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Exposure to indoor air pollution from household energy use in rural China: The interactions of technology, behavior, and knowledge in health risk management

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Abstract

Indoor air pollution (IAP) from household use of biomass and coal is a leading environmental health risk in many developing nations. Much of the initial research on household energy technology overlooked the complex interactions of technological, behavioral, economic, and infrastructural factors that determine the success of environmental health interventions. Consequently, despite enormous interest in reducing the large and inequitable risks associated with household energy use in international development and global health, there is limited empirical research to form the basis for design and delivery of effective interventions. We used data from four poor provinces in China (Gansu, Guizhou, Inner Mongolia, and Shaanxi) to examine the linkages among technology, user knowledge and behavior, and access and infrastructure in exposure to IAP from household energy use. We conclude that broad health risk education is insufficient for successful risk mitigation when exposure behaviors are closely linked to day-to-day activities of households such as cooking and heating, or have other welfare implications, and hence cannot be simply stopped. Rather, there should be emphasis on the economic and infrastructure determinants of access to technology, as well as the details of behaviors that affect exposure. Better understanding of technology–behavior interface would also allow designing technological interventions that account for, and are robust to, behavioral factors or to provide individuals and households with alternative behaviors. Based on the analysis, we present technological and behavioral interventions for these four Chinese provinces.

Keywords: Household energy; Indoor air pollution; Global health; Sustainable development; Health behavior; Risk; Technology diffusion; Environment and development; China

Introduction

Globally, almost three billion people rely on biomass (wood, charcoal, crop residues, and dung) and coal as their primary source of domestic energy

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(Smith, Mehta, & Maeusezahl-Feuz, 2004). Hundreds of harmful pollutants are emitted during the burning of biomass and coal, in particularly large quantities when burned in open or poorly ventilated stoves. Exposure to indoor air pollution (IAP) from the combustion of solid fuels has been implicated, with varying degrees of evidence, as a causal agent of several diseases in developing countries including acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), lung cancer (for coal smoke), asthma, nasopharyngeal and laryngeal cancers, tuberculosis, low birth weight, and diseases of the eye (Boy, Bruce, & Delgado, 2002; Bruce, Perez-Padilla, & Albalak, 2000; Ezzati & Kammen, 2001; Mishra, Dai, Smith, & Mika, 2004; Smith et al., 2004; Smith, Samet, Romieu, & Bruce, 2000). In the year 2000, more than 1.6 million deaths and nearly 3% of the total burden of disease worldwide were caused by IAP from solid fuel use, making this risk factor the 11th leading cause of global mortality and 8th leading cause of global disease burden among 26 major global risks (Ezzati et al., 2002; WHO, 2002).

The magnitude of the health risk associated with exposure to indoor smoke and its concentration among the marginalized socioeconomic and demographic groups (women and children in poor households and the rural population) have motivated efforts towards interventions in international development and public health arenas. Solid fuel use is also an indicator for goal 7 (environmental sustainability) of the millennium development goals (MDGs). At the same time, there is limited knowledge from empirical research to form the basis for designing effective interventions and intervention delivery programs. This limitation arises because much of the initial research overlooked the complex interactions of technological, behavioral, economic, and infrastructural factors that determine the success of environmental health interventions, especially those with non-health dimensions such as household energy (Agarwal, 1983; Ezzati & Kammen, 2002a, b; Kammen, 1995a, b; Karekezi, 1994; Krugmann, 1987; Manibog, 1984).

