of adults (aged ≥15 years) to coal smoke[a]

Subregion	*Exposure (%)* *Point estimate (95% CI)*
SEAR-D	2.1 (0.0–7.1)
WPR-B	12.9 (7.9–17.9)

[a] Assumed to be zero in all other subregions owing to lack of disaggregated data.

2.6 Quantitative and qualitative sources of uncertainty

Estimates of use of solid fuel for countries in the household fuel-use database were arbitrarily assigned an uncertainty range of 5%. The exposure classification system used here is binary (exposed to solid fuels or not exposed), which is consistent with the available epidemiological literature. In reality, exposure to indoor air pollution from use of solid fuel results in a wide range of exposures, which vary according to different types and quality of fuel and stove housing characteristics (e.g. ventilation and size), cooking and heating methods, differences in time-activity patterns (time spent within the household and in close proximity to the pollution source) and season (Saksena et al. 1992). Since the distribution of exposures is continuous, exposures would best be characterized as a continuous outcome, or at least better characterized by multiple categories. As a result, the above binary categorization and uncertainty values significantly underestimate the true uncertainty in levels of exposure. In addition, the need to use the fuel-prediction model for countries without data obviously introduces uncertainty, only part of which may be reflected in the variance of the results obtained from the model.

3. Estimating risk factor–disease relationships

3.1 Health outcomes: evidence for causality and inclusion criteria

Health outcomes caused by indoor exposure to smoke from use of solid fuel were chosen after a review of the epidemiological evidence available for each end-point, using electronic databases, including Medline and TCMLARS (Traditional Chinese Medical Literature Analysis and Retrieval System, an electronic database of Chinese journals). In addition, given that a large body of evidence comes from developing countries, literature was also obtained from other researchers and reputable developing-country journals not currently indexed in international databases. Only articles written or abstracted in English were used, except for articles on lung cancer, for which both the Chinese and the English

Table 18.11 Diseases associated with use of solid fuels and populations affected that were included in the analysis

Disease	*Population affected*
Acute lower respiratory infections (ALRI)	Children aged <5 years
Chronic obstructive pulmonary disease (COPD)	Females and males aged ≥30 years
Lung cancer (coal use only)	Females and males aged ≥30 years

literature were accessed, since, to our knowledge, only in China has there been significant use of coal in unvented household devices in recent decades.

GENERAL ASSESSMENT OF CAUSALITY

The strength of the evidence for each end-point was determined on the basis of a structured assessment of causality, using Bradford Hill's criteria for causality, including temporal relationship, strength of association, specificity, the presence of a dose–response relationship, biological plausibility, coherence, the existence of experimental evidence and consistency of association.

As specificity, dose–response relationships, and experimental evidence are often difficult to assess for environmental exposures and health outcomes with multiple causes or long latency periods, we used the epidemiological evidence in conjunction with available information on emissions, exposures and mechanisms for indoor air pollution (Smith et al. 2000; Zelikoff et al. 2003). Three health outcomes were determined to have strong enough evidence to be included: ALRI, COPD and lung cancer (Table 18.11). Information on assessing causality for these outcomes is given in section 3.3 and excluded outcomes are discussed in section 3.2.

Children aged >5 years (of school-age) were excluded as they spend less time in the house than women and children aged <5 years; this is a conservative assumption as there is some exposure of this group, although levels are unknown on a global scale (Ezzati and Kammen 2001; Saksena et al. 1992). Because of the limitations of the available epidemiological studies, only risks in young children (aged <5 years) and adults were included. Available data indicate that men are also affected by those outcomes considered for women, but presumably at lower risks than women because of lower exposures. Adults aged 15–30 years were excluded because the chronic diseases of concern (COPD and lung cancer) have not yet become manifest in this group. Obviously, however, development of these diseases in later years is partly caused by exposures at these and younger ages.

3.2 EXCLUDED HEALTH OUTCOMES

OUTCOMES WITH INSUFFICIENT EVIDENCE

A number of important diseases that are potentially associated with use of solid fuels have not been included in this analysis owing to insufficient or lack of direct evidence on causality. Lack of inclusion does not necessarily imply inconclusive findings. Rather, it refers to a relatively small set of findings, suggesting that additional, carefully conducted studies are needed to strengthen the evidence base.

Asthma

On the basis of the usual measures (concentrations of small particles, $PM_{2.5}$), typical exposures to indoor smoke from use of solid fuels are much higher than those for urban outdoor pollution (García-Marcos et al. 1999) and ETS (Strachan and Cook 1998), with which asthma has been frequently associated. In addition, a study of children aged <5 years in Malaysia found increased risk associated with the burning of mosquito coils, another important indoor source of $PM_{2.5}$ (Azizi et al. 1995). Studies in China (Xu et al. 1996a) and Kenya (Mohamed et al. 1995) have quantitatively associated asthma in children of school age and in adults with various measures of indoor pollution from solid-fuel use. As the reported background rate is low in most developing countries, however, asthma contributes relatively little to the total burden of deaths or DALYs from indoor air pollution.

Cataracts and other visual impairments

Two case–control studies in India have found an increased risk of cataracts among people using biomass fuel; Mohan et al. (1989) determined an odds ratio of 1.6; Zodpey and Ughade (1999) found an adjusted odds ratio of 2.4. Evaluation of the National Family Health Survey of India (NFHS 1995) found a somewhat lower rate for partial blindness (odds ratio of 1.3; Mishra et al. 1999a), but no significant difference for total blindness. There is also evidence that exposure to ETS is associated with cataracts (West 1992) and animal studies show that cataracts can be caused by wood smoke (Rao et al. 1995; Shalini et al. 1994).

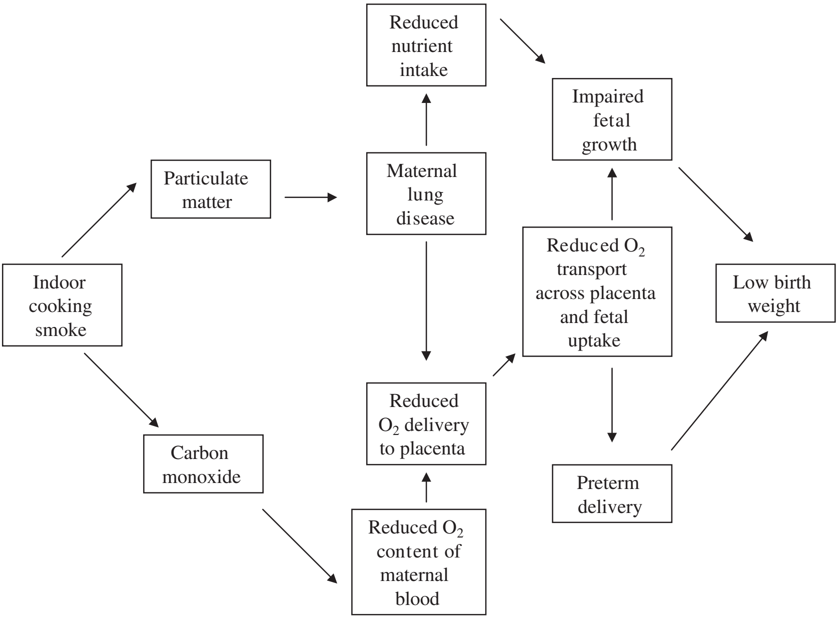
Indoor air pollution may also be linked to blindness through trachoma (Prüss and Mariotti 2000). Two unadjusted studies in the United Republic of Tanzania found such a link (Taylor and West 1989; West and Lynch 1989) although another in Ethiopia found cooking in a central room to be protective, perhaps through reduction of flies (Sahlu and Larson 1992).

Perinatal effects

One study in India found an adjusted excess risk of stillbirth of 50% among women using biomass fuels during pregnancy (Mavalankar et al. 1991), and two Chinese studies of urban ambient pollution, from the same group of researchers, also found a strong relationship between concentrations of particulates and pre-term delivery (Xu et al. 1995) and low birth weight (Wang et al. 1997). Low birth weight was also found to be associated with household exposure to biomass smoke in Guatemala (Boy et al. 2002). Intrauterine mortality, low birth weight, prematurity, and early infant death have been significantly associated with urban outdoor pollution at much lower concentrations than those typically found in households that use biomass (Bobak 2000; Loomis et al. 1999; Pereira et al. 1998; Ritz and Yu 1999; Scram 1999; Woodruff et al. 1997). Exposure of non-smoking pregnant women to ETS has been associated with low birth weight in a meta-analysis of 17 studies (Windham et al. 1999a), with low cognitive development (Johnson et al. 1999), but not with spontaneous abortion (Windham et al. 1999b).

Low birth weight is a risk factor for a number of childhood (Walsh 1993) and, probably, adult (Barker 1997) diseases, not just those of the respiratory system. The potential pathways by which indoor cooking smoke may cause low birth weight are given in Figure 18.4. Although this mechanism seems likely to be important in some parts of the world,

Figure 18.4 Possible mechanisms for indoor air pollution and low birth weight



Source: Adapted from Jere D. Haas' schematic diagram of the causal pathway for indoor cooking smoke and birth weight (Smith et al. 2000).

at present it is difficult to provide a quantitative estimate of the potential burden, and it is not attempted here.

