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INDOOR AIR POLLUTION FROM HOUSEHOLD FUEL COMBUSTION IN CHINA: A REVIEW

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ABSTRACT

Nearly all China's rural residents and a shrinking fraction of urban residents use solid fuels (biomass and coal) for household cooking and heating. As a result, by use of global meta-analyses of epidemiological studies, it is estimated that indoor air pollution from solid fuel use in China is responsible for ~ 420,000 premature deaths annually, more than the ~300,000 attributed to urban outdoor air pollution in the country. To help elucidate more fully the extent of this hazard, we reviewed nearly 200 publications reporting health effects, emission characteristics, and/or indoor air concentrations associated with the use of solid fuels, mainly coals, in both rural and urban areas of China. Health effects include cancer (mainly lung cancer), chronic obstructive pulmonary diseases, respiratory illnesses, immune system weakening, and lung function reductions. Arsenic poisoning and fluorosis, resulting from coal combustion, have also been observed. Although attempts have been made in a few studies to identify specific coal smoke constituents responsible for specific adverse health effects, the majority of indoor air measurements include only particulate matter, carbon monoxide, sulfur dioxide, and/or oxides of nitrogen. Based on the measurements made in 122 individual studies, we summarize the distributions across residences from 29 provinces, showing indoor concentrations exceeding health-based standards in many of the measured households. Finally, we review various past and potential intervention options including the National Improved Stove Program and several emerging fuel technologies.

INDEX TERMS

Biomass fuels, coal, household stoves, cancer, respiratory disease, burden of disease

INTRODUCTION

More than 60% of China's population is still rural and nearly all the rural population still uses highly polluting biomass (e.g., wood, crop residue, animal dung) and coal fuels, which produce substantial pollution in simple stoves, to meet most of their household needs (NBS 2005a,b). In 2003, about 80% of the energy consumed by rural households was in the form of solid biomass, and nearly 10% as coal. Although most Chinese cities have plans to eliminate

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coal for households, there are still many urban communities all over the country – even in the wealthiest cities- that rely on coal. The combustion of biomass and coal (collectively called solid fuels) are the dominant source of indoor air pollution and may contribute significantly to total burden of the ill health. China has done more indoor air pollution studies on household combustion pollutants than any other developing countries; more than 100 studies by the early 1990s, for example, have been summarized in the World Health Organization (WHO) database (Sinton et al. 1996). As a result, the most recent WHO global analysis of the health effects of major risk factors found that indoor air pollution from solid fuel use in China is responsible for about 420,000 premature deaths annually, some 50% more than the 300,000 attributed to all urban outdoor air pollution in the country (WHO 2002, Cohen et al. 2004). As such it is the largest single environmental risk factor in all China for ill-health and second largest globally, after poor water/sanitation/hygiene. To help better understand why exposure to solid fuel smoke contribute so significantly to ill health, we conduct a critical review of indoor air pollution resulting from household solid fuel combustion. Specifically, we attempt to address the following questions: (1) What are the observed or suspected health effects of household solid fuel combustion? (2) What are the major constituents of the smoke released from solid fuel combustion? (3) What are the concentrations typically measured in various rooms (e.g., kitchen, bedroom, and living room) for several common pollutants? (4) What are the current and emerging technologies for reducing smoke exposures?

HEALTH EFFECTS

More than 100 peer-reviewed papers reporting health effects of household solid fuel combustion in China have been published in English- or Chinese-language journals. Almost all these papers, however, focus on the coal smoke health effects both in urban and rural populations. In contrast, the studies conducted in other developing countries have focused on biomass-using households. The relative large research effort on household coal smoke in China reflects the unique status of China as a "Coal Kingdom" where the use of household coal is widely spread throughout the country and that some of the coals contain toxic contaminants with unique health effects. Household biomass use, however, is more prevalent and, as in the rest of the developing world, undoubtedly affects health as well, even though few studies of health effects seem to have been done to date in China itself. [1]

Health effects of indoor coal combustion

Lung Cancer. Associations between lung cancer and coal smoke exposure have been found in numerous epidemiologic studies conducted in urban and rural households in China (Smith and Liu 1994, Smith et al. 2004, Smith and Tian 2005). Among these studies include the decades-long investigations in Xuanwei County, Yunnan Province, which has been the site of numerous studies of the relationship of coal smoke and lung cancer due to its unusually high lung cancer rates in non-smoking women exposed to emissions of so-called "*smoky*" (bituminous) coal when burned without venting (e.g., Mumford et al. 1987, Liu et al. 1991, Chapman et al. 1989). The odds ratios (ORs) for lung cancer due to indoor coal use, were summarized in a recent meta-analysis by Smith et al. (2004). For comparison, the ORs were estimated with and without adjusting two important confounding factors. Tobacco smoking status was either adjusted or analyses were done solely in non-smokers. Since chronic respiratory diseases, such as chronic bronchitis, tuberculosis, asthma, and emphysema, may

[1] Although not directly related to solid fuel combustion, cooking fume from "Chinese style cooking", usually ascribed to wok-frying with certain cooking oils (e.g., rape seed oil), has received attention due to some evidence showing its adverse health effects including lung cancer (Smith and Tian 2005) and immune system weakening (Zhang et al. 2001, Shen et al. 2004).

increase the probability of developing lung cancer later in life (Luo et al. 1996), adjustment was made for these diseases. This may result in underestimating the OR of lung cancer, as some previous lung diseases may be on the intermediate path from exposure to lung cancer – in this case, they are not confounders and should not be adjusted. The overall OR estimate for women was 1.17 with 95% confidence interval (95% CI) of 1.02–1.35. However, when the analysis was restricted to studies that adjusted for smoking and chronic respiratory disease, the estimated OR for women was substantially increased to 1.94 (95% CI: 1.09–3.47). The estimated OR for men was 1.79 (95% CI: 1.18–2.72), and slightly lower when taking into account confounding by smoking and chronic airway disease (OR=1.51 with 95% CI: 0.97–2.46). The combined overall risk estimate for men and women was expressed as an OR estimate of 1.86 (95% CI: 1.48–2.35), and a substantially increased OR of 2.55 (95% CI: 1.58–4.10) when adjusted for smoking and chronic respiratory disease.

The meta-analysis by Smith et al. (2004) presents strong epidemiologic evidence that exposure to indoor coal smoke significantly increases lung cancer risk. The role of certain genotypes and proteins in the development of lung cancer has been examined in the Xuanwei County residents exposed to "*smoky*" coal smoke, suggesting that individual's susceptibility to lung cancer may be increased by the GST1 null genotype (Mumford et al. 1999, Lan et al. 2000, 2001, Lan and He 2004). There is also limited evidence of other cancers from household coal smoke exposures, including esophageal (Pan et al. 1999) and cancers of the head and neck (Dietz et al. 1995). This may be due not only to direct respiration of airborne pollutants, but also to the contamination of food by coal smoke (Roth et al. 1998).

Respiratory illnesses. Indoor coal smoke exposure has been linked to various respiratory symptoms and diseases. A study conducted in Anhui Province shows that the prevalence rates of chest illness, cough, phlegm, and shortness of breath were significantly elevated from non-smoking women living in homes with both smokers and coal heating (Pope and Xu 1993). A survey of 10892 Xuanwei residents found that the ORs for "*smoky*" coal users, compared to "*smokeless*" (anthracite) coal users, were 1.73 for shortness of breath, 3.30 for cough, and 4.23 for phlegm, and that the ORs for "*smokeless*" coal users, compared to wood users, were 1.35 for cough and 1.67 for phlegm (Zhou et al. 1995). A recent study of 5051 seventh-grade students from 22 randomly selected schools in the greater metropolitan area of Wuhan, Hubei Province, found that coal burning for cooking and/or heating increased odds of wheezing with colds (OR = 1.57 with 95% CI: 1.07-2.29) and without colds (OR = 1.44, 95% CI: 1.05-1.97) (Salo et al 2004). In a population-based case-control study of childhood asthma, conducted in Shunyi County located in suburban Beijing, an increased risk was observed for use of coal for heating (OR =1.5, 95% CI: 1.1-1.9) and for use of coal for cooking without ventilation (OR = 2.3, 95% CI: 1.5-3.5) (Zheng et al. 2002). Indoor coal combustion was associated with increased incidence of rhinitis, faucitis, and tonsillitis in children (6-13 years old) living in Taiyan City, Shanxi Province (Cheng et al. 2002). The effects of household coal use were also observed in 624 infants and young children (1-3 years old) in Nantong, Jiangsu Province, as the prevalence of cough and that of pneumonia were significantly higher in coal-use households (Zhou et al. 1994).