The initial emphasis of research on household energy in developing countries was on the environmental impacts of energy use, such as deforestation, resulting in a level of zeal for increased stove efficiency (Agarwal, 1986; Kammen, 1995a). The public health benefits from reducing exposure to indoor smoke became the subject of attention soon after. This perceived "double-dividend"—improving public health while reducing adverse environmental impacts—focused a great deal of effort on the design and dissemination of "improved" (high-efficiency and low-emissions) cookstoves (Barnes, Openshaw, Smith, & van der Plas, 1994; Kammen, 1995b; Smith, Gu, Huang, & Qui, 1993). Initial improved stove programs, however, were often marked by a lack of detailed data on technology performance in field conditions (Kammen, 1995b; Krugmann, 1987; Manibog, 1984). Efficiencies and emissions, for example, were often measured in controlled environments with technical experts using the stoves under conditions very dissimilar to those in the field. More recently, research on IAP interventions has shifted from ideal operating conditions to monitoring stove performance under actual conditions of use, taking into account the various social, behavioral and physical factors that would limit the use of these stoves altogether, or result in "sub-optimal" performance (Agarwal, 1983; Ravindranath & Ramakrishna, 1997; Sinton et al., 2004). Household energy use is tightly coupled with both access to fuel and has multiple non-health welfare outcomes (Ezzati et al., 2004). As a result, household energy choices and energy use behaviors are likely to have complex linkages to household economics and energy infrastructure, as well as knowledge of health hazards and risk perceptions. Characterizing these determinants is important for designing and delivering interventions in diverse environmental and sociocultural conditions.

In this paper, we use data from four poor provinces in China (Gansu, Guizhou, Inner Mongolia, and Shaanxi) to assess the linkages among technology and user knowledge and behavior in IAP exposure from household energy use. Based on the analysis, we present technological and behavioral intervention options for these four Chinese provinces. We also draw general lessons for technological interventions, especially as related to environmental health and other risks with significant non-health dimensions.

Study setting and study populations

More than 70% of China's households rely on solid fuels (biomass and coal) for their domestic energy (Florig, 1997; Smith et al., 2004). IAP caused an estimated 500,000 annual deaths in the developing countries of the Western Pacific region (approximately 85% of the region's population lives in

China) in the year 2000, making IAP the 4th leading cause of regional mortality and 5th leading cause of regional disease burden among 26 major risk factors (Ezzati et al., 2002; WHO, 2002). Although until the 1980s and 1990s biomass was the dominant source of household energy in China, deforestation—and policies to reduce and reverse it—have compelled many rural residents to switch to coal (some urban households, especially in the more prosperous coastal areas, have switched to non-solid fuels with increasing income and development) (Florig, 1997; Sinton et al., 2004). China has also implemented an ambitious program to disseminate improved stoves (Sinton et al., 2004; Smith et al., 1993). The program has primarily targeted reducing IAP exposure during cooking. Home heating remains an important route of exposure, as does the absence of improved stove programs in the poorest provinces and communities. A recent evaluation of the program illustrated that the design and performance of the new stoves cover a large range, with many of the stoves labeled as "improved" lacking flues or other characteristics necessary for reducing pollution and exposure (Sinton et al., 2004). The interactions of behavioral, infrastructural, and technological factors are particularly relevant in China where the diversity of climate, geography, socio-cultural factors such as income or food types, housing, and fuels and stoves require designing intervention technologies and programs that can be adapted to local conditions.

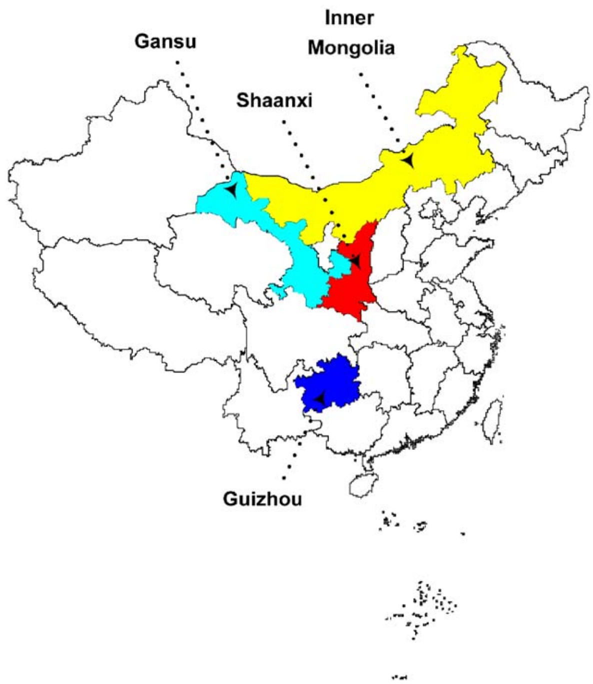

Fig. 1. Study provinces.