Tuberculosis

Recent studies in India and Mexico have suggested that indoor air pollution from use of solid fuel may be a risk factor for active tuberculosis. A statistically significant relationship has been found between reported use of biomass fuel and incidence of tuberculosis in 260 000 adults aged >20 years. Indeed, women in households using biomass fuels were found to be 2.7 (95% CI 1.9–4.0) times more likely to have tuberculosis than women in households using cleaner fuels, even after correction for a range of socioeconomic factors (Mishra et al. 1999b). In addition, an unadjusted but significant odds ratio of 2.5 has been reported for clinically-confirmed tuberculosis in adult male and female householders aged 16–60 years using wood or dung cakes as fuel (Gupta and Mathur 1997). Although these studies were not able to address smoking as a possible confounder, two studies in Mexico City have found an association between exposure to wood smoke and incidence of tuberculosis, after taking smoking into account (Perez-Padilla et al. 1996, 2001). A study in China also found exposure to outdoor air pollution to be associated with tuberculosis (Xu et al. 1995). Animal studies have shown that wood smoke causes immune suppression in the respiratory system (Thomas and Zelikoff 1999; Zelikoff 1994).

Other health effects not included

- Interstitial lung disease has been associated with long-term exposures in several studies (Dhar and Pathania 1991; Gold 2000; Ramage et al. 1988; Sandoval et al. 1993).
- Early studies in Africa seemed to implicate wood smoke as a cause of nasopharyngeal cancer, but this association was not borne out by later studies in Asia (Smith 1987; Smith and Liu 1994).
- Two studies in Brazil have shown increased risk of upper aerodigestive tract cancers, with adjusted odds ratios of 2.7 (Pintos et al. 1998) and 2.5 (Franco et al. 1989).
- An association has been shown with cervical neoplasia among HPV-infected women in Honduras, with an adjusted odds ratio of 5.7 after 35 years or more of cooking over an open fire (Velema et al. 2002).
- Ischaemic heart disease has been associated with exposure to outdoor particulate air pollution (Ponka and Virtanen 1996; Pope et al. 1992; Schwartz 1993; Schwartz and Dockery 1992; Schwartz and Morris 1995) and ETS (Steenland et al. 1998) in some studies, both at much lower levels of exposure than for indoor air pollution (see chapter 17).

EXCLUDED OUTCOMES ASSOCIATED WITH USE OF SOLID FUEL, BUT NOT CAUSED BY EXPOSURE TO AIR POLLUTION

The use of solid fuels for household cooking and heating involves a range of activities with potential health implications that are separate from those involving the pollution created. The most important involve the harvesting of the two major types of fuel.

- The harvesting of biomass in rural settings in developing countries may involve regular carriage of heavy loads for long distances, with consequent physical strain and food energy demands, along with exposure to such hazards as snake-bite, leeches and assault (crime). Women and children typically bear the greatest burden of such harvesting, although there is much variation across the world.
- Coal mining is one of the most hazardous occupations in the world, particularly in developing countries in small mines from which much household fuel is obtained.

In addition, the extra time taken to harvest, store, and prepare solid fuels is time that is potentially deducted from other pursuits that are associated with health benefits, such as child care or the generation of the household income.

Considering that the counterfactual distribution is cooking with non-solid fuels (rather than no cooking at all), there are also categories of health risk that are avoided by the use of solid fuels:

- fires and explosions related to household use of liquid and gaseous fuels;
- poisoning caused by ingestion of household kerosene;
- risk inherent in the operation of the national and international petroleum fuel cycles required to provide liquid and gaseous fuels;
- risks involved in providing electricity for household cooking, such as coal mining, air pollution from power plants, accidents involving nuclear and hydroelectric dams, etc.; and
- additional risk of mosquito-borne diseases owing to absence of repellence from household smoke produced by solid fuel.

In its current form, the system limits of this comparative risk assessment (CRA) do not encompass any of these health effects, positive or negative, that are not directly caused by exposure of humans to pollution in the household.

EXCLUDED OUTCOMES ASSOCIATED WITH SPECIALIZED AIRBORNE PRODUCTS OF INDOOR COMBUSTION

There are several related sources of indoor pollution not covered by this analysis that may be locally important in some countries. However, too few data are available regarding exposures to extrapolate these risks to global burdens, although we suggest that these sources represent potential research topics, as well as priorities for determining exposure distributions, in order to improve the estimated burden of indoor air pollution.

- Smoke from cooking oil: studies in China (including the Province of Taiwan) show relative risks for lung cancer of 3–5 for Chinese-style cooking in a wok with certain cooking oils (Ko 2000; Zhong et al. 1999b).
- Exposures to trace quantities of toxic elements resulting from indoor use of coal in China and elsewhere: significant and widespread impacts from exposures to fluorine and arsenic have been reported in China (Finkelman et al. 1999) and can be expected to occur wherever coal fuels are contaminated with such toxic elements.
- Smoke from incense and mosquito coils, which have been associated with ill-health in some Asian studies (Azizi et al. 1995).

3.3 Evidence and exposure–risk relationships

The estimates of relative risk[5] and confidence intervals used for ALRI, COPD and lung cancer were derived through formal meta-analyses of the available literature.

Searches of the scientific literature were conducted using the Medline computerized bibliographic database, review of bibliographies from previously-retrieved articles and personal communications. In some cases, the authors of articles that were lacking data that were of interest for this analysis were contacted and asked for clarification, and specific requests for information were sent to researchers in this field.

Medline searches were conducted using the following key words:

- For ALRI: indoor air pollution, household fuel, smoke, acute respiratory infections (ARI), pneumonia and ALRI
- For COPD: indoor air, fuel, COPD, chronic obstructive lung disease (COLD) and chronic bronchitis
- For lung cancer: indoor, air, fuel and lung cancer

To be eligible for inclusion in the meta-analysis, studies had to fulfil the following criteria:

- to be a primary study, not a re-analysis or review;
- to examine some proxy for exposure to indoor smoke from the use of solid fuels for cooking and/or heating purposes;
- to report an odds ratio and its variance, or sufficient data with which to estimate them; and

- to be written or abstracted in English. Additionally, for lung cancer only, a Chinese colleague assisted in a comprehensive search of the Chinese literature, extraction of the relevant data and translation.

We considered both fixed- and random-effects models for the meta-analysis. As the results from both were similar, we used those from the fixed-effects model only. Owing to heterogeneity within studies, we performed sensitivity analyses by stratifying the studies by potential sources of heterogeneity, including assessment of exposure and adjustment for confounders. We did not use a random-effects model, even when statistical significance for heterogeneity was present, for the following reasons.

- Random-effects models assume that studies are selected from a population with a single underlying variance. This would be violated given the heterogeneity among the studies in measuring exposure.
- Random-effects models assign the same weight to small and large studies. This would be problematic for the studies of this analysis because the number of cases ranged from 45 to 500.

Smoking is an important risk factor for the diseases associated with indoor smoke from use of solid fuel, especially lung cancer and COPD. At present, information on the combined effects of smoking and use of solid fuel is rare. To avoid possible overestimation of the burden of disease, therefore, attributable fractions for lung cancer and COPD caused by use of solid fuel were applied to disease burdens remaining after removal of the burden attributable to smoking. This is conservative in that some of the effect attributable to smoking could also be attributed to use of solid fuel. To ensure internal consistency within the CRA project, burdens attributable to smoking were obtained from chapter 11. Globally, about 51% and 62%, for men and women respectively, of the total burden of COPD is not attributable to tobacco.

ACUTE LOWER RESPIRATORY INFECTIONS

A number of studies in developing countries (Argentina, Brazil, the Gambia, India, Kenya, Nepal, Nigeria, South Africa, the United Republic of Tanzania and Zimbabwe) have quantified the relative risk of ALRI for children in households that burn biomass (Armstrong and Campbell 1991; Campbell 1997; Cerqueiro et al. 1990; Collings et al. 1990; de Francisco et al. 1993; Ezzati and Kammen 2001; Johnson and Aderele 1992; Kossove 1982; Mtango et al. 1992; O'Dempsey et al. 1996; Pandey et al. 1989b; Shah et al. 1994; Victora et al. 1994). Some work has also been done to identify possible mechanisms in the developing countries (Verma and Thakur 1995).

Studies among native Americans (Navajos in the south-western United States of America) show a strong and significant association between ALRI and use of wood stoves, at much lower levels of indoor pollution than found in developing countries (Morris et al. 1990; Robin et al.

1996). There is a larger group of studies that show various childhood respiratory symptoms (e.g. cough, wheezing) to be associated with exposure to smoke from solid fuel, but do not provide sufficient evidence to calculate odds ratios of ALRI itself.

