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Indoor Air Pollution in Rural China: Cooking Fuels, Stoves, and Health Status

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ABSTRACT. Solid fuels are a major source of indoor air pollution, but in less developed countries the short-term health effects of indoor air pollution are poorly understood. The authors conducted a large cross-sectional study of rural Chinese households to determine associations between individual health status and domestic cooking as a source of indoor air pollution. The study included measures of health status as well as measures of indoor air-pollution sources, such as solid cooking fuels and cooking stoves. Compared with other fuel types, coal was associated with a lower health status, including negative impacts on exhaled carbon monoxide level, forced vital capacity, lifetime prevalence of chronic obstructive pulmonary disease and asthma, and health care utilization. Decreasing household coal use, increasing use of improved stove technology, and increasing kitchen ventilation may decrease the short-term health effects of indoor air pollution.

KEY WORDS: China, indoor air pollution, pulmonary function, rural poverty, solid cooking fuels

Nearly half of the world's population, some 3 billion people, use solid fuels such as coal, wood, animal dung, and crop residues for their domestic energy needs.[1] Solid fuel use is highest among the poor, particularly those living in rural areas, where it continues to be relied on by up to 90% of households.[2]

Often combusted in open fires or poorly ventilated stoves, solid fuel burning is a major source of indoor air pollution. Solid fuel smoke contains thousands of substances, many of which are hazardous to human health. The most well understood of these substances are carbon monoxide (CO); small particulate matter; nitrous oxides; sulphur oxides; a range of volatile organic compounds, including formaldehyde, benzene, and 1,3-butadiene; and polycyclic aromatic compounds, such as benzo-α-pyrene,[3] which are thought to have short- and long-term health consequences. The indoor concentration of these pollutants in households that use solid fuel typically exceeds health-based standards and guidelines.[4] A growing evidence base links these exposures to a range of long-term health effects.[1] The most well established effect from biomass smoke is chronic obstructive pulmonary disease (COPD) in adults, particularly women who have cooked over open fires for many years.[2] In a number of Chinese studies,[2,5] researchers have shown that indoor coal smoke is associated with lung cancer. There is growing evidence that the pollutants from indoor solid-fuel use are also associated with infections of the lower respiratory tract in children.[6] The global burden of disease for the combination of pediatric lower-respiratory infection and adult COPD and lung cancer attributable to solid fuel smoke is 1.6 million premature deaths annually, two thirds of which are in children.[6,7]

China's rural inhabitants, numbering over 818 million,[8] rely on solid fuels for many of their domestic energy needs, including cooking, heating, and lighting. In the early 1980s, the Chinese government organized the world's largest

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publicly financed initiative to improve stove function—the National Improved Stove Program (NISP). It was designed to provide rural households throughout the country with more efficient biomass stoves for cooking and heating. The NISP was administered by the Chinese Ministry of Agriculture, and it focused on biomass stoves. Although the program did not aim at reducing indoor air pollution directly, all the improved biomass stoves authorized by the NISP included chimneys to vent the smoke from the households. With the increased use of coal fuel throughout rural China, the NISP was expanded to include improved coal stoves. However, many of these stoves did not include chimneys for improved ventilation.

China is historically the world's largest producer and consumer of coal.[10] Although coal consumption began to decline in the late 1990s, coal continues to account for 67% of China's primary energy consumption.[11] Like that from biomass burning, indoor air pollution from coal burning is associated with several worrisome long-term health consequences, including an increased incidence of lung cancer.[2,5,12] Used in households, coal fuel produces all the same categories of pollution as biomass fuel; furthermore, in parts of China, it can also contain pathogenic levels of toxic elements, such as arsenic, fluorine, and selenium.[13]

The introduction of the NISP provided researchers with a unique opportunity to evaluate the association between health, fuel use, and stove type. Here we describe the health outcomes associated with indoor air pollution in 3 rural Chinese provinces.

MATERIALS AND METHODS

This study was a collaboration of the University of California, The People's University of China, Tsinghua University, and the China Centers for Disease Control under the aegis of a grant from the Shell Foundation. The data for this analysis come from a large cross-sectional household survey conducted as part of an evaluation of the impact of the NISP to provide more efficient and cleaner stoves for household use.

The survey methods have been described in detail elsewhere.[5] In brief, we employed a stratified random-sampling scheme to select households broadly representative of large areas of rural China. We selected 3,476 households in 3 provinces—Shaanxi, Hubei, and Zhejiang—from village rosters, and we had their residents interviewed.

The household inclusion criteria were that households each had a permanent resident of at least 6 months and that the individuals who lived in the households consented to participate in the study. Trained survey team members hired from local universities interviewed the head of each household. If a child was present in the household, interviewers also administered a separate children's survey to the parent of the child. We defined adults as individuals aged 18 years or older, and we included both tobacco smokers and nonsmokers. Children aged between 6 months and 17 years were also eligible for inclusion.