The study took place in the provinces of Gansu, Guizhou, Inner Mongolia and Shaanxi of China (Fig. 1 and Table 1). Among 31 Chinese provinces and autonomous regions, GDP per capita ranks 25th in Shaanxi, 29th in Inner Mongolia, 30th in Gansu, and 31st in Guizhou. In rural areas of all provinces, IAP exposure from household energy use, including heating needs in winter, is an important source of ill health.

Three clusters of villages (generally in separate townships) were selected for the study in Gansu, Guizhou, and Shaanxi provinces and two in Inner Mongolia such that: (i) the clusters had relatively similar socioeconomic, lifestyle, and environmental conditions; (ii) the majority of households used solid fuels as the main source of energy (coal in Guizhou and Shaanxi and biomass in Gansu and Inner Mongolia); (iii) there was no common market between any two clusters; (iv) township and village community groups accepted and approved the study.

Table 1
Characteristics of study regions

	Gansu	Guizhou	Inner Mongolia	Shaanxi
Study county	Huixian	Guiding	Helinggeer	Ankang
Altitude of study region (m)	800–1500	1100–1400	1400–1600	350–1000
Summer temperature: average (daily min-max) (°C)	28 (19–35)	27 (19–33)	21 (20–22)	28 (23–41)
Winter temperature: average (daily min-max) (°C)	9 (−5–16)	8 (−1–15)	−10 (−13–−8)	5.5 (−8–11)
Average annual rainfall (mm)	240–320	1100–1400	420	1120
Proportion of population rural (%)	88	85	85	80
Under-five mortality (per 1000 live births)	35	32	39	39
Main food staples	Wheat	Rice and corn	Wheat, rice and potato	Wheat and rice
Other foods		Chili		Chili and corn
Number of annual sunny hours	>2500	~1100	>2700	~1500

In each township, approximately 150 households were selected for a survey of household energy technology and energy/IAP knowledge and behaviors based on the following criteria: (i) having lived in the study area for at least 1 year; (ii) using solid fuels as the main source of energy; (iii) including a female member older than 18 years of age and a child younger than 14 years of age; and (iv) joining the study voluntarily. Surveys were conducted by the staff of provincial and county Health Bureau and Center for Disease Control and Prevention (CDC), trained by researchers from Chinese CDC. In addition to face-to-face interviews with uniform questionnaires, data were collected on energy use behaviors through field observation by key informants (village health workers and village committees and leaders). Because cooking and child care are primarily done by women, most respondents were female household members. Demographic and economic characteristics of the study population are given in Table 2, emphasizing the generally high levels of poverty in the study population.

Logistical factors required the units of data collection to consist of villages (i.e. all or most households in a village were asked to participate in the study based on the above criteria). As a result, despite efforts to ensure similarity of study populations, socio-demographic and environmental characteristics of the study communities, households and respondents varied across provinces (see Table 2). For example, the proportion of female respondents in Gansu was higher than other provinces. Although these differences reflect the circumstances of field research in a diverse group of provinces, they may influence direct cross-province comparability of results on risk knowledge and perception.