As all studies included here used either ARI or ALRI, or death caused by ARI or ALRI, in children aged <5 years as a health outcome, we only estimated the burden of disease for children in this age group. A recent study in Kenya (Ezzati and Kammen 2001) found associations between use of solid fuels and ARI in adults (both men and women), suggesting that, once time–activity patterns and spatial dispersion of smoke have been taken into account, men and women may have similar patterns of exposure–response.

A single statistical analysis of all 15 studies identified (Table 18.12) was not appropriate because of the heterogeneous exposure variables and the diverse analytical strategies used by the investigators, especially with respect to potential confounding factors. To address this diversity, different subgroups of these studies were used to conduct several meta-analyses, the results of which were remarkably consistent; pooled relative risk estimates increased with improved precision of exposure measure.[6]

Characteristics of excluded studies

Of the 15 studies identified (Table 18.12), we excluded the study by Kossove (1982), which had an inappropriately-small comparison group. Two studies in South America focused on use of solid fuels in urban populations (Cerqueiro et al. 1990; Victora et al. 1994). The study in Buenos Aires, Argentina, was excluded owing to a very low prevalence of households using solid fuels and, in one of the case groups, missing data on exposure to heating fuelled by charcoal (Cerqueiro et al. 1990). In the study in Brazil (Victora et al. 1994), only a small proportion of the study population was exposed (6%) and exposure was defined loosely, encompassing a wide range of sources of pollution, from open fires to enclosed metal heating stoves and vented fireplaces. The study by Shah et al. (1994) was excluded because its definition of non-exposure (use of stove with chimney provided by the government improved-stove programme) has been shown to produce concentrations of indoor pollutants that were not statistically different from those produced by open fires at that time in India (Ramakrishna et al. 1989) and no observations of direct pollution were made. The study by Mtango et al. (1992) was excluded because, as the study focused on mortality from all causes, no information was given on exposure status for the proportion of deaths caused by ALRI (in this case, pneumonia). Two studies reported on the same study population (Armstrong and Campbell 1991; Campbell et al. 1989). We chose to include the older report by Campbell, which included the odds ratio for girls and boys combined. A recently-published longitudinal study examining rates of episodes of

Table 18.12 Studies on the risk of acute lower respiratory infection associated with use of solid fuels, in children aged <5 years

Study location	*Reference*	*Study design* (n) *Study population*	*Exposure assessment*	*Outcome assessment*	*Covariates adjusted for*	*Odds ratio (95% CI)*
Argentina	Cerqueiro et al. (1990) *Excluded*	Case–control (616–669) Children aged <5 years	Questionnaire: type of cooking fuel used (wood, kerosene, gas)	ALRI within the last 12 days, at a well-baby clinic	None	9.9 (1.8–31.4)
Brazil (urban)	Victora et al. (1994) *Excluded*	Case–control (510–510) Children aged <2 years	Questionnaire: presence of indoor smoke	ALRI hospital cases, clinical signs and X-ray	Smoking, housing, no. of siblings, income, education, history of respiratory illness	1.1 (0.6–2.0)
Gambia	Armstrong and Campbell (1991) *Excluded*	Cohort (500) Children aged <5 years	Questionnaire: mother carries child on her back while cooking	ALRI, by weekly home visits	Birth interval, ETS, crowding, socioeconomic status, nutrition, vaccination, education	Males: 0.5 (0.2–1.2) Females: 1.9 (1.0–3.9)
Gambia	Campbell et al. (1989)	Cohort (271) Children aged <1 year	Questionnaire: mother carries child on her back while cooking	ALRI, by weekly home visits	Birth interval, ETS, crowding, socioeconomic status, nutrition, vaccination, education	2.8 (1.3–6.1)
Gambia Upper River Division	de Francisco et al. (1993)	Case–control (129–270) Children aged <2 years	Questionnaire: mother carries child on her back while cooking	Death from ALRI by verbal autopsy confirmed by three independent physicians	Socioeconomic status, ETS, maternal education, crowding, nutrition	5.2 (1.7–15.9)
Gambia Upper River Division	O'Dempsey et al. (1996)	Case–control (80–159) Children aged <5 years	Questionnaire: mother carries child on her back while cooking	ALRI hospital cases, clinical signs, X-ray and laboratory	ETS, mother's income, weight slope, recent illness, nutrition	2.5 (1.0–6.6)
India	Shah et al. (1994) *Excluded*	Case–control (400) Children aged ≤5 years	Household has a smoke-producing stove	Severe ARI hospital cases, clinical symptoms	Smoking, housing, no. of siblings, income, education, birth weight	1.2 (0.7–2.3)

Kenya	Ezzati and Kammen (2001) *Excluded*	Cohort (93) Children aged <5 years	Mean daily personal PM_{10} exposure from pollution and time-location data	Rate of ALRI during study period by Integrated Management of Childhood Illness (IMCI) diagnosis criteria	Age, sex, crowding, smoking, village type	2.93 (1.34–6.39) Highest vs lowest exposure category plus exposure–response trend
Nepal	Pandey et al. (1989b)	Cohort (280) Children aged <2 years	Questionnaire: Average time spent near the fireplace	ARI, by bi-weekly home visits	None	2.3 (1.8–2.9)
Nigeria	Johnson and Aderele (1992)	Case–control (103–103) Children aged <5 years	Questionnaire: type of cooking fuel used (wood, kerosene, gas)	ALRI hospital cases, clinical signs, X-ray and laboratory	None	0.8 (0.4–1.7)
South Africa	Kossove (1982) *Excluded*	Case–control (132–18) Children aged ≤1 year	Questionnaire: does the child stay in the smoke?	ALRI hospital cases, clinical signs and X-ray	None	4.8 (1.7–13.6)
United Republic of Tanzania	Mtango et al. (1992) *Excluded*	Case–control (456–1160) Children aged <5 years	Questionnaire: child sleeps in room where cooking is done	Death from all causes, by verbal autopsy and physician	Village, age, questionnaire respondent, maternal education, parity, water source, child eating habits	2.8 (1.8–4.3)
USA Arizona	Morris et al. (1990)	Case–control (58–58) Children aged <2 years	Questionnaire: primary source for heating and cooking	ALRI hospital cases, clinical signs and X-ray	Family history of asthma, recent respiratory illness, dirt floor, running water	4.9 (1.7–12.9)
USA Arizona	Robin et al. (1996)	Case–control (45–45) Children aged <2 years	Questionnaire: household uses wood for cooking	ALRI hospital cases	No. of siblings, electricity, running water, difficulty in transport to clinic, ETS, housing	5.0 (0.6–42.8)
Zimbabwe	Collings et al. (1990)	Case–control (244–500) Children aged <3 years	Questionnaire: household uses open wood-fire for cooking	ALRI hospital cases, clinical signs and X-ray	ETS, crowding, housing, number of siblings	2.2 (1.4–-3.3)

ALRI in a range of age groups across several categories of exposure to smoke from combustion of biomass in Kenya (Ezzati and Kammen 2001) was excluded from the formal meta-analysis because the outcome, expressed as "fraction of weeks with illness", could not be translated into an odds ratio in a manner consistent with the other epidemiological studies. This study did provide strong collaborative evidence, nevertheless, for it showed effects in older children and women as well as in young children and demonstrated a statistically significant trend in the exposure–response relationship. In a subsequent analysis, the authors reported an odds ratio of 2.14 for children exposed to PM_{10} concentrations of >1000 µg/m^3 (Ezzati 2002).

Estimating risk factor–disease relationships

After the exclusions noted above, there remained eight studies that reported relative risks of acute respiratory illness for young children exposed to indoor smoke from use of solid fuel (Campbell et al. 1989; Collings et al. 1990; de Francisco et al. 1993; Johnson and Aderele 1992; Morris et al. 1990; O'Dempsey et al. 1996; Pandey et al. 1989b; Robin et al. 1996). Of these, the majority were case–control studies. One study used the outcome "pneumococcal infection", which includes meningitis and septicaemia (O'Dempsey et al. 1996). However, 80% of patients in this study were diagnosed with pneumonia. Although most of the studies were conducted in developing countries, two were carried out in populations of Navajo and Hopi Indians in the United States (Morris et al. 1990; Robin et al. 1996). The populations in the United States are likely to differ in socioeconomic characteristics from the rest of the studies, thus potentially influencing the rates of incidence of ALRI. As the overall odds ratio did not change substantially with the exclusion or inclusion of these studies, all subsequent analyses included these two studies.