Data Collection

Survey team members administered structured questionnaires to gather information on health status, household fuels, stove type, and dwelling characteristics. The fuel types we considered were biomass (wood, crop residue, and dung), coal, charcoal, and cleaner sources (biogas, electricity, and liquefied petroleum gas, known as LPG). Most households used multiple fuels.[5] Because the main cooking fuel accounted for an average of 82% of total household fuel consumption, we used the household's main cooking fuel for our analysis of health outcomes and fuel type. We also evaluated cooking stoves in the same questionnaire; we characterized biomass stoves by their designs and the presence of specific features, including flues and grates, to classify them as either traditional or improved stoves.

In addition, we gathered objective physiologic information by using tests of health function, including heart rate, blood pressure, respiratory rate, pulmonary function, and exhaled CO levels. Trained personnel measured pulmonary function according to guidelines from the American Association for Respiratory Care,[14] using a portable spirometer (Micro Medical, Ltd, Rochester, Kent, UK) that determined forced vital capacity (FVC). After receiving instruction and viewing a demonstration, all participants performed the FVC maneuver 3 times. If the outcomes of the 3 tests were within 0.20 L of each other, then the personnel accepted the results; if the outcomes were not within this limit, they discarded these unacceptable results and had the participants repeat the tests after 15 minutes' rest. We report the mean of the 2 largest FVC volumes measured in an acceptable series. We also had personnel measure exhaled CO by using a portable handheld device (Micro Direct, Inc, Auburn, ME).

We obtained approval for human subjects from the US and Chinese institutions collaborating on the survey. We obtained informed verbal consent from each participant before we collected data. All participation was strictly voluntary.

Analysis

Trained supervisors monitored raw data on a daily basis for coding errors or incomplete questionnaires and then sent it to a central data-processing center where 3 coders entered the data. The triple data entry was blinded, and the raw input was checked for input errors, outliers, and missing values.

We performed descriptive univariate analyses, cross-tabulation, and multivariate regression analyses by using STATA statistical analysis software, version 7.0. The descriptive analyses examined population characteristics by province; utilization of health care by age and sex; and health status (subjective and objective as already described) by age group, disease prevalence, household fuel and stove use, and socioeconomic status. We used linear and logistic regression models to examine the relationship between household stove use, fuel use, and health outcomes. We estimated separate regression models for the adult and pediatric populations. The dependent variables in these models included prevalence of respiratory diseases, prevalence of physical health complaints, exhaled CO level, pulmonary function, and health-care utilization. We determined prevalence of respiratory disease on the basis of any reported history of asthma, COPD (including emphysema, chronic bronchitis, or both), or tuberculosis in adults or any reported history of asthma in children. We used exhaled CO level as an objective health-status measure and analyzed this on a log scale. We analyzed FVC as an objective measure of pulmonary function. We determined health-care utilization from reports of visits to an outpatient ambulatory care center, including hospitals, public clinics, private clinics, or other non-Western health-care providers over the 1-month interval prior to the interview. For statistical modeling, we dichotomized health-care utilization as either present or absent within the past month.

Fuel type and stove type were the exposures we considered in the regression analyses. Cooking fuel was based on reported fuel usage during the spring season to correspond with the timing of data collection. Fuel types consisted of wood (logs, twigs, or other wood), crop fuel (crop residues and other biomass, including dung), coal (coal, coke, or lignite), charcoal, and cleaner fuels (electricity, LPG, or biogas). Stove types consisted of coal, traditional biomass, improved biomass, and cleaner-fuel stoves (defined as LPG, biogas, or electrical stoves). We differentiated improved versus traditional biomass stoves on the basis of actual stove structure as determined by surveyor observation. We considered stoves to be improved only if they incorporated at least a flue and a grate. We categorized households on the basis of the worst stove present in the following order (from worst to best): coal, traditional biomass, improved biomass, and cleaner fuel.

For both the adult and the pediatric cohorts, we controlled for age, sex, active smoking status, geographical location (by province), and income level as covariates. We analyzed age and income as continuous variables with income on a log scale. Sex and smoking status were binary variables. The initial modeling showed that coal fuel and coal stoves tended to be associated most frequently with worsening health outcomes. Thus, in the models comparing fuel and stove types, coal fuel and coal stoves were the omitted reference variables, respectively. We also fitted additional models by using traditional biomass stoves as the reference variable to assess differences between traditional and improved stoves.

To assess any dose-response relationship between cooking fuel type and health, we analyzed daily duration of exposure to cooking stoves (in minutes, a continuous variable) independently as a predictor of health and as a covariate in the fuel-type models among adult respondents.