Determinants of exposure to indoor smoke

Exposure to IAP from solid fuels depends on emissions source (fuel and stove), pollution dispersion (housing characteristics and ventilation), and exposure behavior (Fig. 2). IAP exposure, accounting for spatial and temporal exposure "microenvironments", can be represented in the following relationship:

$$E = \sum_{i=1}^{n} \sum_{j=1}^{m} w_j t_{ij} c_i,$$

where c_i is the pollution concentration in the ith period of the day, with each period corresponding to one type of activity (n is the total number of activities for each individual); j is the spatial microenvironment defined on the basis of the distance from pollution source (m is the total number of microenvironments); t_{ij} time spent in the jth microenvironment in the ith period, and w_j the conversion (or dilution) factor for the jth microenvironment which converts the concentration at the measurement point to concentration at the jth microenvironment. Therefore the two summations together represent all the activity–location pairs for each individual (e.g. cooking inside near fire, resting inside away from fire, playing/shopping outside, and so on). The three parameters approximately represent the three determinants of exposure with c_i corresponding to emissions source (fuel–stove combination), t_{ij} to time-activity budget (behavior), and w_j to spatial distribution of pollution (housing characteristics) (Ezzati, Saleh, & Kammen, 2000; Wilson & Spengler, 1996). All parameters may change (e.g. day-to-day or across seasons) due to variations or systematic changes in technological and behavioral factors. For example, there is higher energy use during winter, when the windows are also closed and household members spend more time indoors and near the stove. In the following three sections we describe the components of exposure to IAP in the study populations,[2] with emphasis on their interactions and implications for interventions.

Housing

Table 3 provides basic information on housing characteristics of the study households. Most houses in Gansu have a kitchen separated by a wall from the sleeping/living room, with separate entrances. The most common housing design in Guizhou consists of 2–3 rooms—cooking/living, sleeping, and entrance/storage—connected with doors. Although most houses have a separate cooking area, cooking is done almost entirely in one of the main rooms (cooking/living room), especially during the heating season. The separate cooking area is used primarily for large family events (e.g. Spring Festival) and for making animal feed. Almost all houses have an attic above the

[2] All results apply only to the study households. The study took place in the poorest townships of each province. For this reason, the distributions of housing or energy technology may not reflect those of the province as a whole.

Table 2
Demographic and economic characteristics of the study households and respondents

	Gansu ($n = 463$)	Guizhou ($n = 476$)	Inner Mongolia ($n = 323$)	Shaanxi ($n = 479$)
Gender of respondent				
Male	4.3	30.9	35.9	35.9
Female	95.7	69.1	64.1	64.1
Age of respondent				
< 40	89.2	64.1	78.6	67.2
40–59	9.7	30.9	21.1	28.8
60 +	1.1	5.0	0.3	4.0
Education level of respondent				
Illiterate	19.0	34.5	25.7	36.3
Elementary school	52.7	45.8	39.6	38.6
Junior high school	25.7	17.4	26.9	21.7
Senior high school	2.6	2.3	5.9	1.9
Junior college and over	0.0	0.0	1.9	1.5
Number of household members				
< 4	13.0	19.2	84.8	17.7
4–7	86.2	76.8	13.9	80.8
$\geqslant 8$	0.8	4.0	1.2	1.5
Family annual income in the previous year (RMB)[a]				
< 1000	47.4	14.3	12.4	39.6
1000–1999	18.1	6.5	6.8	9.4
2000–2999	19.1	28.3	13.6	26.3
3000–3999	8.5	18.4	10.2	9.6
$\geqslant 4000$	6.8	32.6	57.0	15.1
Family annual subsistence income in the previous year (RMB)[b]				
< 1000	45.6	68.1	10.8	40.7
1000–1999	26.2	10.4	17.6	19.6
2000–2999	18.3	10.0	18.0	22.4
3000–3999	5.5	3.8	18.6	9.9
$\geqslant 4000$	4.3	7.7	35.0	7.5
Rank order correlation of monetary and subsistence incomes	0.31	0.47	0.30	0.26

Numbers show % households/respondents unless otherwise stated.