EXPOSURE ASSESSMENT USED IN THE STUDIES

The studies provide relatively little information on the indoor concentrations of or exposures to specific pollutants produced by use of solid fuels, or on the baseline concentrations within similarly-constructed households that do not use solid fuels. All but one study used binary classifications of exposure (Table 18.12). On the basis of evidence for an exposure–response relationship between ARI and exposure to smoke from solid fuels (Ezzati and Kammen 2001; Pandey et al. 1989a), we attempted to analyse the studies according to the precision of the exposure measure used and the likely intensity of exposure. Exposure measures used were grouped in three major categories, in what was assumed to be an increasing order of precision: type of fuel used, duration of exposure to smoke from solid fuels, and using solid fuel and carrying the child on the mother's back (Table 18.13). Although it is generally true that concentrations of pollutants are likely to be lower in households using cleaner fuels, such as kerosene or gas, there is a wide variation in con-

Table 18.13 The risk of ALRI associated with use of solid fuels, in children aged <5 years: subgroup analyses

Subgroup analyses	*Studies included*	*Odds ratio (95% CI)*
All studies	Campbell et al. (1989); Collings et al. (1990); de Francisco et al. (1993); Johnson and Aderele (1992); Morris et al. (1990); O'Dempsey et al. (1996); Pandey et al. (1989b); Robin et al. (1996)	2.3 (1.9–2.7)
Use of solid fuel	Johnson and Aderele (1992); Collings et al. (1990); Morris et al. (1990); Robin et al. (1996)	2.0 (1.4–2.8)
Duration of time child spent near the cooking fire	Pandey et al. (1989b)	2.3 (1.8–2.9)
Child is carried on the mother's back	Campbell et al. (1989); de Francisco et al. (1993); O'Dempsey et al. (1996)	3.1 (1.8–5.3)
Studies adjusting for nutritional status	Campbell et al. (1989); de Francisco et al. (1993); O'Dempsey et al. (1996)	3.1 (1.8–5.3)
Studies not adjusting for nutritional status	Collings et al. (1990); Johnson and Aderele (1992); Morris et al. (1990); Pandey et al. (1989b); Robin et al. (1996)	2.2 (1.8–2.6)
Children aged <2 years old	Campbell et al. (1989); de Francisco et al. (1993); Morris et al. (1990); Pandey et al. (1989b); Robin et al. (1996)	2.5 (2.0–3.0)
Children aged <5 years old	Collings et al. (1990); Johnson and Aderele (1992); O'Dempsey et al. (1996)	1.8 (1.3–2.5)

centrations reported in households using solid fuels (Mehta and Smith 2002). Some studies report whether or not children remained indoors when the mother was cooking, but, for reasons noted above, all of these studies were excluded (Awasthi et al. 1996; Kossove 1982; Mtango et al. 1992). Only one study reported the average time that the child spent near the cooking fire (Pandey et al. 1989b). We assumed that carrying the child on the mother's back during cooking represented the most precise measure of exposure, as this suggests that the child was in close proximity to the fire, where exposures are generally higher (although the type of fuel used in control households in these studies was not specified).

We performed separate analyses for each category of exposure, as summarized in Table 18.13. Cooking with wood or other biomass was associated with an odds ratio of 2.0, 95% CI 1.4–2.8. The Pandey study reported an intermediate estimate of relative risk of 2.3, 95% CI 1.8–2.9, for children spending more than two hours near the cooking fire each day. The highest odds ratio was found to be associated with the child being carried on the mother's back during cooking (odds ratio of 3.1, 95% CI 1.8–5.3).

In only three of the studies were the results adjusted for nutritional status in multivariate analyses, an important confounding variable for

ARI in young children (Victora et al. 1999). The odds ratio found by those studies that did adjust was 3.1, 95% CI 1.8–5.3, whereas the effect was slightly smaller in the studies that did not adjust, with an odds ratio of 2.2, 95% CI 1.8–2.6. This may be explained, however, by the fact that the studies that controlled for nutrition also used a different exposure proxy (child was carried on mother's back during cooking).

Age is another potential confounding variable because younger children are more likely to remain close to their mothers and are therefore also more likely to be exposed to indoor smoke from cooking or heating, and because age is independently associated with ALRI, with younger children being more susceptible than older children. Most case–control studies adjusted for age by matching controls to cases. When the analysis was restricted to include only studies in children aged <2 years, the risk of ALRI was found to be slightly higher (odds ratio of 2.3, 95% CI 1.9–2.7) than that obtained from studies in children aged ≤5 years (odds ratio of 1.6, 95% CI 1.2–2.2). Armstrong and Campbell (1991) noted that, in their study population, girls were more likely to be carried on their mothers' backs than boys and were thus exposed to higher concentrations of pollutants for a longer duration of time. This study found that girls who were carried on the mother's back during cooking had an increased risk of ALRI; no association was observed for boys. The risk in girls was much higher (odds ratio of 6.0 vs odds ratio of 1.9) when only the first episode of ALRI (rather than all episodes) was included in the analysis, although the confidence interval was also much wider, owing to the smaller sample. Data were not disaggregated by sex in any of the other studies (although several did control for sex in the multivariate analyses).

As we could not separate the effects of measures of exposure from adjustment for nutritional status, we used the combined odds ratios for all eight studies remaining after exclusions. The results of this approach are similar to those that would be produced if the difference between the most and least precise exposure measures were to be used as the range, i.e. 2.0–3.1 (geometric mean, GM=2.4). This is also consistent with the differences in the odds ratios for the two age groups, that is, 1.8 for children aged <5 years and 2.5 for children aged <2 years. The overall estimate, from all eight studies, of the risk of ALRI in young children exposed to indoor air pollution caused by use of solid fuels was 2.3, CI 95% 1.9–2.7.

CHRONIC OBSTRUCTIVE PULMONARY DISEASE

Globally, the most important risk factor for COPD is thought to be smoking of tobacco (NHLBI/WHO 2001) (see also chapter 11). A number of studies have examined various symptoms of chronic respiratory ill-health in women who cook with open stoves burning biomass (Smith 2000). Eight studies in six countries—Bolivia (Albalak et al. 1999), Colombia (Dennis et al. 1996), India (Gupta and Mathur 1997;

Malik 1985), Mexico (Perez-Padilla et al. 1996), Nepal (Pandey 1984b; Pandey et al. 1988) and Saudi Arabia (Døssing et al. 1994)—have quantified the association between indoor air pollution and COPD. Although there are no comparable studies reporting odds ratios in China, the high rates of COPD in non-smoking Chinese women argue that this risk can be related to exposure to coal smoke (Liu et al. 1998).

Cor pulmonale, a heart condition that is secondary to COPD and that is also found among non-smoking rural women in south Asia (Smith 1987), has long been attributed to long-term exposure to smoke from biomass (Padmavati and Pathak 1959). Other studies have attributed silicosis (Norboo et al. 1991; Saiyed et al. 1991), reductions in lung function, cough and various other respiratory conditions to exposure to smoke from biomass, in women,[7] but were not however included here, owing to limited evidence and the relatively small burden of disease associated with these conditions.

Studies that were included in the meta-analysis used a specific definition of COPD or chronic bronchitis, such as cough and sputum on every day for at least three consecutive months for two successive years, and/or a forced expiratory volume in first second/forced vital capacity (FEV1/FVC) ratio of <70% or a FEV1 of <70% of the predicted value. We identified 11 studies reporting the relative risks of chronic airway disease in adults exposed to indoor smoke (Albalak et al. 1999; Behera et al. 1991; Dennis et al. 1996; Døssing et al. 1994; Dutt et al. 1996; Gupta and Mathur 1997; Malik 1985; Menezes et al. 1994; Pandey 1984a; Perez-Padilla et al. 1996; Qureshi 1994). Of these, one was a cohort study (Dutt et al. 1996) and three were case–control studies (Dennis et al. 1996; Døssing et al. 1994; Perez-Padilla et al. 1996). The remaining six studies were cross-sectional (Table 18.14).

Where studies reported exposure as a continuous variable, categories were constructed post hoc to be consistent with studies that presented the same exposure or a similar exposure as a categorical variable (e.g. average time spent daily near the stove, <2 hours and >2 hours). More than half of the study populations in Table 18.14 originated from rural areas where cooking on an open fire in ill-ventilated huts was common. Five study sites, however, were in urban or peri-urban settings where a mixture of fuels might be used (see Table 18.14) and where exposure to indoor smoke is likely to be lower than for women living in rural areas.