RESULTS

Demographics

The 3 provinces have a combined population of 103.4 million people.[15,16] In general, the people of Shaanxi were poorer ($180 US per capita annual income) and less literate, whereas those of Zhejiang were more affluent ($553 US per capita annual income) and better educated than the national average. Table 1 compares the socioeconomic characteristics found in our study sample by province. We found, as we had expected, that the income of the households we surveyed was dramatically lower than the provincial average incomes (This is at least partly because this study was conducted in rural areas and excluded cities, which have higher average incomes).

Table 1.—Study Population Characteristics

Characteristic	Shaanxi	Hubei	Zhejiang
Avg. number of children/ household (SD)	1.29 (0.87)	1.30 (0.89)	0.91 (0.73)
Avg. income/household (SD)*	587 (504)	788 (669)	1547 (1849)
Adults			
N	1409	1480	1749
Age, mean years (SD)	39.7 (12.6)	39.0 (11.7)	43.7 (14.2)
Female (%)	1061 (75.3)	1065 (72.0)	1166 (66.7)
Smokers (%)	255 (18.1)	281 (19.0)	346 (19.8)
Children			
N	759	767	759
Age, mean years (SD)	5.1 (3.0)	5.6 (3.1)	4.8 (3.0)
Female (%)	328 (43.2)	402 (52.4)	461 (60.7)
Smokers (%)	10 (0.3)	2 (1.3)	5 (0.7)

*Income is shown in US dollars; in 2002, the official conversion rate was 8.28 Chinese yuan per US dollar.

Health Status

Table 2 shows reported health measures. The average exhaled CO level varied from an average of 2.4 parts per million (ppm) among children to 11.4 ppm among middle-aged men. Cigarette smoking among men (more than 60% of men in our study population smoke) was associated with increased CO breath levels. As we expected, FVC peaked in the 15- to 45-year-old age groups. Smoking rates themselves were relatively even among the provinces, ranging from 18% to 20% of all adults aged older than 18 years.

Self-reported disease history of hypertension, tuberculosis, and asthma ranged from 5.9 per 1,000 to 41 per 1,000 in adults; these values may represent an underreporting of the true prevalence of these diseases as a result of underdiagnosis, limited health care resources, or individuals' misunderstanding of their diagnosed disease. The reported prevalence of other respiratory diseases (COPD, emphysema, and chronic bronchitis) was approximately 40 per 1,000 in adults. Nonspecific symptoms were present in a large number of individuals (see Table 3). In children, reported symptoms were also common—particularly cough requiring medical attention.

Table 2.—Respiratory Health Measures by Age Group (in years)

Measure	Children	Women			Men		
	0–10	15–45	46–60	61+	15–45	46–60	61+
Expired CO: ppm (SD)	2.4 (2.0)	4.8 (3.4)	5.0 (6.5)	4.3 (2.8)	10.2 (9.1)	11.4 (10.0)	8.2 (5.6)
Expired CO, nonsmokers: ppm (SD)	2.4 (2.0)	4.7 (3.4)	5.0 (6.5)	3.9 (2.1)	6.6 (5.4)	7.9 (6.5)	6.1 (6.0)
FVC: L (SD)	1.79 (0.55)	2.91 (0.64)	2.72 (0.76)	2.36 (0.81)	3.11 (0.71)	2.79 (0.77)	2.44 (0.86)

Table 3.—Reported Disease and Symptom Prevalence

Disease and symptom	Percentage
Adults (n = 4638)	
History of disease	
Hypertension	4.1
Emphysema, chronic bronchitis, COPD	3.8
Tuberculosis	0.6
Asthma	1.3
Symptoms in the past month	
Headache >4 h	9.9
More than 5 headaches/wk	9.7
Nausea >8 h	2.2
Nausea with vomiting	10.6
Dizziness	29.4
Cough (productive)	10.9
Irritation of both eyes (4 h)	2.6
Irritation of eyes >5 times/wk	2.7
Itching of both eyes	9.4
Children (n = 2285)	
History of disease in past year	
Couth with fever	70.5
Asthma	2.4
Symptoms in past month	
Diarrhea (requiring medical attention)	11.5
Cough (requiring medical attention)	31.0
Asthma diagnosis	1.6
Asthma (requiring medical attention)	1.2

Utilization of Health Services

On average, the rate of ambulatory health care visits was 318 per 1,000 person-months. Care for adults was most often obtained in a private clinic (which had costs comparable with those of a public clinic) and was least often obtained in a larger hospital (where care was 10–30 times more expensive and drugs were 6–20 times more expensive than in public or private clinics). The average cost for any type of ambulatory care was $7.81 US (at a conversion rate of 8.28 yuan per US dollar). This pattern of utilization and costs was virtually the same for children, although drugs tended to cost less in the pediatric population. The rate of inpatient hospitalization in the last year was 41 per 1,000 person-years, with most of the care being provided at the township and county hospitals (86%).