Exposure-response relationships have been examined in a study of 7058 elementary school children living in the four Chinese cities of Chongqing, Guangzhou, Lanzhou, and Wuhan. When lifetime exposure to heating coal smoke was classified into four ordinal levels (no reported exposure, light exposure, moderate exposure, and heavy exposure, monotonic and positive exposure-response relationships were observed for ORs of phlegm, cough with phlegm, and bronchitis. In addition, although in a non-monotonic exposure-response pattern, ORs for cough, wheeze, and asthma were all higher in the exposed groups than in the non-exposed group (Qian et al. 2004).

Chronic obstructive pulmonary diseases (COPD), including chronic bronchitis and emphysema, is a major cause of ill heath in China, causing >1.3 million deaths annually (WHO, 2002). A case-control study conducted in Shanghai shows that indoor use of coal has stronger associations with COPD than estimated exposure to outdoor SO_2 and PM_{10} (Tao et al. 1992). A survey of 21648 rural residents in Anhui Province shows that the COPD rate was significantly higher in those who used coal for heating than in those who did not (Li et al. 2002). In Xuanwei County, COPD incidence rate was ~33% and ~72%, respectively, higher in female and male residents who had used unvented coal stoves than those who used vented coal stoves (Chapman et al. 2005).

Lung function impairment. The effects of coal smoke exposure on lung function have been investigated in a few studies of children or adults. In school children (10–13 years old) living in the cities of Chengde (Hebei Province) and Shanghai, measurements made in a winter show reduction in forced vital capacity (FVC), forced expiratory volume in one second (FEV1), or peak expiratory flow rate (PEFR), by 1.5% to 10.7%, associated with the use of coal for cooking and/or heating, with reference to the use of gas or liquefied petroleum gas (LPG) (Shen et a. 1992). In adults, evidence of coal smoke impairment of lung function has also been found in a few studies (Xu et al. 1991, Jin et al. 1995, Wang et al. 2004). In 1986 when domestic coal use was still prevalent in Beijing, 1440 of the city's adult residents (40-69 years old), who had never smoked, were measured for lung function in the study of Xu et al. (1991). This study found that heating with coal stoves was associated with a reduced FEV1 (-91 ± 36 ml) and FVC (-84 ± 41 ml), compared with radiator-based heating from steam or hot water supplied from a centralized facility (Xu et al. 1991). Simple and inexpensive PEFR measurement can be self conducted by subjects, making a study possible to measure a large number of people, such as the one conducted in 10892 adults (40-70 years old) living in 18 villages of Xuanwei County. This study of rural residents compared the relative importance of "*smoky*" coal, "*smokeless*" coal, and wood in affecting PEFR. The results show that the strongest risk factor for low PEFR was "*smoky*" coal, followed by "*smokeless*" coal, and then by wood. The study also found that use of coal stoves with chimneys was associated with increased PEFR compared to use of unvented coal stoves (Jin et al 1995). Women using coal for cooking were found to have lower FVC and several other lung function indices than those using gas for cooking, in a recent study conducted in Shanxi Province (Wang et al 2004).

Immunologic effects. Direct exposure to indoor coal smoke or coal smoke condensate has been tested for potential effects on the human immune system. A study of non-smoking women (55-65 years old) living in Shanghai found that those who had used coal for cooking had significantly lower serum IgG content, peripheral T lymphocyte activity, E-rosette formation rate, and IL-2 induction activity, than those had used gas for cooking (Wang et al. 1993). Similar findings were reported in another paper that additionally reported decreased activity of natural killer (NK) cells in women using coal for cooking (Mao et al. 1994). In the study of Mao et al. (1994), however, no significant association was found for IL-2 induction activity in T lymphocyte cells. A study of 624 infants and young children found that serum IgG content was significantly lower in those whose households used coal for cooking than those whose households used gas for cooking (Zhou et al. 1994). These findings suggest that exposure to indoor coal smoke weaken the human immune system, making those exposed individuals more susceptible for developing illnesses (Jin et al. 2002).

CO poisoning. There have been numerous reported acute carbon monoxide (CO) poisonings, including fatal cases, especially during heating seasons, resulting from indoor coal combustion under poor ventilation conditions. Health effects of chronic exposure to CO, at elevated concentrations but lower than levels of acute poisoning, have not been examined in China. High blood levels of CO adduct to hemoglobin (COHb) were measured in residents of coal-use households; and the contribution to COHb from indoor coal combustion was found to be larger than that from cigarette smoking (Zhang et al. 1996). CO is a known neurotoxin and there is a potential for chronic exposure to exert neurological effects. In addition, it has been associated with effects on pre-natal and early post-natal mortality and low growth in children of women exposed during pregnancy, presumably due to oxygen deprivation.

Endemic arsenism and fluorosis. In China, there are ~ 100 counties (out of ~2000) that have been deemed "endemic" because of the high levels of toxic elements in local coals (Sinton et al. 2004). The most noticeable coal-related endemics are *arsenism* resulting from chronic arsenic poisoning and flurosis resulting from chronic fluorine poisoning. Burning arsenic-contaminated coals occurs widely at least in 8 counties of 2 provinces (Guizhou and Shaanxi), affecting some 300,000 people (Jin et al. 2003, He et al. 2005). The primary source of arsenic exposure appears to be consumption of chili peppers and corn dried over fires of arsenic contaminated coal although direct airborne exposure occurs as well. Reported illness includes symptoms of arsenicosis (Shraim et al. 2003). It is known that arsenic exposure causes bladder, lung, and skin cancer in people ingesting drinking water contaminated with high levels of arsenic (Boffetta 2004). However, cancer has not been examined in the areas of chronic exposure to arsenic-containing coal smoke in China.

It is estimated that >10 million people in Guizhou Province and surrounding areas (e.g., the Three Gorges region and Jiangxi Province) suffer from dental and skeletal fluorosis (Finkelman et al. 1999, Cao 1991, Chen et al. 1993). The excess fluorine intake in affected people also results primarily from eating food dried over burning briquettes made from high-fluorine coals and high-fluorine clay binders (Yan 1990, Wu and Li 1990). In the fluorosis areas, almost all elementary and junior high school students (10-15 years old) had dental fluorosis; and osteosclerosis in the skeletal fluorosis patients was very serious (Watanabe et al. 1997, Ando et al. 1998, 2001). In addition to fluorine and arsenic poisoning, chronic selenium poisoning and possibly mercury poisoning have also been reported to result from domestic coal burning in affected areas (Finkelman et al. 1999, Hovat et al. 2003, Fang et al. 2004).