Estimating the relationship between risk factor and disease

Smoking is an important potential confounding variable for COPD and particularly so if men are included in the analysis, given the higher prevalence of smoking in men than in women in developing countries. Only two studies adjusted for smoking (Dennis et al. 1996; Menezes et al. 1994). Of the studies that did not adjust for smoking, two included non-smokers only (Behera et al. 1991; Dutt et al. 1996), another reported an overall prevalence of smoking of <1% in the entire study population

Table 18.14 Studies on the risk of chronic obstructive pulmonary disease associated with use of solid fuels

Study location	*Author (year of publication)*	*Study design (n)* *Study population*	*Exposure assessment*	*Outcome assessment*	*Covariates adjusted for*	*Odds ratio (95% CI)*
Bolivia	Albalak et al. (1999)	Cross-sectional (241) Females+males aged >20 years	Cooking inside or outside	CB	Age, sex	2.5 (1.25–5)
Brazil (urban)	Menezes et al. (1994)	Cross-sectional (1 053) Females+males aged >40 years	Presence of at least two of the following: open fire, charcoal stove, paraffin lamp or coal heater	CB	Age, sex, race, income, schooling, smoking, childhood respiratory illnesses, occupational exposures	1.3 (0.75–2.27)
Colombia (urban)	Dennis et al. (1996)	Case–control (104–104) Females aged >35 years	Use of solid bio-fuel for cooking (wood)	COPD,[a] COPD+CB	Age, smoking, hospital	3.92 (1.16–9.1)
India (rural)	Gupta and Mathur (1997)	Cross-sectional (707) Females+males aged >15 years	Use of solid bio-fuel for cooking (wood+dung)	CB+bronchial asthma	Age	7.9 (2.84–21.8)
Northern India	Behera et al. (1991)	Cross-sectional (3 718) Females involved in cooking	Use of solid bio-fuel for cooking (wood+dung)	CB	None	1.97 (1.16–3.22)
Northern India	Malik (1985)	Cross-sectional (2 180) Females aged >20 years	Use of solid bio-fuel for cooking (wood)	CB, COPD+CB	None	3.0 (1.77–4.93)
Southern India (urban)	Dutt et al. (1996)	Cohort (315) Females aged 15–60 years	Use of solid bio-fuel (wood) for cooking	CB	None, age-stratified sampling	2.8 (0.7–11.4)

India						
Ladakh, Himalaya	Norboo et al. (1991) *Excluded*	Cross-sectional (364) Females + males aged >20 years	Carbon monoxide level	CB	NA	NA
Kashmir	Qureshi (1994)	Cross-sectional (560) Females + males aged >15 years	Average time spent near the fireplace (>4 hours vs <4 hours)	CB	None	3.5 (1.4–8.77)
Mexico (urban)	Perez-Padilla et al. (1996)	Case–control (127–375) Females aged >40 years	Use of solid bio-fuel for cooking and heating (wood)	CB	Age, place of residence, education, income, smoking	4.1 (2.3–9.4)
Mozambique (urban)	Ellegard (1996) *Excluded*	Cross-sectional (1 188) Females + males aged >14 years	Estimate of lifetime exposure to cooking fuel	Cough index	Economic and environmental variables	NA
Nepal	Pandey (1984a)	Cross-sectional (1 375) Females + males aged >20 years	Use of solid bio-fuel for cooking (wood + straw)	CB	Age	5.4 (2.96–9.78)
Nepal	Pandey et al. (1985) *Excluded*	Cross-sectional (150) Females aged 30–44 years	Daily duration of exposure to domestic smoke	FVC	None	NA
Saudi Arabia	Døssing et al. (1994)	Case–control (50–71) Females + males admitted to the hospital	Ever exposed to open cooking fire	COPD[b]	None, matched for age and sex	14.4 (5.5–37.5)

Key: CB, chronic bronchitis, defined as cough and sputum on most days for at least three consecutive months of two successive years; NA, not applicable; FEV, forced expiratory volume; FEV1, forced expiratory volume in first second; FVC, forced vital capacity.

[a] COPD = FEV1/FVC <70% without asthma or FEV1<70% of predicted value.

[b] COPD = FEV1/FVC <70%, FEV1<70% of predicted value and <15% or <250 cm^3 absolute increase after 200 μg of aerosolized salbutamol.

(Albalak et al. 1999). Pandey (1984a) reported the data stratified by smoking status and finally, the study by Perez-Padilla et al. (1996) reported that 70–80% of the subjects indicated that they had never smoked.

Two studies (Døssing et al. 1994; Gupta and Mathur 1997), which included men and women and reported a relatively high prevalence of smoking in their study populations (not equally distributed between COPD cases and controls), did not adjust for smoking. The combined estimate of risk from the group of studies that accounted for smoking, and excluding the Døssing et al. and Gupta and Mathur studies, was 2.5, 95% CI 1.9–3.3. The combined estimate of relative risk for the studies by Døssing et al. and Gupta and Mathur that did not adjust for smoking, and which is thus likely to be an overestimation, was substantially higher at 10.8, 95% CI 5.4–21.8. Another major confounding variable in the association between risk of COPD and exposure to indoor smoke is age, with absolute risk increasing with age. Most studies adjusted for age by matching, stratified sampling (Dutt et al. 1996), or by adjustment in the analysis; two studies (Malik 1985; Qureshi 1994) reported the mean age to be similar in the exposed vs unexposed subjects. A potential problem of confounding by age remains with the studies by Pandey (1984a) and Behera et al. (1991), which showed no data on the age distribution. The combined estimate of the relative risk excluding these two studies was 2.9, 95% CI 2.2–3.6.

This analysis primarily included women as they comprise the population that is most frequently exposed to smoke from wood during cooking and which is thus at greatest risk of developing chronic airway disease. Therefore, we included estimates for women or the combined estimate adjusted for sex, if available. With two exceptions (Døssing et al. 1994; Gupta and Mathur 1997), all studies reported the data separately for men and women, or combined the data while adjusting for sex. The overall estimate of relative risk for all studies included was 2.9, 95% CI 2.2–3.8. For men, it was 2.8, 95% CI 1.4–5.7, but this was based on only two studies, one of which did not correct for age (Døssing et al. 1994; Qureshi 1994). See Table 18.15 for details.

All three case–control studies were hospital-based; control groups consisted of visitors to patients other than the study subjects (Døssing et al. 1994), patients with illnesses other than those of the respiratory tract (Dennis et al. 1996) and a mixture of visitors, patients diagnosed with tuberculosis or interstitial lung disease and patients with otolaryngological problems (Perez-Padilla et al. 1996). Bias could have been introduced by the choice of visitor controls if exposure to indoor smoke was related to the likelihood to come to the hospital to visit a patient, or by the selection of inpatient controls, if exposure to indoor smoke made the patients with the control diseases less or more likely to be referred to the hospital (e.g. tuberculosis).

Table 18.15 The risk of chronic obstructive pulmonary disease associated with use of solid fuels: subgroup analyses

	Subgroup analyses	*Studies included*	*Odds ratio (95% CI)*
Males and females	Rural population	Too few studies available to allow odds ratio to be calculated	NA
	Urban population	Too few studies available to allow odds ratio to be calculated	NA
	Adjusted for smoking	Albalak et al. (1999); Menezes et al. (1994); Pandey (1984a)	2.51 (1.76–3.56)
	Not adjusted for smoking	Qureshi (1994); Døssing et al. (1994); Gupta and Mathur (1997)	5.8 (3.74–8.99)
	Adjusted for age	Albalak et al. (1999); Døssing et al. (1994); Gupta and Mathur (1997); Menezes et al. (1994)	3.3 (2.32–4.69)
Females only	Adjusted for smoking but not for age	Behera et al. (1991); Pandey (1984a); Qureshi (1994)	2.56 (1.75–3.75)
	Adjusted for smoking and age	Dutt et al. (1996); Perez-Padilla et al. (1996); Dennis et al. (1996); Malik (1985)	2.83 (2.0–3.97)
Males only	Not adjusted	NA, too few studies—Døssing et al. (1994) adjusted for age; Qureshi (1994) adjusted for none	NA, see also text
	Adjusted for smoking and age	None of the studies in males adjusted for both age and smoking	NA

NA Not applicable.

The final model for women excluded the three studies that did not adjust for age and/or smoking status. The overall risk of COPD in women exposed to indoor air pollution from use of solid fuels was estimated as 3.2, 95% CI 2.3–4.8. There is much less evidence available about the impact on men, but the risk seems to be lower, 1.8, 95% CI 1.0–3.2,[8] presumably because of lower exposure.

Lung cancer

Lung cancer in women has been associated with cooking with open coal stoves in China on the basis of a number of studies. In China, there is also evidence that lung cancer is caused by use of certain cooking oils

(Zhong et al. 1999a, 1999b) as well as by exposures to known carcinogens contained in coal smoke, such as arsenic (Finkelman et al. 1999). There is limited evidence available for an association between lung cancer and use of biomass fuels in women, but not in men (Gao et al. 1987; Liu et al. 1993; Sobue 1990), although several pollutants in biomass smoke are known or suspected human carcinogens (Smith 1987).

The majority of the internationally published studies on lung cancer and indoor air pollution that we were able to locate were conducted in China. One took place in Japan (Sobue 1990) and one in the United States (Wu et al. 1985). Two eligible studies were published in Chinese only (Huang 1999; Wu et al. 1999). All 19 studies identified were case–control studies, including either newly-diagnosed cases of lung cancer at a hospital or using death registries, and of these, 14 studies were hospital-based. Inherent in the choice of this design is Berkson's bias, referring to the possibility that controls (men and women hospitalized with other diseases) are not selected independently of exposure in the source population. With two exceptions (Ko et al. 1997; Sobue 1990), all studies used population controls, which minimizes such bias (Table 18.16).