The most commonly cited reason for ambulatory care visits for both adults and children was a pulmonary or respiratory complaint. For visits in the past month, 29% of adult visits and 46% percent of pediatric visits were primarily for respiratory complaints.Few ambulatory and inpatient visits were made outside of the provinces where the respondents live. Of the most recent visits, 96.7% of ambulatory visits and 89.2% of inpatient visits were in the local province.

Fuel Use

In the households, wood and coal were the dominant main fuels used overall as well as the main cooking fuels. Seventy-eight percent of the households were using more than one fuel type at the time of the survey and many residents described varying patterns of usage across seasons. However, electricity, kerosene, and biogas were never used as the sole household energy source. It is of note that, in Shaanxi Province, coal was the most common primary cooking fuel (at 45.6%), presumably because of the high availability of coal from abundant local mines.

Stove Use and Dwelling Characteristics

The majority of surveyed households used improved biomass stoves for cooking. However, coal stoves were dominant in Shaanxi Province.

There was a consistent, expected association between fuel and stove types: 97.2% of respondents who used coal stoves for primary cooking use also claimed to use coal as their primary cooking fuel. Traditional biomass and improved biomass stove users used wood or crop residue as their primary fuels 98.8% and 98.4% of the time, respectively. Biogas stoves and open fires were uncommon. Although nearly 40% of households owned LPG stoves, they used them infrequently as the main cooking stove.

We found kitchens to have an average of 2 windows. Mean ceiling height in kitchens was 3.4 meters, and mean kitchen area was 16.0 square meters.

Health Outcomes by Fuel and Stove Type

We modeled the association between stove or fuel type exposures and the following health measures: history of a disease, physical health complaints, exhaled CO level,

Table 4.—Fuel Type and Health Outcomes: Summary of Statistically Significant Relationships

Health outcome	Fuel type: Fewer health problems	More health problems
Adults		
Exhaled CO level	wood, crop residue	coal
History of respiratory disease	wood	coal
History of COPD	wood, crop residue	coal
History of asthma	wood	coal
FVC	crop residue	coal
Health care utilization	wood, crop residue	coal
Children		
Exhaled CO level	wood, cleaner fuel	coal
Asthma history	crop residue	coal
FVC	coal	wood
Health care utilization	coal	wood

Table 5.—Stove Type and Health Outcomes: Summary of Statistically Significant Relationships

Health outcome	Stove type: Fewer health problems	⟶	More health problems
Adults			
Exhaled CO level	improved	traditional	coal
History of respiratory disease	improved	traditional	coal
History of COPD	improved	traditional	coal
History of asthma	traditional		coal
FVC	traditional	improved	coal
Health care utilization	traditional		coal
Children			
Exhaled CO level	cleaner		coal
	improved		traditional
History of asthma	improved		wood
Health care utilization	improved		traditional

pulmonary function, and health-care utilization. With a few notable exceptions, we observed that coal fuel and coal stoves were associated with more health problems than were other stoves and fuel types. This was the case whether we considered fuel type or stove type. We found specifically that, in both adults and children, coal fuel was associated with increased exhaled CO level, increased health-care utilization, and increased history of asthma compared with other fuels. In adults, coal fuel was also associated with decreased FVC, increased history of overall respiratory disease (including asthma, chronic bronchitis, emphysema, COPD, and tuberculosis), and increased history of both asthma and COPD, specifically. In children, FVC was significantly higher in coal-fuel users than in wood-fuel users, a finding opposite of that seen in adults. Tables 4 and 5 summarize these findings.

We also compared different health outcomes across different fuel types and different stoves, respectively (see Tables 6 and 7). Within each table, these comparisons are made separately for adults and children. Because coal use was associated with more health problems in our initial modeling, coal fuel and coal stoves are the omitted reference variable in these tables.

Compared with other fuels (shown in Table 6), coal-fuel use is most clearly associated with worse health, particularly compared with wood fuel and crop residues. Adult wood-fuel users had decreased history of respiratory disease, decreased history of COPD, decreased history of asthma, decreased exhaled CO level, and decreased outpatient health care utilization compared with coal fuel users. Crop-residue users had decreased history of COPD, increased FVC, decreased exhaled CO, and decreased outpatient health care utilization compared with coal-fuel users. We saw a similar trend with cleaner fuels, although no health outcome or utilization was statistically significant. Among children, wood-fuel users had decreased exhaled CO level, but they also had decreased FVC and increased health-care utilization compared with coal users. Crop-residue users had decreased history of asthma compared with coal-fuel users, and cleaner-fuel users had decreased exhaled CO compared with coal-fuel users.