Health effects of indoor biomass combustion

Although few studies seem to have been published in China, there are dozens of studies in other parts of the developing world showing significant health effects from household use of biomass fuels (mainly wood and agricultural residues) in simple stoves. Because of the difficulty and expense of exposure assessment in households, however, most have used surrogates for exposure, often simply whether the households are using biomass fuels or not or other similar binary parameter such as whether a child is carried on the mother's back during cooking. Even with such an imprecise measure, however, health effects of several sorts have repeatedly been found (Smith 2000). The best evidence is for increased risk of COPD in adult women from years of cooking on unvented stoves and increased risk of acute lower respiratory infections (ALRI) in children under 5 years living in households with use of biomass fuels, particularly when the cultural practice involves high exposures to infants. Systematic reviews and meta-analyses of available published studies in developing-country households, done for the WHO's Comparative Risk Assessment (CRA) project (Ezzati et al. 2004), found an OR of 3.2 (95% CI: 2.3-4.8) for COPD in adult women and 2.3 (95% CI: 1.9-2.7) for ALRI in children under 5 (Smith et al. 2004). More recent publications not included in these meta-analyses have come to similar results (e.g., Ezzati and Kammen 2001, Smith 2003).

Although childhood episodes of ALRI may lower growth rates, increase the risk of diarrhea and other childhood diseases, and lead to chronic respiratory disease in adulthood, the main importance of ALRIis that it often progresses to pneumonia and death. Indeed, because it kills so many small children, ALRI causes the most lost life years of any disease in the world. It is difficult to study mortality in these field settings, however, and so the assumption has been that the increased risk of ALRI incidence found in research projects from biomass air pollution is reflected as well in increased mortality. More recent studies indicate that the past studies of solid fuel use and pneumonia in young children probably overestimated the risks due partly to confusion of upper and lower respiratory infections, the former not bringing a death risk but being quite difficult to distinguish in field research from dangerous lower respiratory infections. On the other hand, there is now growing evidence of health effects of other kinds from biomass smoke, including increased risks of tuberculosis, cataracts, lung and other cancers, low birth weight, and heart disease. Effects in men are also being seen. Thus, while the estimated impact on childhood pneumonia may decrease in future risk assessments, the impact of other diseases will probably be added (Smith et al. 2004, Bruce et al. 2000).

Burden of Disease from Indoor Air Pollution in China

Figure 1 shows the estimated burden of disease, measured as lost healthy life years, for the largest risk factors identified for China based on the WHO CRA project (Ezzati et al. 2004). The importance of indoor air pollution from solid fuel use is clearly shown, as it is the largest environmental risk factor (sixth among all risk factors) and accounts for about 50% more than the impact of outdoor air pollution in the country. The estimated total mortality attributable to indoor air pollution in China is about 420,000.

Although useful for showing the potential scale of the health impact of indoor air pollution in the country from solid fuel use, it is important to recognize that a number of additional assumptions were needed to make the calculations behind Figure 1 beyond those common to the entire risk assessment:

- That the scale of total impact in China is reasonably indicated solely by the COPD, ALRI, and lung cancer produced. Given that a range of other types of health effects have been found in China with coal and in other countries with biomass, however, this assumption probably results in an underestimate of total effect.
- That the biomass studies in other countries can be reasonably applied to China. This implies that the use of solid fuels produces similar exposures in different parts of the world. Given that housing, stove, and cultural patterns differ, however, this assumption may not be valid. For example, China has a larger fraction of chimneys in use compared to other developing countries, which probably reduces average exposures from biomass use. Although ventilation factors were applied to take this into account in the calculations, they may not be accurate.

- That the risks of ALRI and COPD from coal use are similar to those from biomass use. As the mixture of pollutants is different between coal emissions and biomass emissions, however, this may be incorrect.
- That the background disease burdens for China in the WHO databases are more accurate than the official Chinese statistics. In particular, official government statistics for childhood mortality from ALRI are much lower than found in the WHO databases. Use of Chinese statistics would substantially lower the burden on childhood mortality from indoor air pollution, but would make comparisons across countries difficult.

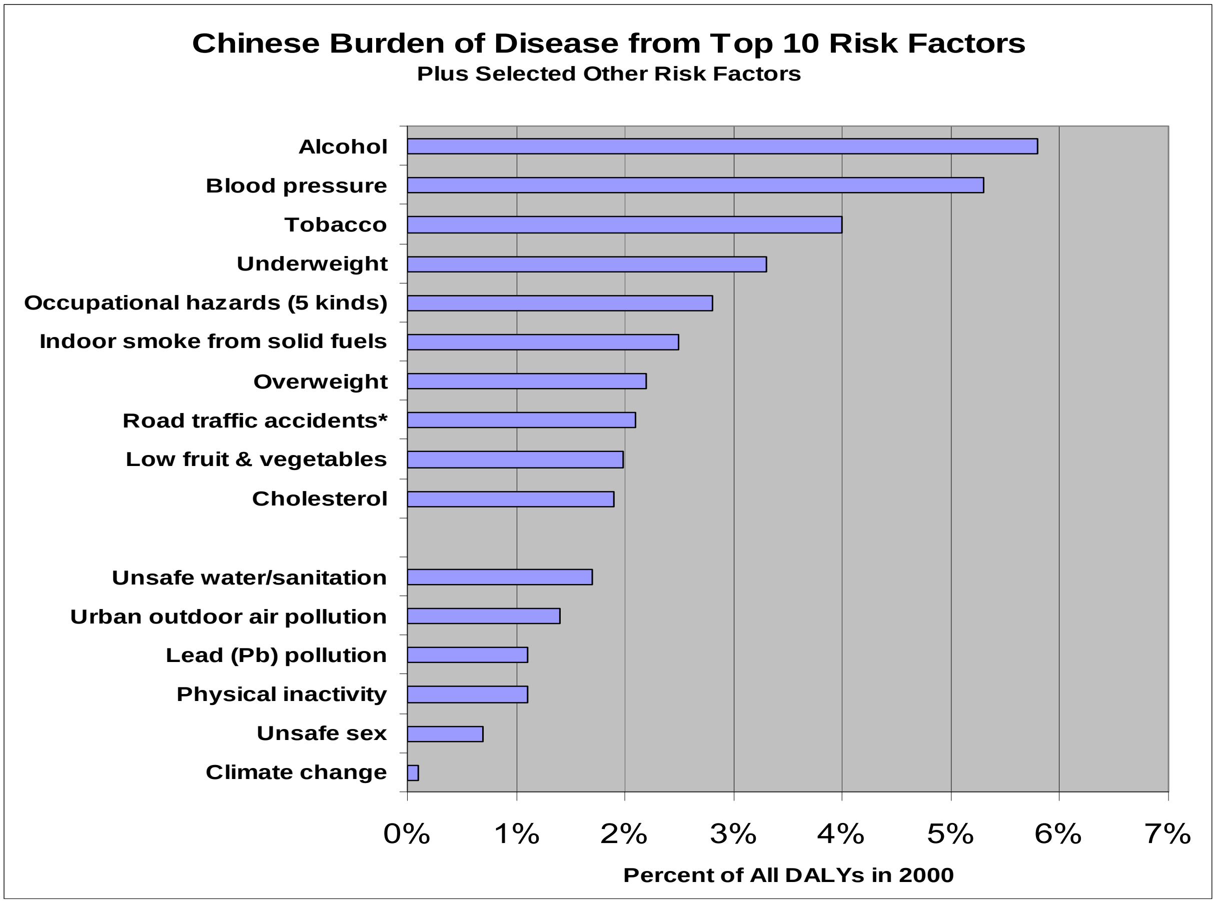

Figure 1. *Major cause of ill-health in China (adapted from WHO data in Smith et al. 2005)*

CONSTITUENTS OF BIOMASS AND COAL SMOKE

It is important to characterize the constituents of coal smoke and biomass smoke in order to understand the etiology of adverse health effects of household solid fuel combustion. Even if intrinsically free of contaminants, solid fuels are difficult to burn without substantial emissions of gaseous and particulate pollutants in small simple combustion devices such as household cooking and heating stoves due principally to the difficulty of completely pre-mixing the fuel and air during burning, which is easily done with liquid and gaseous fuels (Smith et al 2000). Consequently, a substantial fraction of the fuel carbon is converted to products of incomplete combustion (PICs), i.e., compounds other than the ultimate product of complete combustion, carbon dioxide (CO_2). For example, typical household coal and biomass cookstoves in China divert more than 10%, and up to 38%, of their fuel carbon into PICs (Zhang et al. 2000).