Characteristics of excluded studies

Of the 19 studies identified, we excluded three (Du et al. 1988; Xu et al. 1996b; Yang et al. 1990). The ecologic study by Yang et al. (1990) neither adjusted for smoking or other risk factors nor provided sufficient information to calculate odds ratios. Of two articles which reported on the same study population (Du et al. 1988, 1996), we included the more recent, which provided 95% CIs for the relative risk. More than one article reported on a collaborative study that included men and women of two major cities in the Province of Liaoning (Wu-Williams et al. 1990; Xu et al. 1996b); we included only the study by Wu-Williams et al. (1990), which combined all female lung cancer cases from the death registries of the two cities. The study by Xu et al. (1996b) considered cases in males and females from one city only.

Estimating risk factor–disease relationship

Although the 16 studies included in this analysis were all case–control designs, measurement of exposure to indoor air pollution was carried out by a multitude of methods. Seven studies assessed exposure to indoor air pollution in terms of years of exposure (Dai et al. 1996; Ko et al. 1997; Lei et al. 1996; Liu et al. 1991; Sobue 1990; Wu et al. 1999; Wu-Williams et al. 1990). The remaining eight studies merely determined whether coal and/or bio-fuel were generally used for cooking or heating (Du et al. 1996; Gao et al. 1987; Huang 1999; J. Liu and H. Hu, unpublished data, 1996; Liu et al. 1993; Shen et al. 1996; Wang et al. 1996; Wu et al. 1999). In order to explore the characteristics responsible for

Table 18.16 Studies on the risk of lung cancer associated with use of solid fuels

Study location	*Reference*	*Study design (n)* *Study population*	*Exposure assessment*	*Outcome assessment*^{a}	*Covariates adjusted for*	*Odds ratio (95% CI)*
China Fujian Province Fuzhou	Luo et al. (1996)	Case–control (102–306) Females+males	Indoor combustion of coal	Newly-diagnosed lung cancer	Smoking, passive smoking, chronic bronchitis and matched for age and sex	ADC: 6.0 (1.36–23.49) SCC: 14.1 (1.67–119.4)
China Gaunxi Province Nanning	Huang (1999)	Case–control (122–244) Females+males	Use of coal	Newly-diagnosed lung cancer	Smoking, chronic lung disease, meat consumption, depression, SES, BMI, exercise	1.76 (1.3–2.38)
China Guangzhou	Du and Ou (1990) *Excluded*	Case–control (662–662) Females+males	Exposed to coal fumes yes/no	Deaths from lung cancer over 5 years	Matched for age, sex, residence	14.52 (—)
China Guangzhou	Du et al. (1996)	Case–control (120–240) Non-smoking females+males	Exposed to coal fumes yes/no	Death from lung cancer	Smoking and chronic respiratory disease	Females: 1.56 (0.57–4.25) Males: 1.5 (0.69–3.27)
China Guangzhou	Lei et al. (1996)	Case–control (792–792) Females+males	Cooking for >40 years	Death from lung cancer	Matched for age and sex	0.93 (0.67–1.21)
China Guangzhou	Liu et al. (1993)	Case–control (316–316) Females+males	Use of coal and wood for cooking	Newly-diagnosed lung cancer	Smoking, passive smoking, education, SES, history of cancer	Coal: 1.46 (0.83–2.56) Bio-fuel: 1.19 (0.46–3.11)
China Guangzhou	Wu et al. (1999)	Case–control (258–258) Females	Use of coal as residential fuel	Newly-diagnosed lung cancer	Smoking, history of tuberculosis, fruit consumption, ventilation of kitchen	1.57 (0.89–2.82)

continued

Table 18.16 Studies on the risk of lung cancer associated with use of solid fuels (*continued*)

Study location	*Reference*	*Study design* (n) *Study population*	*Exposure assessment*	*Outcome assessment*[a]	*Covariates adjusted for*	*Odds ratio (95% CI)*
China Liaoning Province Harbin	Dai et al. (1996)	Case–control (120–120) Non-smokers, females	Use of coal heater for 25–34 years	Newly-diagnosed lung cancer	History of family cancer, income, carrot consumption, deep fried cooking	4.7 (1.28–17.18)
China Liaoning Province Harbin and Shenyang	Wu-Williams et al. (1990)	Case–control (956–952) Females	Use of coal stove for >40 years	Newly-diagnosed lung cancer	Age, education, smoking	1.3 (1–1.7)
China Liaoning Province Shenyang	Wang et al. (1996)	Case–control (135–135) Females	Use of coal for cooking	Newly-diagnosed lung cancer	Family history of cancer, ETS	0.75 (0.43–1.31)
China Liaoning Province Shenyang	Xu et al. (1996b) *Excluded*	Case–control (1249–1345) Females + males	Use of coal stove for cooking	Newly-diagnosed lung cancer from cancer registry	None	Females: 1.5 (—) Males: 2.3 (—)
China Shanghai	Gao et al. (1987)	Case–control (672–735) Females	Cooking with coal or bio-fuel	Newly-diagnosed lung cancer	Smoking, education, age	Coal: 0.9 (0.7–1.3) Bio-fuel: 1.0 (0.6–1.8)
China Beijing and Shunyi	J. Liu and H. Hu, unpublished data, 1996	Case–control (220–440) Females + males, farmers	Combustion of coal cakes	Death from lung cancer	Smoking, chronic respiratory disease and matched for age	1.9 (1.16–3.43)

China Hubei Province Wuhan	Yang et al. (1990) *Excluded*	Cross-sectional; ecologic design (50–200) Females+males, two parts of city	Use of coal for cooking	Death from lung cancer	None	—
China Jiangsu Province Nanjing	Shen et al. (1996)	Case–control (263–263) Females+males	Use of solid fuels	Newly-diagnosed lung cancer	Matched for age and sex and multivariate (final model not shown)	4.97 (0.8–30.88)
China Yunnan Province Xuanwei	Liu et al. (1991)	Case–control (110–426) Females+males, farmers	Starting to cook before 10 years of age	Newly-diagnosed lung cancer	Smoking and matched for age, sex, and village	Females: 1.25 (0.45–3.49) Males: 3.36 (1.27–8.88)
China Province of Taiwan	Ko et al. (1997)	Case–control (117–117) Females	Start cooking either coal or bio-fuel between 20–40 years of age	Newly-diagnosed lung cancer	Education, place of residence, SES	Coal: 1.3 (0.3–5.8) Bio-fuel: 2.7 (0.9–8.9)
Japan Osaka	Sobue (1990)	Case–control (144–731) Non-smoking females	Use of bio-fuel for cooking at 15 or 30 years of age	Newly-diagnosed lung cancer	Age, education	1.77 (1.08–2.91)
USA Los Angeles	Wu et al. (1985)	Case–control (220–220) Females+males	Use of coal for cooking and heating during childhood	Newly-diagnosed lung cancer	Smoking and matched for age and place of residence	ADC: 2.3 (1.0–5.5) SCC: 1.9 (0.5–6.5)

Key: ADC, adenocarcinoma; SCC, squamous cell carcinoma; Bio-fuel, wood, straw; BMI, body mass index; SES, socioeconomic status.

— No data.

[a] Studies that were included in the meta-analysis examined as primary outcome either cases of lung cancer (as defined by either clinical signs and symptoms, X-ray and/or histological and pathological findings) or death due to lung cancer.

heterogeneity found in the results of a meta-analysis of all studies, several subgroup analyses were conducted, in which stratification by type of fuel used (mostly coal and some wood) and sex was used. The variability of exposure categories was too great and the number of studies too small to be grouped for duration of exposure. If a study reported an estimate of relative risk for several exposure categories, the odds ratio for the category representing the longest period of exposure was used (Lei et al. 1996; Wu-Williams et al. 1990). Two studies (Luo et al. 1996; Wu et al. 1985) reported separate estimates for adenocarcinoma and squamous cell carcinoma; these were entered as separate studies as we were unable to achieve a combined estimate. Whenever possible, separate estimates for men and women were extracted and entered as individual studies (Du et al. 1996; Liu et al. 1991).

In a recent review of the literature on indoor air pollution and several health outcomes (Bruce et al. 2000), the most prominent concern voiced was regarding the lack of control for confounders. Therefore, we conducted stratified analyses based on studies that accounted for the most common potential confounders, such as smoking and the presence of a chronic respiratory disease. All studies included in the meta-analysis either adjusted for smoking or included only non-smokers. It has been suggested that chronic respiratory diseases such as chronic bronchitis, tuberculosis, asthma and emphysema that originate from infections or other predispositions may increase the probability of developing lung cancer later in life (Luo et al. 1996). We examined the effect of indoor air pollution from coal smoke on men and women separately. Nine studies either only included women or presented risk estimates for men and women separately (Dai et al. 1996; Du et al. 1996; Gao et al. 1987; Ko et al. 1997; Liu et al. 1991; Sobue 1990; Wang et al. 1996; Wu et al. 1985, 1999). The overall estimate for females was 1.17, 95% CI 1.02–1.35. The analysis restricted to studies that adjusted for smoking and chronic respiratory disease indicated a substantial increase in risk for women of almost two-fold (odds ratio of 1.94, 95% CI 1.09–3.47).