The coal stove type generally compared with other stove types performed similarly to the coal fuel type in modeling (see Table 7). Among adults, coal stoves were associated with more health problems compared with either improved or traditional stoves in all of the same measures as coal fuel as compared with other fuels. Compared with coal-stove use, improved biomass-stove use was associated with decreased history of respiratory disease, decreased history of COPD, increased FVC, and decreased exhaled CO level. Traditional biomass-stove use was associated with decreased history of asthma and decreased outpatient health-care utilization compared with coal-stove use. Again, cleaner-fuel-burning stove use trended toward improved health compared with coal-stove use, but the associations were not statistically significant. In children, coal-stove use was associated with an increased history of asthma compared with improved-stove use and increased exhaled CO levels compared with cleaner-fuel stove use, but there were no other significant relationships. To further investigate the association between coal-stove use and health outcomes, we modeled coal stoves with and without flues. The inclusion of flues on coal stoves was not associated with improved health.

When we compared improved biomass stoves with traditional biomass stoves, we found significant differences in health status (see Table 8). Traditional stoves were associated with increased history of respiratory disease, increased history of COPD, decreased FVC, and increased exhaled CO level in adults (In these models, improved stove is the omitted variable). Compared with children in households with improved stoves, children in households with traditional stoves had increased exhaled CO levels. It is interesting that health-care utilization within the past month was decreased in children in households with traditional stoves, compared with those in households with improved ones.

The duration of exposure to cooking was also associated with decreased health among adults. A 30-minute increase

Table 6.—Health Outcome Regression Models: Coal Versus Other Fuels

Health outcome	Wood fuel	Crop residues	Cleaner fuels	N	(Pseudo) R^2
Adults					
History of respiratory disease†	0.52** (0.32–0.84)	0.66 (0.42–1.03)	0.35 (0.04–2.67)	4211	0.0683
History of COPD†	0.48** (0.28–0.87)	0.57* (0.34–0.96)	0.43 (0.05–3.36)	4211	0.0771
History of Asthma†	0.42* (0.17–0.99)	0.72 (0.34–1.52)	—	4162	0.0417
FVC (L)‡	0.060 (−0.04–0.16)	0.11* (0.01–0.19)	−0.19 (−0.30–0.26)	2146	0.0534
Exhaled CO (log ppm)‖	−0.09* (−0.18, −0.01)	−0.15** (−0.23–0.07)	−0.10 (−0.25–0.04)	1829	0.3154
Outpatient utilization in last 4 weeks§	0.74* (0.57–0.98)	0.64** (0.50–0.81)	1.08 (0.50–2.31)	4211	0.3130
Children					
History of asthma§	0.94 (0.43–2.04)	0.23* (0.08–0.62)	0.56 (0.13–2.51)	1664	0.0436
FVC (L)‖	−0.15 (−0.29, −0.19)	0.025 (−0.98–0.15)	−0.025 (−0.25–0.20)	501	0.0996
Exhaled CO (log ppm)‖	−0.19 (−0.33, −0.04)	0.078 (−0.05–0.21)	−0.29 (−0.54, −0.04)	457	0.1217
Outpatient utilization in Past 4 weeks§	1.51 (1.07–2.13)	0.97 (0.71–1.31)	0.68 (0.37–1.28)	1714	0.0750

†This is the odds ratio (95% confidence interval).
‡This is the coefficient (95% confidence interval). Note that odds ratios and coefficients reflect an adjustment for age, sex, smoking status, income, and province of residence.
*$p < .05$. **$p \leq .01$.

in daily exposure to cooking stoves was associated with a 1.04-ppm increase in exhaled CO ($p < .001$; 95% confidence interval [CI] = 1.02–1.06) and an increase in likelihood of outpatient health-care utilization in the past month (odds ratio [OR] = 2.88; $p = .006$; 95% CI = 2.76–3.04). When introduced into the multiple regression models with fuel type, the significance of duration of exposure persisted. After adjustment for fuel type and the other covariates, a 30-minute increase in daily stove exposure was associated with a 1.03-ppm increase in exhaled CO ($p = .003$, 95% CI = 1.01–1.04) and a marginally significant increase in likelihood of outpatient health-care utilization in the past month (OR = 1.05, $p = .075$, 95% CI = 1.00–1.10).

When we analyzed the effect of household ventilation characteristics on health status, only the number of windows in the kitchen was significant. Increasing the number of windows in kitchens was associated with a decreased exhaled CO level. However, ceiling height and kitchen size were not associated with statistically significant changes in health status.