[a]Exchange rate in 2003, with the exception of a short period during the SARS outbreak, was between 8 and 8.5 RMB per US$. Per capita GDP in China was RMB 6640 in 2000 before adjustment for purchasing power.

[b]The value of foods and other agricultural products that families produced and consumed at home or stored in the previous year, estimated by the respondent.

cooking/living and sleeping rooms which is used for food drying and storage, and contains an additional bed in some homes. The lower rooms and the attic are separated by a porous ceiling (e.g. made of pieces of wood) which allows air flow between the two levels (Figs. 3g and h). Older homes in Inner Mongolia are constructed inside a cave-like structure with a single room used for cooking, living, and sleeping. This room contains a "bed-stove" configuration which consists of a cooking stove connected to a bed for heating (see Table 4 for details). Some homes have an additional room used for sleeping or storage. Newer homes are made with modern construction material with similar structure. The newest homes in the study area have a wall with windows and door between the cooking and sleeping/living areas. Most houses in Shaanxi have a cooking area connected to the main house by a door, a living room with a ground stove (fire-pit) used for heating and boiling water, and one bedroom which sometimes also has a ground stove. Most houses have a small attic used for storage but not for sleeping.

Energy use and energy technology

Table 4 summarizes fuels and stoves used in the study households. Multi-fuel use and multi-stove use are common features of household energy in China, because of multiple uses of energy (e.g. cooking and heating) as well as fuel availability, in particular limitations in access to fuelwood caused by deforestation and policies to prevent or reverse it; see also Sinton et al. (2004). In particular, while coal is the nearly universal fuel for *heating* in Guizhou and Shaanxi, 18% and 52% of study households in the two provinces, respectively, used biomass as their main *cooking* fuel. Multi-fuel/stove use means that successful intervention programs would have to account for different uses of energy, its source (fuel), and its combustion technology (stove). Multi-fuel use is likely to be a dynamic phenomenon in China, determined by both energy infrastructure (e.g. coal availability and pricing, and coal briquette manufacturing) and energy policies (e.g. restrictions in wood harvesting to avoid deforestation and increased energy generation).

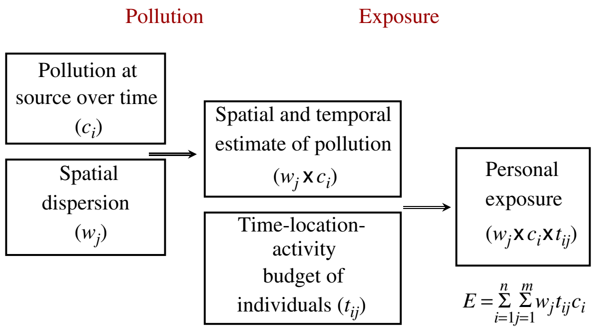

Fig. 2. Determinants of exposure to indoor air pollution from household energy use: emissions from the source (c_i), which may vary over different periods of the day (i), and dispersion of pollution inside the house (w_j) determine the level of pollution at each location (j) around the house. Exposure depends on pollution and time–location activity budgets of household members (t_{ij}) at point j in time period i.

Table 4 also illustrates the interactions of housing and energy technology as determinants of exposure to IAP. For examples, a separate cooking room in Gansu results in different exposure patterns for household members who do not cook compared to

Table 3
Housing characteristics of the study households

	Gansu ($n=463$)	Guizhou ($n=476$)	Inner Mongolia ($n=323$)	Shaanxi ($n=479$)
Construction material				
Mud, wood and tile	70.2	41.8	37.5	82.5
Brick, wood and tile	26.8	41.6	37.5	5.8
Other	3.0	16.6	25.1	11.7
Location where cooking activity usually takes place				
Specialized kitchen[a]	88.8	24.3	54.7[b]	94.6
In bedroom	11.2[c]	4.0	45.3[c]	0.0
In living room	NA[c]	71.7[d]	NA[c]	5.4
Other characteristics				
Houses with gaps between wall and roof	69.5	18.2	11.1	1.7
Kitchens with window	90.3	73.8	72.8	60.3
Kitchens with ventilation fans	1.3	0.6	14.9	4.8

Numbers show % households unless otherwise stated.