Five studies presented a combined risk estimate for men and women (Huang 1999; Lei et al. 1996; Liu et al. 1993; Luo et al. 1996; Shen et al. 1996), producing a summary odds ratio of 1.86 (95% CI 1.48–2.35). Restricting the analysis to the three studies that controlled for smoking and chronic respiratory disease showed a substantial increase in risk (odds ratio of 2.55, 95% CI 1.58–4.10).

Only three studies either included males only (Wu et al. 1999) or presented sufficient data to extract a separate estimate for males (Du et al. 1996; Liu et al. 1991). The risk associated with coal use for the male population was 1.79, 95% CI 1.18–2.72, and slightly lower when taking into account confounding by smoking and chronic airway disease (odds ratio of 1.51, 95% CI 0.97–2.46). Although the results of the two studies

Table 18.17 Summary of results of subgroup meta-analyses

	Odds ratio (95% CI)	
Subgroup analyses	*Not adjusted*	*Adjusted for smoking and chronic airway disease*
Males and females—coal use	1.86 (1.48–2.35)	2.55 (1.58–4.10)
Males only—coal use	1.79 (1.18–2.72)	1.51 (0.97–2.46
Females only—coal use	1.17 (1.02–1.35)	1.94 (1.09–3.47)

comprising this model were not quite statistically significant (lower confidence limit was 0.97), the pattern of significance of the five studies assessing risks for men and women combined, give confidence that there is likely to be a real effect on men. Odds ratios are shown in Table 18.17.

3.4 SOURCES OF UNCERTAINTY

Uncertainty estimates were generated through the use of meta-analyses for all the disease end-points included. A critical problem with extrapolating the results of epidemiological studies from one subregion to another, particularly between developed and developing regions, is the difference in other potentially interactive risk factors, such as malnutrition, which are not addressed by the methodology. That all the studies used for the calculations of solid-fuel use were done in developing countries, however, does provide some confidence that differences in competing risks were not excessive. Meta-analytical confidence intervals probably underestimate true uncertainty because of variations in the way different studies dealt with measures of exposure, adjustment for confounding, and outcome definitions, as well as the need to extrapolate results across populations.

3.5 RISK REVERSIBILITY

There are few studies on the reversibility of the health effects of smoke from solid fuel. For acute outcomes (ALRI), evidence from risk factors for other childhood infectious diseases may provide some guidance (Jones et al. 2003). For the chronic conditions, COPD and lung cancer, the timing is less clear, however, since the increased risk presumably results from many years of exposure. A retrospective cohort study in China, however, did find a statistically significant drop in lung cancer rates associated with introduction of improved stoves with flues in around 1980 (Lan et al. 2002). The delay between intervention and a discernible reduction in lung cancer incidence was about 10 years, consistent with that observed after smoking cessation (see chapter 11).

4. RESULTS

4.1 ATTRIBUTABLE BURDEN OF DISEASE

As shown in Table 18.18, the burden of disease attributed to use of household solid fuels is dominated by that caused by ALRI in young children, which accounts for 59% of all attributed premature deaths and 78% of DALYs. COPD accounts for nearly all the remainder, with the burden from lung cancer a relatively minor contributor, owing to the concentration of estimated use of coal in two subregions only. Because ALRI in children does not cause many years lost due to disability, however, COPD is responsible for a much larger portion of the total disability.

As shown in Table 18.18, five subregions account for nearly all deaths (94%) and DALYs (93%) attributable to indoor air pollution from solid fuel. The subregions with the largest numbers of DALYs, in descending order, are SEAR-D, WPR-B, AFR-E, AFR-D and EMR-D. When the subregions are ranked according to numbers of deaths, the relative positions of SEAR-D and WPR-B shift, because there are more deaths in SEAR-D in a younger age group (ALRI-related deaths in children) compared to WPR-B (mortality is dominated by COPD in adults).

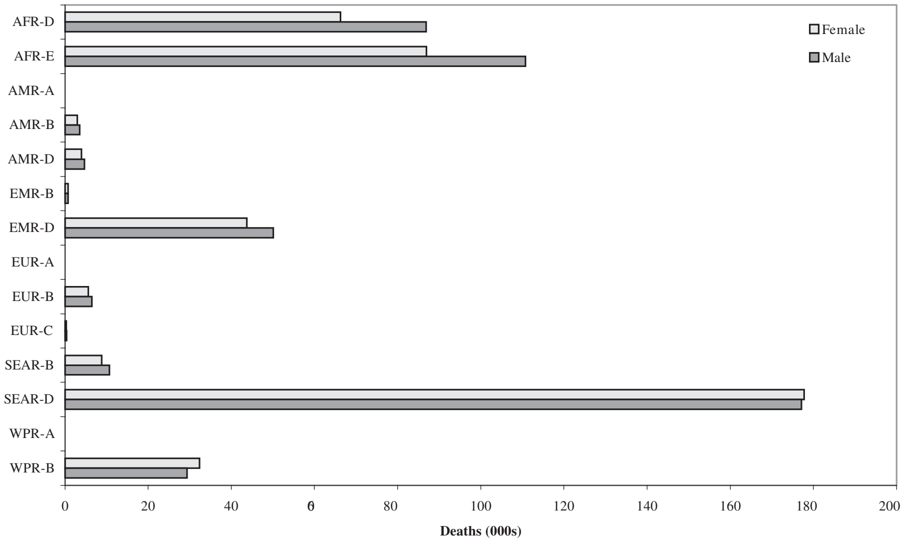
As shown in Figure 18.5, because of differences in baseline rates of disease, not exposure or risk from use of solid fuel, effects on mortality

Table 18.18 Burden of disease from use of solid fuel, 2000

	Deaths (000s)				*DALYs (000s)*			
Subregion	*ALRI*	*COPD*	*Lung cancer*	*All causes*	*ALRI*	*COPD*	*Lung cancer*	*All causes*
AFR-D	153	20	NA	173	5221	173	NA	5394
AFR-E	198	21	NA	219	6746	178	NA	6924
AMR-A	0	0	NA	1	1	6	NA	6
AMR-B	6	9	NA	16	291	153	NA	444
AMR-D	9	2	NA	10	314	16	NA	330
EMR-B	2	0	NA	2	59	5	NA	64
EMR-D	94	22	NA	116	3306	203	NA	3508
EUR-A	0	0	NA	0	0	0	NA	0
EUR-B	12	5	NA	17	417	60	NA	477
EUR-C	1	4	NA	4	22	44	NA	67
SEAR-B	19	17	NA	37	761	229	NA	990
SEAR-D	355	167	1	522	12506	1724	8	14237
WPR-A	0	0	NA	0	0	0	NA	0
WPR-B	62	426	15	503	2275	3662	160	6097
World	910	693	16	1619	31919	6453	168	38539

NA Not applicable.

Figure 18.5 Deaths from acute lower respiratory infection attributable to indoor smoke from use of solid fuels, 2000



attributable to ALRI are larger for males than females in AFR-D and AFR-E, similar in EMR-D and WPR-B, and greater for females in SEAR-D.

As shown in figure 18.6, the vast majority of attributable deaths from COPD and lung cancer appear to be experienced by the women of SEAR-D and WPR-B. This is partially because lung cancer deaths associated with solid fuel use were only estimated in these two subregions, due to lack of information on coal use in the other subregions. In addition, women appear to bear a higher proportion of the burden not only because they are likely to be more exposed, but because smoking attributable deaths (which are a higher proportion of male deaths) have been removed.

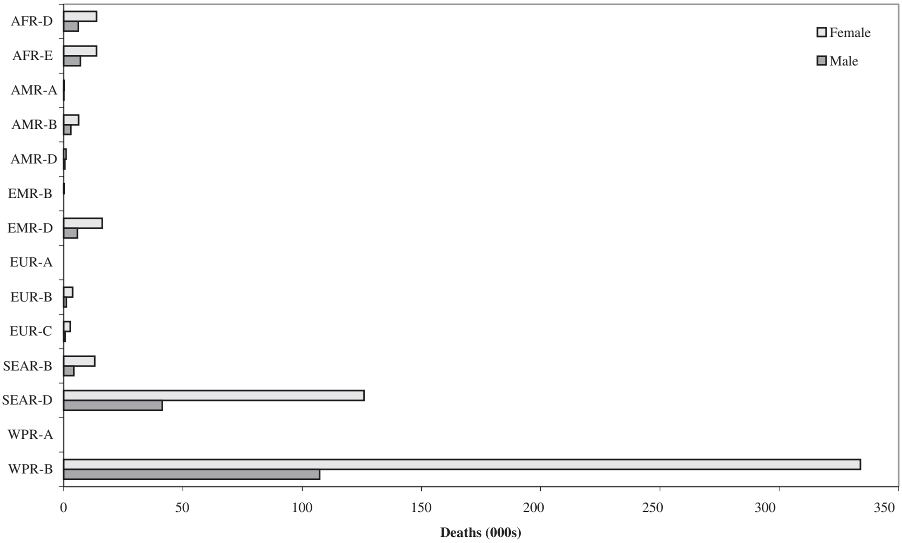
5. Discussion

5.1 Sources of uncertainty

Of a large number of sources of uncertainty, four major factors dominate these estimates.