COMMENT

We conducted a large cross-sectional study of rural Chinese households to determine associations between domestic cooking fuels and domestic cooking stoves and individual health status. To our knowledge, this study is the largest assessment to date of the effects of fuel and stove use on health in a developing nation. We demonstrate multiple associations between sources of indoor air pollution and self-reported and objective measures of health status. We measured a broad array of health outcomes, including self-reports of health status, symptomatic complaints, disease history, health-care utilization, pulmonary function, and expired CO level.

In both adults and children, we generally found that coal fuels and stoves were associated with poorer health outcomes (summarized in Tables 4 and 5). The substantially smaller sample size for children than for adults in this study may account for differences in statistically significant outcomes. In addition, compared with traditional biomass stoves, improved biomass stoves (defined as stoves incorporating a flue and a grate) were associated with improved health outcomes in both adults and children.

Compared with stove models, models of fuel type more consistently produced statistically and clinically significant differences in health outcomes in both adults and children than did models incorporating stove type. Although both fuel type and stove type are indirect measures of exposure to indoor air pollution, the results of this study suggest that fuel type may be a better proxy of pollution exposure than stove type.

Although we measured a number of dwelling characteristics, only the number of windows in a kitchen was associated

Table 7.—Health Outcome Regression Models: Coal Stove Versus Other Stoves

Health outcome	Improved biomass	Traditional biomass	Cleaner-fuel stove	*N*	(Pseudo) R^2
Adults					
History of respiratory disease†	0.54** (0.34–0.85)	0.74 (0.46–1.21)	0.41 (0.05–1.18)	4220	0.0704
History of COPD†	0.41** (0.24–0.70)	0.77 (0.45–1.33)	0.49 (0.06–3.83)	4220	0.0838
History of asthma†	0.62 (0.29–1.33)	0.41 (0.16–1.05)	—	4175	0.0403
FVC (L)‡	0.18*** (0.08–0.27)	−0.14 (−0.12–0.09)	0.15 (−0.14–0.44)	2144	0.0662
Exhaled CO (log ppm)‡	−0.12** (−0.19, −0.04)	−0.072 (−0.16–0.02)	−0.10 (−0.23–0.03)	1929	0.3193
Outpatient utilization in past 4 weeks†	0.70** (0.55–0.88)	0.80 (0.61–1.06)	0.73 (0.30−1.79)	4220	0.0294
Children					
History of asthma†	0.52* (0.27–0.99)	0.69 (0.31–1.55)	0.46 (0.10–2.01)	1763	0.0222
FVC (L)‡	−0.088 (−0.21–0.03)	0.0065 (−0.13–0.14)	−0.017 (−0.24–0.21)	542	0.0836
Exhaled CO (log ppm)‡	−0.098 (−0.22–0.03)	0.067 (−0.07–0.21)	−0.27* (−0.51, −0.02)	494	0.1114
Outpatient utilization in past 4 weeks†	1.21 (0.91–1.60)	0.78 (0.53–1.13)	0.58 (0.32–1.08)	1815	0.0760

†This is the odds ratio (95% confidence interval).
‡This is the coefficient (95% confidence interval). Note that odds ratios and coefficients reflect adjustment for age, sex, smoking status, income, and province of residence.
*$p < .05$. **$p \le .01$. ***$p \le .001$.

with health outcomes in our study. Having more windows was associated with lower levels of exhaled CO. The apparent suggestion is that more kitchen windows lead to better ventilation and, in turn, better health.

CO poisoning is one of the best known and most worrisome health consequences of indoor air pollution.[17] We measured exhaled CO, which reflects exposure to CO over the previous 5 to 15 hours and is a measure of the degree to which the hemoglobin in blood has previously taken up CO. We found that the majority of individuals surveyed in this study had some degree of elevated exhaled CO. In our study sample, the exhaled CO level in nonsmokers ranged from an average of 2.4 ppm in children up to an average of 8.0 ppm in 46- to 60-year-old men. In comparison, Cunnington and Hormbrey[18] found a mean exhaled level of 1.26 ppm among nonsmoking individuals in Oxford, UK. In our study, coal-fuel use was associated with a 1.2-ppm average increase in CO level, compared with wood-fuel use and a 1.4-ppm increase, compared with crop-residue use in adults, who had an overall mean CO level of 3.0 ppm. In children, whose mean exhaled CO level was 0.7 ppm, coal-fuel use was associated with an increased average CO level of 1.6 ppm, compared with wood-fuel use. These observed changes are large and are likely to be clinically significant.