PICs released from solid fuel combustion are a complex mixture of particulate phase and gaseous phase chemical species. Some of the PICs are well known health-damaging pollutants, including commonly regulated air pollutants such as CO and particulate matter (PM). In studies characterizing PIC emissions from 28 fuel/stove combinations commonly found in China, more than 60 hydrocarbons and some 17 aldehydes and ketones were found at larger quantities in the flue gases of stoves burning solid fuels than in the flue gases of stoves burning liquid and gaseous fuels (Zhang et al, 2000, Zhang and Smith 1999, Tsai et al. 2003). The identified gas-phase hydrocarbons include carcinogenic compounds such as benzene, *1,3*-butidiene, and styrene. An analysis of cancer risk indicates that the estimated lifetime cancer risk of benzene or that of styrene from use of a biomass cookstove exceeded published risk estimates from all sources of airborne benzene or styrene (excluding active tobacco smoking) in the United States (Zhang and Smith 1996). The results also show that the tested biomass stoves generated formaldehyde emissions, when translated to indoor concentrations under typical village house conditions, which can cause acute health effects (e.g., eye and mucosal irritation) documented for formaldehyde exposure as well as cancer (Zhang and Smith 1999).

Polycyclic aromatic hydrocarbons (PAHs) are a well-known class of chemicals formed during incomplete combustion of all carbon-based fuels, including wood and coal. Lower molecular-weight PAHs (with 2 to 4 aromatic rings) are present predominantly in the gas phase while higher molecular-weight PAHs are present predominantly in the particle phase. Because carcinogenic PAHs, especially benzo[a]pyrene (B[a]P), a 5-ring PAH of high cancer potency, are predominantly present in the particle phase, particles emitted from household coal combustion have been subjected to compositional analysis of PAHs and PAH derivatives. These analyses shed light on the carcinogenicity and mutagenicity of coal smoke (e.g., Mumford et al. 1987, 1990, Chapman et al. 1989, Chuang et al. 1992, Chen 1994, He and Yang 1994). For example, carcinogenic PAHs, methylated PAHs, and nitrogen-containing heterocyclic aromatic compounds were found, in large abundance, in the particles emitted from bituminous coal combustion, as typically found in numerous households in Xuanwei County (Keohavong et al. 2003, Granville et al. 2003, Mumford et al. 1987, Chuang et al. 1992a). These PAHs and PAH derivatives found in the coal smoke exhibited strong mutagenicity; and the sub-fractions containing alkylated 3- and 4-ring PAHs were found to contribute to most of the mutagenicity in the PAH fraction of coal combustion particles (Chuang et al. 1992b). In the aromatic fraction, coal combustion particles appear to contain higher concentrations and more species of methylated PAHs than wood combustion particles (Chuang et al. 1992a, Chen 1994).

Unlike biomass, some coals contain intrinsic contaminants such as sulfur, arsenic, silica, fluorine, lead, mercury, etc. During combustion, these contaminants are not destroyed but released into the air in their original or oxidized form. For example, sulfur contained in the fuel is converted to mainly sulfur dioxide (SO_2) in the flue gas. In households that use sulfur-rich coals, SO_2 pollution affects not only indoor air quality, but also outdoor air quality at a local or regional scale. Since the temperature of coal combustion is normally substantially higher than that of biomass combustion, higher emissions of nitrogen dioxide (NO_2) or oxides of nitrogen ($NO_x = NO + NO_2$) were measured for household coal combustion than for biomass combustion (Zhang et al. 2000). Some carcinogenic substances in coal were found to be released into air during the combustion of lignites used in Shenyang City of northern China and "*smoky*" coals used in Xuanwei County. It has been reported that lignites from a local Shenyang coal field had the highest concentrations of nickel (Ni) (81 ppm) and chromium (Cr) (86 ppm) (Ren et al. 1999, 2004) in the world (ranges 0.5-50 ppm for Ni, and 0.5-60 ppm for Cr) (Swaine 1990). One of the sulfides of nickel, nickel subsulfide (Ni_3S_2), has the highest carcinogenic potency relative to other Ni compounds such as oxides and sulfates (Oller et al. 1997). Micro fibrous quartz (Si) has been found in some "*smoky*" coals and the resulting coal smoke in Xuanwei (Tian 2005). Particles emitted from burning coals contaminated with toxic elements in Guizhou Province and other areas contain high levels of the corresponding elements (Gu et al. 1990, Shraim et al. 2003, Yan 1990).

Although PM generated from the fuel combustion itself is fine and ultra-fine in size (well below a micron in diameter), the smoke may contain larger particles resulting from suspension of ash and solid fuel debris. Because combustion-generated particles and ash/debris particles have different chemical composition and because particle size determines how deep the particles can travel within and beyond the respiratory tract, determining size distribution is an important part of assessing health impacts. For this reason, there has been a switch from measuring total suspended particles (TSP) to measuring inhalable particles (<10 µm, referred to as PM_{10}) or respirable particles (<2.5 µm, referred to as $PM_{2.5}$) in more recent studies. Although it has been postulated that ultrafine particles (from a few nm to 0.1 um) may be able to cross the respiratory tract to enter the blood stream, exerting cardiovascular and systemic effects (Oberdörster et al. 2005), no health effects studies focusing on ultrafine particles have been done in China. One study did show, however, that indoor coal use was an independent risk factor for stroke in 957 male Shanghai residents (Zhang et al. 1988). Such research would be important, because the vast majority of fresh particles from both biomass and coal combustion fall into the ultrafine size range.

INDOOR CONCENTRATIONS

Indoor concentrations of PICs and other contaminants emitted from solid fuel combustion depend on indoor emission rate, air exchange rate, and room volume. Indoor emission rate can be largely reduced if there is a well-functioning flue to vent smoke outdoors, but flues are absent or poorly maintained in many households using biomass or coal for cooking in China. In open-fire Xuanwei households, for example, mean indoor concentrations of PM_{10} and dichloromethane extractable organics were 24.4 mg/m^3 and 17.6 mg/m^3 during burning of "*smoky*" coal, 22.3 mg/m^3 and 12.3 mg/m^3 during burning wood, and 1.8 mg/m^3 and 0.5 mg/m^3 during burning "*smokeless*" coal, respectively (Mumford et al. 1987). Although open fire pits do not make up a large fraction of cook fires today in China as a whole, there are still tens of millions of people exposed to them. Small portable unvented coal stoves, however, are quite common throughout much of the country. It is difficult to generalize about them since emissions depend on local coal quality, but such stoves have been found to produce indoor 24-h levels of several hundred µg/m^3 of fine particles (Edwards et al. 2005). Even where vented outdoors, "neighborhood" pollution levels of smoke can sometimes be significant because of the large emission rates, particularly on winter days of poor atmospheric dispersion (Smith et al. 1994). The neighborhood pollution elevates both outdoor and indoor background concentrations. As a result, studies have shown that even solid-fuel stoves with well-working flues do not lower indoor concentrations sufficiently to meet Chinese indoor air quality (IAQ) standards in most rural households (Edwards et al. 2005).