- The choice of exposure variable, which, although necessary to match with current epidemiological studies, only roughly captures the population distribution of exposure and its variability in different populations.

Figure 18.6 Deaths from chronic obstructive pulmonary disease and lung cancer attributable to indoor smoke from use of solid fuels, 2000



- Distribution of the ventilation factor worldwide, i.e. what fractions of solid-fuel-using households do so in ways that vent some or all of the smoke outside and away from the householders.
- The different patterns of competing and confounding risks for ALRI in different circumstances, particularly those related to the severe forms affecting mortality.
- The relationship between the risks of indoor pollution and tobacco smoking, particularly for COPD and lung cancer in China where tobacco smoking is an important contributor (Liu et al. 1998).

5.2 Possible interventions

Although not included in the primary calculations here, as previously noted, there is growing evidence that other important health end-points can be attributed to exposure to indoor air pollution. Three of these, in particular, are of increasing concern worldwide: tuberculosis (because it is so closely related to the HIV epidemic); ischaemic heart disease (because of the shift in age and diet occurring in developing countries); and asthma (because of rising trends in diagnosed asthma in many parts of the world) (ISAAC 1998). There is some urgency that the associations of all potentially policy-sensitive risk factors (including use of solid household fuels) with these diseases be investigated.

There are four general categories of interventions that have been identified to reduce the health impacts of household use of solid fuel (Barnes et al. 1993; Ezzati and Kammen 2002; NCAER 2002; Smith and Desai 2002; Smith 1987, 1989).

- Behavioural changes to reduce exposure, for example, encouraging women to keep their young babies away from the fire.
- Changes in household ventilation, such as increasing the number of window openings in the kitchen, providing gaps between roof and wall, and moving the stove out of the living area.
- Improvements in stoves, either through venting by use of flues or hoods and/or improvements in stove combustion efficiency that reduce the emissions of toxic pollutants, nearly all of which are products of incomplete combustion.
- Shifts to higher-quality, low-emission liquid or gaseous fuels, such as kerosene and liquefied petroleum gas (which are based on petroleum) or biomass-based alcohol and biomass-based gaseous fuels derived either from biological processes (bio-gas) or thermochemical processing (producer gas).

Most research has focused on improvements in stoves and shifts to higher-quality, low-emission liquid or gaseous fuels; it seems that the efficacy of the interventions listed above generally increases as one moves down the list. The extent to which they can be successfully applied varies across different populations depending on income, housing, biomass availability, cultural factors and climate. It seems possible, however, that programmes can be designed to encourage many urban and peri-urban solid-fuel-using populations to move to using liquefied petroleum gas or kerosene, at lower incomes (i.e. sooner) than would occur without intervention. On the other hand, the poorest rural populations with nearly no cash income, but with access to wood and/or agricultural waste, are unlikely to move to clean fuels or use significantly improved stoves without large subsidies, which are usually not sustainable. There do seem to be large populations between these extremes, however, that can be targeted by efforts to introduce improved stoves. Although the fraction of improved-stove programmes that have succeeded is small, the total number of stoves successfully introduced is impressive because of the remarkable achievement of the Chinese programme, which has apparently been responsible for the introduction of nearly 200 million stoves since the early 1980s (Goldemberg et al. 2000; Smith 1993). More research and development work is needed, however, to learn how to successfully translate the lessons learned in China and elsewhere to other parts of the world in a sustainable cost-effective manner.

6. EXPOSURE PROJECTIONS

The use of solid fuel will probably slowly decrease in absolute, as well as relative, terms, as economic development proceeds. This shift is occurring most rapidly in China and Latin America, at interim rates in south Asia, and slowest or not at all in sub-Saharan Africa (World Resources Institute 2000). Cooking outdoors, on the other hand, is likely to decrease with development, but as the number of separate kitchens may increase, it is not clear how exposures will change overall. Current trends in vented stoves are less certain outside China. The Indian national stove programme, for example, had mixed success (NCAER 2002) and was dismantled in 2002 (Mahapatra 2003). In China, however, nearly 90% of the rural population seems to have adopted higher-efficiency vented stoves in recent years.

Table 18.19 Use of solid fuel and exposure to its smoke: estimates for 2000 and predictions for 2010

	Estimated fuel use[a]		*Estimated exposure of adults*[b]	
Subregion	*2000*	*2010*	*2000*	*2010*
AFR-D	73.4	69.0	55.1	52.0
AFR-E	85.8	83.0	64.3	62.0
AMR-A	1.5	1.0	1.1	1.0
AMR-B	24.6	20.0	18.4	15.0
AMR-D	52.9	52.0	39.7	39.0
EMR-B	6.1	5.0	4.6	4.0
EMR-D	55.2	50.0	41.4	37.0
EUR-A	0.2	0.2	0.0	0.0
EUR-B	41.5	35.0	20.5	19.0
EUR-C	22.8	21.0	6.4	6.0
SEAR-B	66.5	62.0	49.9	46.0
SEAR-D	83.5	77.0	62.6	58.0
WPR-A	0.2	0.0	0.1	0.0
WPR-B[c]	78.1	70.0	41.8	23.0

[a] These projections only address changes in biomass use, i.e. for India and China, rates of coal use are not predicted to decline in the same manner. Indeed, recent trends in China indicate that coal is being substituted by gas in urban households, but is substituting for biomass in many rural households (Fridley et al. 2001).

[b] Children's exposures differ from adult exposures at present in that they are modified by a different ventilation factor, since adults experience the health effects of exposures that took place before improvements in ventilation occurred. In the future, child and adult exposures will converge.

[c] We assumed that the Chinese improved-stove programme would reach 90% penetration for biomass but that rates of coal use would not decrease (Goldemberg et al. 2000). When estimating exposure, the ventilation factor for China was therefore fixed at 0.25 for both adults and children, making the exposures of these two groups the same.

Some insight can be gleaned about the potential for reduction in exposure by application of the model of solid-fuel use employed in this chapter. Estimates of income growth and shift of the population from rural to urban areas have different impacts on use of solid fuels in different subregions. Economic growth and urbanization over the next 10 years, for example, might substantially reduce the fraction of households that use solid fuel in the subregions that currently have the largest burdens. We examined changes that might occur over a 10-year period in two major model parameters: GNP per capita and rural–urban population shift (World Bank 2001). Estimates based on changes in income and urbanization beyond 2010 would be highly unstable, since current trends are unlikely to be sustained over several decades. Countries for which data are lacking are assigned the global average values for GNP per capita (equivalent to a 1.3% annual growth rate) and global rate of urbanization (rural population decreases from around 58% to 51% of the total population. Among many other assumptions, of course, such an extrapolation supposes that the structure of the model remains valid over this period. Table 18.19 shows how predicted changes in GNP per capita and urbanization affect predictions of future household use of solid fuel and of future exposure in each subregion. The net impact of shifts in these factors seems to indicate that, globally, exposure to indoor smoke from use of solid fuel is likely to decrease. There are subregional variations in the pattern, however, with continuing large exposures in sub-Saharan Africa and south-east Asia (Indian subcontinent).

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NOTES

1 Particulate matter, often abbreviated as PM, is categorized by size, specifically by aerodynamic diameter in microns (millionths of a meter or µm). For example, $PM_{2.5}$ refers to particulate matter with a diameter of less than 2.5 µm. In general, small particles are thought to be more damaging to health.

2 See preface for an explanation of this term.

3 Seven urban and three rural areas were omitted because of missing data or likely errors in the government statistical publications, which suggested improbable levels of energy consumption per household (i.e. in provincial households, average levels of consumption that were more than one standard deviation from the mean).

4 All analysis was done using SPSS Version 8.0 (SPSS Inc., USA) and STATA 7.0 (Stata Corporation, USA).

5 Cross-sectional studies report odds ratios rather than relative risks. These terms are used interchangeably in this chapter.

6 Two hospital-based case–control studies in India came to our attention too late for inclusion in the meta-analysis. In New Delhi, Broor et al. (2001) found an adjusted odds ratio of 2.5 (95% CI 1.5–4.2) for ALRI in children aged <5 years in homes not using liquefied petroleum gas. In Calcutta, Mahalanabis et al. (2002) found an adjusted odds ratio of 4.0 (95% CI 2.0–7.9) for pneumonia in children aged 2–35 months living in homes using solid fuels.

7 For further discussions, see reviews by Bruce et al. (2000), Chen et al. (1990) and Smith (1987).

8 For males, it did not seem appropriate to use the unadjusted estimate of risk, particularly when the adjusted estimates for both sexes were lower than either the unadjusted estimate for males only or the adjusted estimates for females only. Simple averaging of the risk chosen for males, 1.8, with the adjusted risk for females, 3.2, results in the combined mean risk of 2.5 observed when analyses included both sexes. The lower bound of the confidence interval was set at 1.0 (no effect) and the higher bound only at the unadjusted risk for males, 3.2.

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