Exposure to CO has several known health effects. Short-term exposure to CO results in a dose-related range of problems, from symptomatic complaints, such as headache, dizziness, irritability, fatigue, and dimness of vision, to unconsciousness, respiratory collapse, and death.[19] Although some such symptomatic complaints were prevalent among respondents in this study, we did not find a significant variation in these symptoms based on fuel or stove type or based on exhaled CO level. Longer-term exposure to ambient CO has been associated with a number of chronic health problems, such as early onset of cardiovascular disease,[20] reduced birth weight,[21] sudden infant death syndrome,[22] and increased daily mortality rate.[23]

There was an increased overall history of respiratory disease, specifically an increased history of asthma and COPD, associated with coal use in our study. Asthma is a major global health problem; between 100 and 150 million people are affected by the disease and prevalence is on the rise.[24] Although asthma-associated mortality may be relatively low (approximately 180,000 annual deaths globally), the common nature of the disease and its effects on health and well-being have a tremendous impact; the annual cost of treatment for asthma is currently estimated to exceed that of tuberculosis and human immunodeficiency virus combined.[24] In our study sample, prevalence of asthma was 13 per 1,000 for adults and 16 per 1,000 for children. Coal-fuel use was particularly associated with an increased history of asthma, compared with wood-fuel use for adults and crop-residue fuel use for children. The observed ORs

Table 8.—Health Outcome Regression Models: Traditional Versus Improved Stove Use

Health outcome	Value	*N*	(Pseudo) R^2
Adults			
History of respiratory disease†	1.39* (1.01–1.92)	4220	0/0709
History of COPD†	1.87*** (1.30–2.69)	4220	0.0845
History of asthma†	0.67 (0.33–1.37)	4220	0.0406
FVC (L)‡	−0.19*** (−0.27, −0.12)	2144	0.0661
Exhaled CO (log ppm)‡	0.11* (0.02–0.21)	1927	0.3218
Outpatient utilization in past 4 weeks†	1.15 (0.43–2.51)	4220	0.0294
Children			
History of asthma†	1.32 (0.60–2.94)	1763	0.0222
FVC (L)‡	0.095 (−0.03–0.22)	542	0.0836
Exhaled CO (log ppm)‡	0.17* (0.02–0.31)	494	0.1114
Outpatient utilization in past 4 weeks†	0.64* (0.45–0.92)	1815	0.0760

†This is odds ratio (95% confidence interval).
‡This is the coefficient (95% confidence interval). Note that odds ratios and coefficients reflect adjustment for age, sex, smoking status, income, and province of residence.
$^*p < .05$. $^{***}p \le .001$.

correspond to an approximately doubled prevalence of asthma and COPD with the use of coal fuel or coal stoves; this is a significant increase when it is considered on a population level. Although the mechanism of the association between coal-fuel burning and asthma cannot be determined from this study, this is not the first instance in which coal has been associated with asthma; Fritz and Herbarth[25] found an increased prevalence of asthma among children of households with coal heating in Leipzig, Germany. Researchers must investigate further to determine the mechanism and implications of coal as a potentially significant contributor to global asthma disease burden.

COPD is most commonly associated with cigarette smoking in more developed countries, but indoor air pollution is a significant contributor in less developed countries, where exposures are high. Coal, particularly coal dust from mining, has been associated with COPD in the past.[26] It is possible that the association seen in our study is actually confounded by coal dust exposure from mining, as those exposed to coal mining are likely to also use coal as a cooking fuel, but this is unlikely given the large sample size relative to the number of individuals who identified themselves as miners. Regardless, the implication of increased lifetime prevalence of both asthma and COPD among coal users is concerning, as both of these diseases are substantial contributors to global disease burden.

FVC, an objective measure of current pulmonary function, was also affected by fuel- and stove-use patterns. Coal-fuel use was associated with decreased FVC compared with crop-residue use in adults, as were coal stoves compared with improved stoves. Among adult coal-fuel users, FVC was a mean of 94.4% of expected value based on age, sex, and height, whereas FVC among noncoal users was 97.3% of the expected value. Decreased FVC in this setting is clinically mild, but it may be indicative of otherwise undiagnosed pulmonary disease or an early preclinical decline in pulmonary function. However, in children coal-fuel use, compared with wood-fuel use, was associated with increased FVC. This relationship is in opposition to the majority of other health-related outcomes found in this study, and the underlying cause of the association is unclear.

The associations among fuel and stove type with health status were also found in the associations with health-care utilization. Adult coal-fuel users were 1.3 to 1.6 times more likely than users of other fuels to use outpatient health care within the past month, at an average cost of $7.81 US per visit, as reported by survey respondents; this is equal to an additional health care cost of $52.50 US per primary coal user per year for outpatient health care. This represents 9% of a Shaanxi resident's income and, when extrapolated to the entire provincial population, results in approximately $1.1 billion US in additional health-care cost attributable to coal-fuel use in cooking. In the provinces of Hubei and Zhejiang, the additional cost is $235 million US and $2.6 million US, respectively. These values could provide a strong economic incentive for mitigating the problem of coal-fuel use in cooking.