Systematic and probability-weighted sampling of household indoor pollution levels from solid fuel combustion has not been done in China. However, we have found some 120 studies,[2]

[2] Including 112 studies summarized in a 1996 database (Sinton et al. 1996) and 10 separate studies since 1995.

published in either English- or Chinese- language journals, in which indoor concentrations of one or more PICs and other pollutants were measured in one or more locations within a household. These studies have impressively covered rural and/or urban households of 29 provinces plus municipalities of Beijing, Shanghai, Tianjin, and Chongqing. Most of these studies concerned coal combustion. In Figure 2, we summarize indoor concentrations of 6 commonly measured pollutants by rural vs. urban, by fuel type, and by indoor locations (kitchen, bedroom, living room, and unspecified indoor location). A significant fraction of the urban households measured in the published studies used both coal and gas fuels (LPG, coal gas, or natural gas). In this case, we designate fuel type as Coal&Mixed. In addition to the median, percentiles, and outliers that a standard box plot presents, number of data points, mean, and standard deviation are also presented in Figure 2. It is important to note that no standardized protocol was used in the studies summarized here. For example, air sampling methods used in different studies were not standardized; sampling duration ranged from minutes in some studies using grab sampling methods to 24 hours in a few studies of daily exposure; most of the studies did not provide information on when and how long the air samples were taken. It is, therefore, difficult for us to define peak concentrations and time-averaged concentrations using the dataset gathered from the ~120 studies. The concentrations shown in Figure 2 are simply the data available in the publications with some ambiguous ones excluded (e.g., predicted concentration data not supported with any measurements). Although these data are not derived from population-based studies using systematic approaches and, hence, are not necessarily representative, the information summarized in Figure 2 may be useful in assessing inter-household variability that can aid designing intervention studies of proper statistical power. Indoor concentration ranges shown in Figure 2 should give what concentrations can be expected for typical Chinese households using biomass or coal stoves.

Figure 2 (a, c, e, g, i, k) shows that biomass fuels were only used in the rural households and that fewer measurements were made in the biomass fuel households, making comparisons between biomass and coal households difficult. Indoor TSP concentrations were > 200 $\mu g/m^3$, and indoor PM_{10} concentrations were >100 $\mu g/m^3$ in any indoor locations of more than 50% of all the measured rural households. This is consistent with the findings, from recent rural monitoring studies in several Chinese provinces, that coal and biomass stoves produced PM_{10} levels well in excess of the new Chinese IAQ standard of 150 $\mu g/m^3$ (Sinton et al. 2004, He et al. 2005). Based on the non-systematic data, we do not see higher concentrations in kitchen than in other indoor locations in rural households. Consistently across the measured urban households, however, PM_{10} (TSP sometimes) and SO_2 had highest concentrations in kitchen (see Figure 2 b, d, j). This “kitchen effect” was, however, less profound and consistent for NO_x, CO, and B[a]P, perhaps due to the confounding from coal heating stoves and tobacco smoking. Presumably, coal combustion for heating occurs at more steady burning conditions than coal combustion for cooking. It is known that highest emissions of particles occur during unsteady combustion stages such as the beginning and end of the fire (Smith 1987). Results from individual studies comparing concentrations in various indoor locations, however, often show highest peak concentrations in kitchens (Qin et al. 1991, He et al. 2005).

The published concentrations data indicate that indoor CO levels were up to 560 mg/m^3 and were >10 mg/m^3 (IAQ standard for CO) in 35% of the measured households. High indoor SO_2 concentrations, up to 23,000 $\mu g/m^3$, were measured in coal and Coal&Mixed households, of which ~50% had indoor SO_2 concentrations > 500 $\mu g/m^3$ (IAQ standard for SO_2). Household biomass combustion generates lower NO_x and NO_2 emissions than fossil fuel combustion (Zhang et al. 2000); and, thus, higher NO_2 concentrations were measured in coal and gas households than biomass households. The published data on NO_2 measurements (excluding NOx measurements) show that about 30% of the coal and gas households had NO_2 levels exceeding the NO_2 IAQ standard (240μg/m^3). A study comparing households using coal stoves and those using LPG stoves found 24-h NO_2 indoor concentrations significantly higher in the coal-using households (Zhang et al. 1996). This is not surprising because typically coal burning takes much longer than LPG or other gas burning for cooking. China has also established IAQ standard for B[a]P at 1.0 ng/m^3, which was exceeded in nearly all the coal and biomass using households.

Few of the measured urban households used solely coal and thus they were excluded from the current analysis. The lack of more detailed information (e.g., frequency of coal use vs. gas use) prohibits us from constructing more accurate category than a simple "Coal&Mixed". Even so, indoor concentrations of TSP, PM_{10}, CO, and SO_2 were higher in the vast majority of the urban Coal&Mixed households than in the urban gas households.

INTERVENTIONS

The infamous smog episode killing thousands of people in the winter of 1952 eventually led to the ban of domestic use of coal fireplaces in London, UK. Today, in UK and other developed countries, domestic use of coal in cities is almost non-existent. With the rapid economic growth in China, coal stoves are becoming less common in cities, as they are being replaced with gas stoves and with space heating methods other than direct coal combustion (e.g., centralized steam heating, electric heating). Despite the declining trend, household coal use is still common in urban communities across China. There have also been proposals by national and international agencies to promote household coal use, often in the form of "clean coal," as a way to use domestic fossil energy supplies and/or relieve the pressure on biomass resources. In rural areas of China, coal use seems to be increasing, as coal substitutes for biomass that, nevertheless, still currently dominates. Although gas stoves are increasing in cities and among affluent rural households, widespread use of gas fuels in rural households is unlikely to occur in foreseeable future due to cost and unreliable supplies of gas fuels. Hence, interventions to make solid fuel combustion less polluting still have high public health priority.

Fuel/stove intervention

Since the amount of PICs and other pollutants released to the indoor air depends on both fuel quality and stove design, interventions can be done on improving fuel quality, improving stove design, or both. In China, stove interventions appear to have predominantly occurred in rural biomass-burning households and fuel interventions appear to have mainly focused on coal.

On a global scale, the most impressive organized intervention of rural household stove in human history is perhaps the China's National Improved Stove Program (NISP), through which China has done more than any other developing countries to improve household energy use by introducing more than 180 million improved stoves starting in the early 1980s. Although focusing on improving fuel efficiency, all introduced stoves had chimneys and some had manual or electric blowers to promote more efficient combustion. Unfortunately, the program ended in the mid-1990s and now there is relatively little action to further improve the rural situation. A major independent review of NISP, including a 3500-household survey in 3 provinces at different levels of coverage, basically found that NISP improved IAQ and health in rural households, but not sufficiently to meet the Chinese IAQ standards. In addition, because it focused mainly on biomass, the rising coal use in rural areas, often in stoves without chimneys, is threatening to erode the benefits unless action is taken soon. Although the Chinese Ministry of Health has embarked on a program to introduce improved coal stoves to those ~100 endemic arsenism and fluorosis counties, progress has been slow due to lack of resources (Sinton et al. 2004). Eliminating household use of these contaminated fuels, appropriately termed “poisonous coals” needs to be the focus of greater immediate attention in the country. See Appendix 1 (International Workshop 2005).

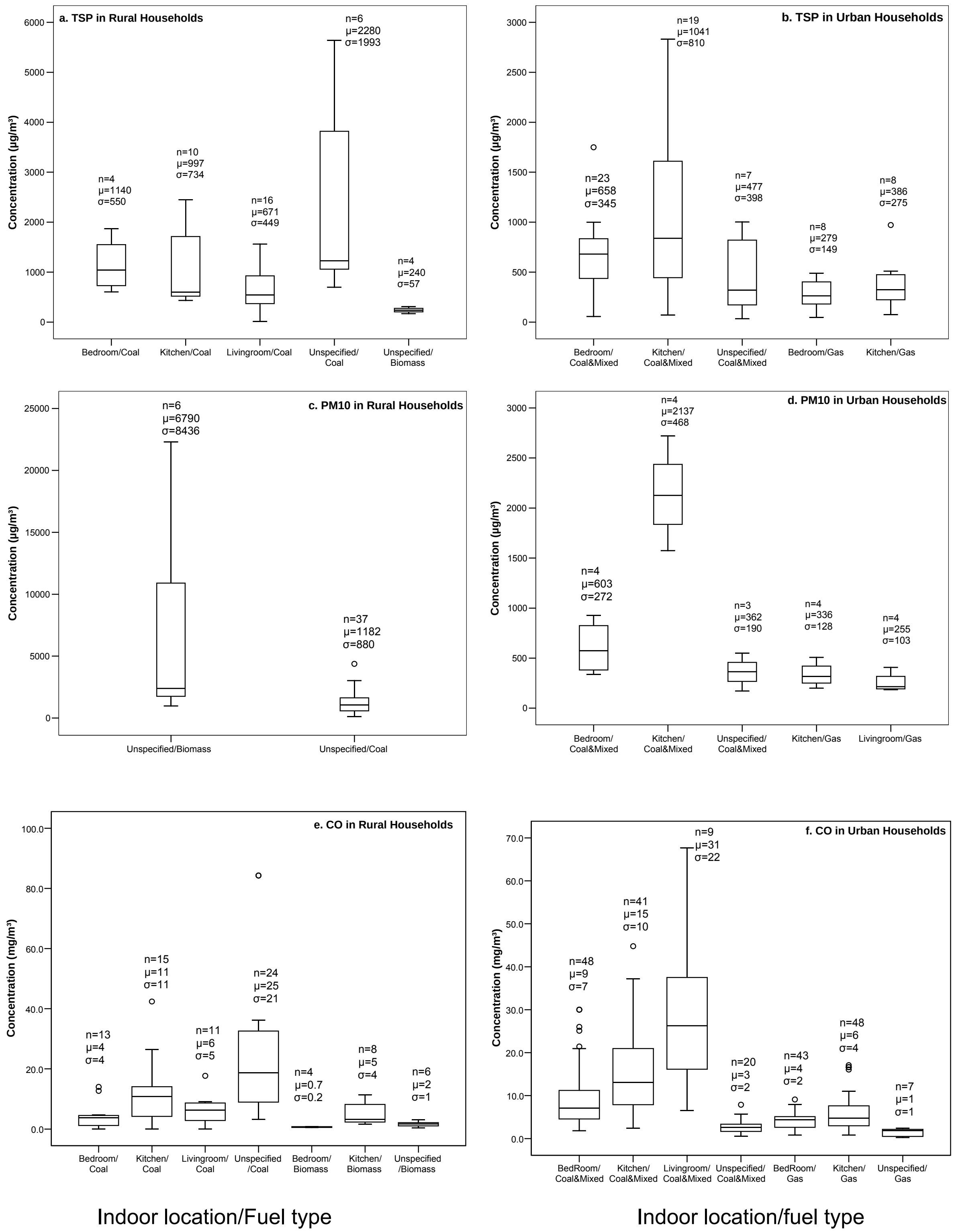

***Figure 2**. Concentrations of pollutants measured in solid-fuel-use households, extremely high values may not be shown so that the plot scales are more appropriate for the vast majority of the data points.*

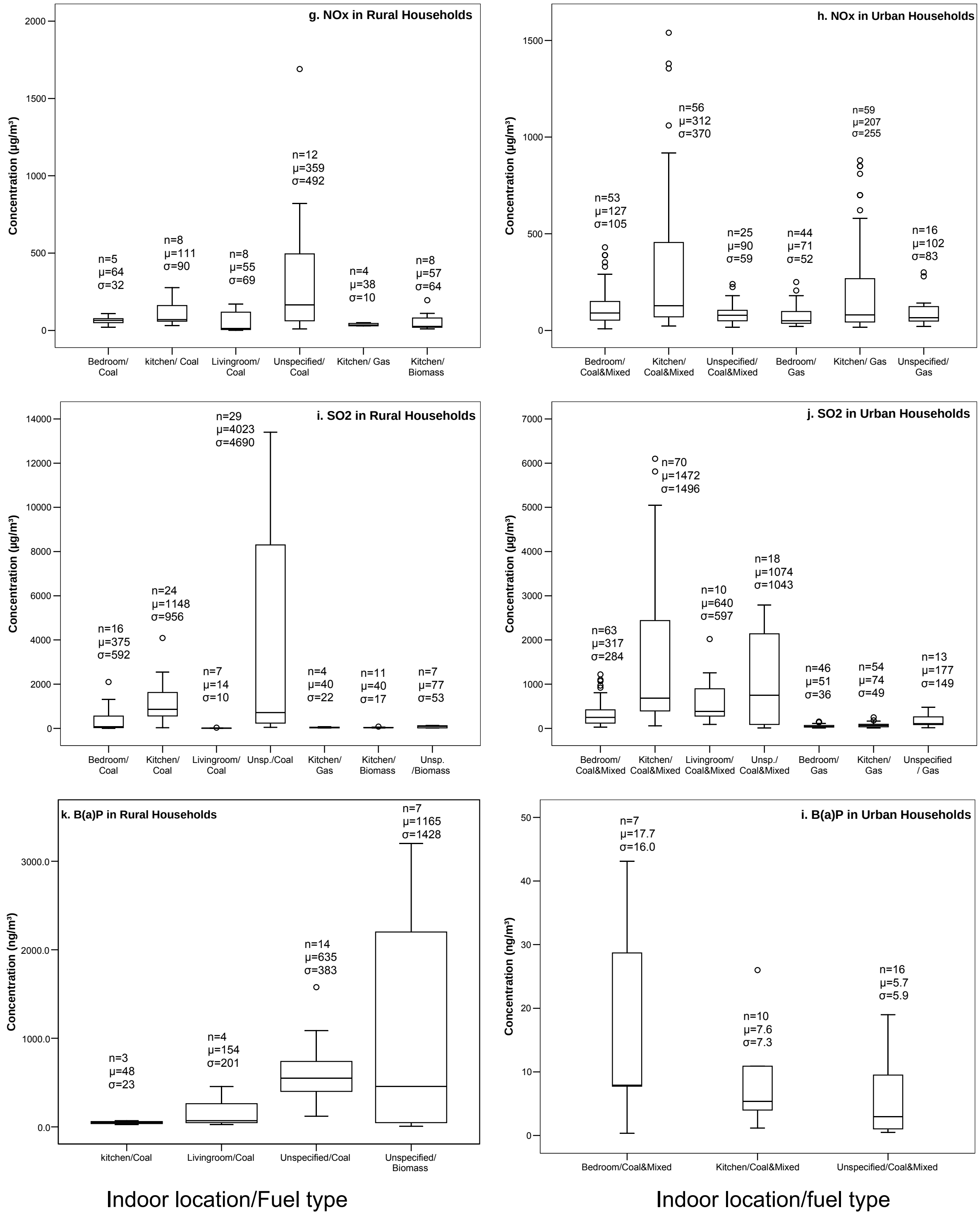

Figure 2 (Cont). *Concentrations of pollutants measured in solid-fuel-use households, extremely high values may not be shown so that the plot scales are more appropriate for the vast majority of the data points.*

Efforts have also been made in China to improve fuel quality and developing formulated coals to reduce hazardous emissions. The most noticeable fuel intervention is the formulation of so-called honeycomb coals that have been widely used in numerous urban and rural households across China for decades. The principal feature of the honeycomb coal is that the shape of the coal allows for more efficient and evener air supply, consequently leading to higher combustion efficiency. Coal dust suspension is also substantially reduced during the transportation and combustion of the honeycomb coal, compared to the situation for directly transporting and burning raw coal powders. Some honeycomb coals are specially formulated to further reduce toxic emissions. For example, a patented honeycomb coal formulation consists of pulverized coal mixed with hydrate lime (15%), a combustion-promoting agent (0.5%), a waterproofing agent (0.03%), and a binding agent (11.5%). The addition of hydrate lime, $Ca(OH)_2$, is to react with sulfur and retain the product of reaction, $CaSO_4$, into ash and slag, instead of releasing into the flue gas as SO_2 and sulfate particles (Ge et al. 2004). Because of different coals, different formulations, and different measurement methods, it is difficult to generalize about the impact of such coal fuels (Yao et al. 1983, 1992, Bond et al. 2003, Perlack and Russel 2001, Kasper et al. 1999).