The finding of an increase in exhaled CO level as well as an increase in outpatient health-care utilization in association with an increased duration of exposure to cooking stoves provides further support for the observed relationships between cooking stoves, fuels, and health. This finding may be interpreted as evidence of a dose-response relationship: It exists both independently and in association with the relationship between fuel type and health.

The health impacts, particularly long-term impacts, of household coal use have been the subject of other investigations done in China. In these studies, coal has been associated with symptomatic respiratory complaints, chronic arsenic poisoning, fluorosis, lung cancer, and potentially other forms of cancer. For example, among children living in urban areas, exposure to heating coal has been associated with the higher reporting of cough with phlegm, wheeze, and asthma.[27] Indoor air pollution has been associated with decreasing pulmonary function in other studies.[28–30] Our study, done on a larger scale and in rural areas, supports and adds to these findings.

This study has several limitations. The interpretation of the relationship between household energy source and health outcomes in this study was complicated by the heterogeneity and diversity of energy resources used in our sample of rural Chinese households. Most households used multiple energy sources for cooking and other household uses, and fuel types often varied seasonally. Ours is a cross-sectional study design, limiting our ability to infer any causality. The data were collected during a single season that may not be reflective of overall fuel usage or health status. There is also no control group in this study in which individuals are not exposed to any indoor air pollution from cooking stoves. The best proxy for such a control group among the respondents of this study are users of clean fuels, but they were a small minority of our sample, and differences in health outcomes were generally not statistically significant. The provinces surveyed in this study were selected nonrandomly, and although they were chosen to represent the variations within China's household energy-use spectrum, their purposeful selection may have introduced a selection bias. Nevertheless, the selected provinces offer a wide range of demographic variation; households within the study provinces were randomly sampled by use of a stratified frame. We took a generally conservative approach to the modeling of the associations between fuel or stove type and health outcomes. For example, we chose to include income and province of residence as covariates in our regression modeling, despite the fact that these factors almost certainly are determinants of exposure. This may result in model overspecification and, if so, underestimation of the true effects of exposure on health outcomes. However, this approach seems justified to ensure adjustment for confounding effects from these variables. Finally, further analysis should be done to determine the relative contributions of indoor versus ambient outdoor air pollution on acute health and to assess any confounding between these 2 factors.

Indoor air pollution has been an issue of major concern of Chinese policy makers for some time. However, the NISP, which introduced more than 180 million improved stoves since the early 1980s never had the reduction of indoor air pollution as an explicit goal, but rather fuel efficiency.[5] Nevertheless, all approved improved biomass stoves did incorporate chimneys, greatly improving indoor air quality. Unfortunately, the smaller effort on improved coal stoves did not specify the incorporation of chimneys in redesigned coal stoves. As a result, much of the indoor air pollution that we found in rural homes is now caused by coal (as will be reported in a forthcoming companion study). Although this analysis was ostensibly conceived to demonstrate the association between improved stoves and better health, our data suggest that today, coal usage may be a more significant source of compromised health than is type of stove.

There are some promising trends regarding coal use in China. Overall coal usage in China is on the decline, despite increasing energy needs as the rate of development in China skyrockets. Between 1996 and 2000, household consumption of coal decreased by 66 million metric tons and was reportedly replaced largely by cleaner fuels, such as LPG, natural gas, and electricity.[31] However, in the rural population studied in this survey, these cleaner fuels remain relatively rare, comprising a small portion of overall energy use. It is worrisome that coal usage could potentially increase in rural areas of China as deforestation, desertification, and urbanization result in a decreased availability of biomass fuel before cleaner fuels become available. According to reports, the Chinese government has taken other steps toward reducing the coal burden; in 2000, legislation allowed the prohibition of coal use in designated zones within cities and proposed the development of incentives for the use of higher-quality refined coal.[32] The Ministry of Health, for example, recently introduced a program designed to introduce improved coal stoves with chimneys using cleaner coals in selected counties to reduce fluorine and arsenic contamination.[5] However, these policies may not effectively reach the problem of indoor coal combustion in millions of other households in rural China. Our analysis suggests that there may be strong financial incentives for China, in the form of reduced health-care costs, to address this problem.

Decreasing household coal combustion, increasing the use of improved stoves with chimneys, and increasing kitchen ventilation by increasing the number of windows could all be targets of policy actions that may decrease the short-term health effects of indoor air pollution. Although efforts aimed at mitigating these problems will certainly come at capital cost, they may in fact be cost effective when compared with the health-care burden caused by current household fuel use patterns.

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