China is now promulgating "clean" forms of coal for urban use, but their sustainability is uncertain. In addition, few of these "clean" coal fuels are required to undergo standard emissions testing and there is even less regulation of what is actually sold in the market place. In rural China, little attention is placed on clean coals and coal used in household also varies dramatically across the country according to the character of local coal deposits (mines). In developing clean coal strategies, it is useful to consider some historical lessons from other parts of the world. Before moving to the stage of actually banning coal in cities, the UK and other former household-coal-using countries, developed and deployed a range of "clean coals" for small-scale use. This might have helped lessening the pollution problem in the short term but, eventually, it was realized that in simple household combustion, even these processed forms of coal or cleaner natural forms, such as anthracite, could not be burned clean enough to use in urban areas and still meet health-based pollution standards.

Emerging technologies

In rural China, there are potentials for modernization of its rich bio-energy resources. The generation rate for crop residues (e.g., corn stover, rice straw, and wheat straw) in the field plus agricultural processing residues (e.g., rice husks, corn cobs, and bagasse) amounts to about 790 million metric tonnes (Mt) per year (Gu and Duan 1998), or about 10 EJ. For comparison, total coal use in China was 39 EJ in 2004. It has been estimated that about half of the total crop residues might be available for energy after accounting for other uses (e.g., fodder, fertilizer, and industrial feedstock) (JPERA 1998). In fact, nearly half (333 Mt in 2003) are already being used for cooking and heating houses through direct and poor combustion in simple cooking stoves and heating devices (e.g., *kang*, heated bed), producing high emissions of PICs (NBS 2005b).

One approach for more healthful and efficient use of these resources is to promote "gasifier" stoves that achieve high combustion efficiency through designs that promote secondary combustion. Reliably high combustion efficiency is easier to accomplish with small electric blowers, but some models attempt to do so with natural draft. Another approach to achieve high-efficiency (low emission) biomass combustion is through fuel pelleting, although this requires the development of fuel processing industries. A national competition is being held in 2005-2006 by the Chinese Association of Rural Energy Industries funded by the Shell Foundation to promote the development and dissemination of such low-emission biomass stoves and fuel cycles.

Recently new pollution problems are arising from crop residues, because in better off parts of the country, farmers are becoming less willing to gather biomass residues from the field and store them for cooking and heating use throughout the year. Households prefer coal briquettes or LPG instead if they can afford them. This shift to modern fuels creates an excess of crop residue supplies that is problematic. The residues dry out quickly in the field and thus decay so slowly that if kept on the field, they are not easily absorbed in the soils; the build-up of residues creates insect infestation problems. To prevent insect infestation, the excess crop residues are increasingly burned off in the fields, creating additional air pollution problems.[3] One strategy proposed by the government of Jilin Province to deal with these challenges related to crop residue use and waste disposal aims initially at widespread introduction of village-scale corn-stalk gasifier, with distribution of the gas to individual households for use in cooking and heating. It also includes a bio-energy modernization project supported by United Nation's Development Program (UDDP) and other agencies, which intends to demonstrate combined heat, electricity, and cooking fuel production (tri-generation) from corn stalks. A demonstration project conducted in villages of Jilin shows the tri-generation technology is reliable. Its widespread use, however, is limited by lack of commercial viability and potential risks due to acute CO poisoning (UNDP et al. 2004).

Simple bio-digestors have long been available for converting animal waste into biogas containing methane, but these are limited to areas with sufficient dung, water, temperatures, and financial capital. Where these conditions are met, extremely clean combustion is possible (Smith et al. 2000). More recently, advanced technologies are being explored for converting crop residues into dimethyl ether (DME), a non-toxic fuel with characteristics similar to LPG (Larson and Yang 2004). The bio-briquette technology also appeared recently, by which "bio-briquettes" are made of biomass, coal, and sulfur fixation agents, through high pressure manufacturing processes. Such a fuel has shown its ash's acid-neutralizing capacity but may have a potential for reduction in SO_2 and other toxic emissions (Dong et al. 2004).

Coal conversion technologies have been always of interest in China. Coal gas has been widely used for decades in China. However, conventional coal-gas production is very polluting. Finding ways to convert coal to DME has been attractive to researchers and the Chinese government (Han et al. 2004); and the first Chinese commercial plant for DME fuel production from coal was built in 1995. The operation of this plant and other research results indicate that the established technologies can be successfully implemented in terms of technology, but not at present at competitive costs (Han et al. 2004, Larson and Yang 2004). With further cost reduction in DME production technologies and anticipated increase in LPG cost, converting coal to DME for household use may become more market competitive in the future (Larson and Yang 2004).

Benefits of fuel/stove interventions

In large Chinese cities, policies of banning household coal use have been in place with a main aim at reducing outdoor air pollution, but with the side benefit of reducing indoor pollution levels. Although health benefits from eliminating coal stoves have not been directly reported or measured in Chinese cities, the findings from elsewhere, e.g., Ireland's Dublin that enacted a city-wide ban on coal sales on September 1, 1990, indicate that such an intervention can generate sudden decreases in atmospheric concentrations of PM and SO_2 as well as a significant reduction in cardiovascular and respiratory death rates apparently from the reduction in total exposure produced (Clancy et al. 2002). However, the health benefits brought from eliminating coal stoves in urban Chinese households may be compromised by

[3] The smoke during a few reported episodes of in-field crop residue burning was so severe that nearby airports had to be closed for an extended period.

other IAQ problems in addition to some lifestyle changes. When solid fuels were used, households cannot afford to have low ventilation rates, otherwise acute poisoning would occur. Using cleaner gas stoves under low ventilation rate, which is the case for many urban residences, can lead to higher concentrations of NO_2. Some studies conducted in Western countries suggest that children's respiratory symptoms and lung function impairment were associated with indoor NO_2 exposure or the use of gas stoves (Speizer et al. 1980, Garrett et al. 1998). (Indoor air pollution has been long recognized worldwide from non-combustion sources, e.g., synthetic chemicals from building materials, in poorly vented buildings.) It is, therefore, important to balance the trade-offs between energy conservation benefits and ventilation rate reduction brought by making houses/buildings more airtight.

Fuel/stove interventions often produce measurable reductions in indoor concentrations (Sinton et al. 2004). This improvement of indoor air quality can be directly translated to health benefits, as clearly demonstrated in a retrospective examination of a natural experiment, which documented the reduction of lung cancer and COPD attributable to the introduction of improved stoves with flues in Xuanwei County. The estimated risk ratios (RRs) for lung cancer due to the stove intervention were 0.59 (95% CI: 0.49–0.71) for men and 0.54 (95% CI: 0.44-0.65) for women after 10 years of use of improved stoves (Lan et al. 2002). The stove improvement was also associated with distinct reduction in COPD: the estimated RRs of the stove improvement were 0.58 (95% CI: 0.49-0.70) in men and 0.75 (95% CI: 0.62-0.92) in women (Chapmen et al. 2005). The study further demonstrates that the RRs for COPD incidence decreased as time since stove improvement increased and that in both men and women, COPD risk reduction became unequivocal about 10 years after stove improvement (Chapman et al. 2005). Household indoor pollution levels were apparently reduced by a factor of ~3 due to the stove intervention (Lan et al. 2002). However, systematically designed studies to assess the magnitude of health benefits brought by fuel/stove interventions have not yet been done in China.

Reducing pollutant emissions through fuel/stove intervention can also bring indirect benefits. One obvious benefit is improved local air quality and improved atmospheric visibility. Another benefit is the reduction in greenhouse gas emissions. For example, biomass smoke contains PICs that are direct greenhouse gases (e.g., methane, and nitrous oxide) or indirect greenhouse pollutants (e.g., CO, black carbon particles, and hydrocarbons) (Zhang et al. 2000, Smith et al. 2000). These pollutants contribute to global warming because of their higher radiative forcing than CO_2 or their indirect greenhouse effects (IPCC 1995), even under renewable biomass harvesting. Given that over 2 billion people use biomass today in ways that generate high emissions of PICs, the contributions of "renewable" biomass to greenhouse gas concentrations in the atmosphere are probably not inconsequential (Smith et al. 2000).

CONCLUSIONS AND IMPLICATIONS

Combustion of solid fuels occurs in numerous households in China, leading to pollutant levels often exceeding the China IAQ standards, and contributing significantly to the national and global burden of ill health. Evidence for certain adverse health outcomes resulting from indoor exposure to coal and biomass smoke is strong, including lung cancer, respiratory symptoms and diseases, acute respiratory infection, and COPD. There is some evidence for impacts on lung function and immune system impairment. Therefore, improving indoor air quality in numerous solid-fuel-use households throughout China should be an urgent and priority task in China's public health agenda. A range of intervention technologies, from as simple as adding a chimney to modernized bio-energy program, are available; but they can only be viable with coordinated support from the government and interested private parties in the commercial sector. Substituting cleaner fuels for the poisonous coals still used as household fuels in millions of households should have an especially high priority. This was one of the principal recommendations from a Chinese and international scientific and policy workshop convened in early 2005 to review the status of improved stoves in China. The full set of recommendations is found in Appendix 1.

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Appendix 1.

Consensus Reached by Participants at the International Workshop on Rural Energy, Stoves, and Indoor Air Quality in China

Beijing, January 17, 2005

This workshop brought together representatives and experts from universities, research institutes, non-government organizations, provincial and national government agencies, rural energy industries, and international organizations from China, South Asia, Europe, North America, and Africa to discuss the results of an independent study and evaluation of the Chinese National Improved Stove Program (NISP) conducted by the University of California, Tsinghua University, Renmin University, and the Centers for Disease Control of China. The Ministry of Agriculture and its affiliated agencies as well non-governmental organizations briefed the participants of the workshop on the achievements in extending improved stoves and other advanced rural energy technologies in China, and demonstrated on the spot a number of high-efficiency stoves with crop stalks and wood residues as fuel. Participants from India, Nepal, Kenya, Tanzania and the Nature Conservancy of the United States briefed the workshop respectively on relevant issues of their own.

The workshop reached consensus on the following points and proposed recommendations to the relevant agencies of China.

- As with other developing countries, most of the Chinese rural population relied on biomass fuels (wood, crop residues, and animal dung) for their household energy about 20 years ago.
- Such fuels are traditionally used in inefficient stoves that waste resources and produce substantial amounts of indoor air pollution.
- NISP, which operated from the 1980s through the 1990s, was the largest and most successful improved stove program ever implemented anywhere in the world. Similar successful programs were also initiated at the provincial and local levels in many parts of the country.
- Nearly a billion rural Chinese citizens have benefited from improved efficiency and reduced indoor air pollution from the improved stoves promoted by these programs.

Recommendation 1 The successful undertaking initiated and implemented by the Ministry of Agriculture and its Rural Energy Offices should be widely acknowledged and highly praised.

- Biomedical research in recent years in China and elsewhere, however, indicates that indoor pollution caused by incomplete burning of solid fuels – both biomass and coal – is still an important factor threatening the health of rural residents.
- Thus, although the high pollution levels caused by traditional biomass stoves seem to have decreased, remaining pollution from coal and biomass stoves needs to be brought down further to reach health standards, including the new national indoor air pollution standard.
- Since solid fuel will continue to dominate energy supplies to rural households for many years, improving the way solid fuels are used is a key part of rural energy strategy, in addition to widening access to and use of higher-quality forms of energy.

Recommendation 2 Participants of the workshop noted that there were many new technologies developed largely by the private sector in China, offering possibilities for using biomass fuels in a much cleaner and more efficient way. Such advanced biomass stove technologies should be encouraged, and new policies should be formulated to deploy such technologies on a larger scale.

Recommendation 3 As China is different than at the initial stage of NISP in the early 1980s, there is a need now to find ways to promote sustainable commercialization of the stoves in the private sector rather than relying on direct intervention by the government, except in the poorest areas. The China Association of Rural Energy Industry (CAREI) can play an important role in this effort.

Recommendation 4 As important players, the central and local governments certainly need to continue their efforts in many areas, including the development and enforcement of energy efficiency and environmental standards, protection of intellectual property of advanced technologies, public education regarding health hazards, training of technicians, and support for focused health and environmental studies.

- Unlike other developing countries, a significant and rising portion of Chinese rural households use coal for cooking and/or heating.
- Many households in China use coal stoves without chimneys, which cause even more serious indoor air pollution than the current generation of stoves that use biomass as fuel.

Recommendation 5 From the viewpoint of health concern, it is necessary to speed up the development and dissemination of improved coal stoves with chimneys if coal is to be used as fuel for rural communities for a prolonged period.

- In China, poor-quality local coal generates severe pollution during burning, and such coal is not suitable for use in households, even with advanced stoves.

Recommendation 6 As time goes on, and expectations of rural residents for environmental and health protection continue to rise, there will be a need to provide high-quality coal to all users, which can be efficiently and cleanly burnt in household stoves.

- An astonishing finding reported to the workshop was that tens of thousands of households in dozens of poverty-stricken counties in China still rely on local coals that are heavily contaminated with toxic elements. Such elements as fluorine and arsenic pose serious health hazards, including inducing cancer, to local populations.
- The participants were pleased to learn that the Ministry of Health is making efforts to introduce improved stoves to the above-mentioned areas. Meanwhile participants were concerned that the use of such poor-quality coal is expanding. Furthermore, the public health sector has not implemented timely and forceful intervention measures in line with the expansion of pollution.

Recommendation 7 There is an urgent need to address the serious problems created by use of poisonous coals in the country through an inter-ministry effort of the Chinese Government:

- in the short term by immediately providing improved stoves with chimneys, and
- as soon as possible banning sale and use of coal from the most poisonous coal deposits and providing access to alternative clean fuels to the local populations.

- The international workshop participants noted the impressive signs of modern development in Beijing and elsewhere in the country, with the most modern hotels, airports, roads, factories, universities, and other infrastructure comparable to those of highly developed countries.
- The participants were concerned, however, that China is not fully able to be proud of its great modern advances until it finds ways to bring its poor rural population into the modern world as well.

Recommendation 8 Taking advantage of significant progress made by NISP and other past success, China should re-emphasize the importance of modern energy supplies, especially gas fuels and electricity, for all households as part of its laudable efforts to bring the benefits of economic development to all of its people.

- The participants noted the great advances that China has made in developing and deploying improved rural energy systems in the country, and the potential China thus has to help other countries trying to assist their poor rural populations with sustainable, clean, and efficient energy systems.

Recommendation 9 The participants of the workshop agreed that China should work collaboratively with other developing countries to assist them in achieving similar successes, including providing an ongoing compendium of new biomass and coal stove technologies and working to share those technologies and lessons for organizing development and dissemination programs. The participants also expressed their appreciation to the Department of Science and Education of the Ministry of Agriculture for its successful organization of a workshop that provided all participants with an opportunity for exchange and learning.

Recommendation 10 The participants expressed a strong vote of thanks to the Shell Foundation for supporting the workshop and for promoting clean household energy solutions for the world's poor.

(English and Chinese versions of these recommendations and papers from the workshop arefound at http://ehs.sph.berkeley.edu/hem/page.asp?id=29.)