[a]Specialized kitchen is separated by a wall or glass from the sleeping/living room. The two areas have separate entrances in Gansu, and are connected with doors in Guizhou and Shaanxi. In Inner Mongolia specialized kitchen may either have a separate entrance or connected to the sleeping/living room with a door.

[b]Given the changing house construction in Inner Mongolia, specialized kitchen may be fully or partially separated from the living/sleeping area. In 4.8% of study households, it was connected to the living/sleeping room with a partial separation wall; in 49.5% of study households, it was connected to the living/sleeping room with a full separation wall (with door or glass windows; Fig. 3n); in 0.4% of study households, it was outside the house.

[c]In Gansu and Inner Mongolia, living and sleeping areas are usually the same, in one room.

[d]Most households in Guizhou also have a specialized kitchen with a biomass stove which is generally used for cooking animal feed or for large events (e.g. Spring Festival) (see also Table 4).

Fig. 3. Stoves in the four study provinces: (a) and (b) biomass cooking stoves in Gansu, Guizhou, and Shaanxi; (c) chimney of an unimproved stove; (d) "bed-stove" configuration in Inner Mongolia (the bed is behind the stove and connected to it); (e) metal coal stove in Guizhou; (f) air circular stove in Guizhou; (g) and (h) chimney of stoves in Guizhou province, ending in the attic; (i) and (j) ground coal stove (primarily for heating) in Shaanxi; (k) and (l) fuel compartment of a bed-stove in Gansu; (m) fire pan; (n) specialized kitchen and alternative bed-stove design in Inner Mongolia. The bed is on the right side of the glass divider, but is heated with the stove on the left.

Shaanxi where cooking area is connected to the main house, Guizhou where cooking is often performed in the living area (combined with heating in winter), and Inner Mongolia where cooking, living, and sleeping areas are the same. The attic in houses in Guizhou requires a longer chimney to remove or reduce pollution from the house. In most houses, the chimney ends in the attic (Figs. 3g and h). Because the ceiling between the ground floor and the attic is porous, pollutants then disperse back into the main floor, even to those areas (e.g. bedroom) where there is no stove (He et al., 2005; Jin et al., 2005).

Coal is a common fuel in both Guizhou and Shaanxi, used by nearly all households for heating and by many for cooking. The types of coal and combustion technologies are however different in the two provinces. Most of the coal used by the study households in Guizhou is bituminous coal

Table 4
Fuel and stove characteristics in the study households

	Gansu ($n = 463$)	Guizhou ($n = 476$)	Inner Mongolia ($n = 323$)	Shaanxi ($n = 479$)
Main cooking fuel				
Coal	1.6	81.4	8.0	48.2
Biomass (wood and crop residue)	98.4	17.9	91.7	51.8
Liquefied petroleum gas (LPG)	0.0	0.1	0.3	0.0
Biogas	0.0	0.6	0.0	0.0
Main heating fuel				
Coal	21.7	97.3	90.8[a]	97.4
Biomass (wood and crop residue)	78.3	2.7	98.7[a]	2.5
LPG and biogas	0.0	0.0	0.2	0.1
Commonly used cooking stove(s)[b]				
Biomass stove[c]	98.8	40.8	95.2	66.1
Coal stove[d]	2.7	75.5	44.0	57.1
Fire pan[e]	15.4	0.2	7.9	0.1
Open fire	8.0	0.3	0.6	0.1
Other	0.1	0.6	1.1	0.1
Commonly used heating stove(s)[b]				
Biomass stove[f]	42.5	7.2	91.8	4.3
Coal stove[d]	32.6	94.4	8.2	96.7
Fire pan[e]	35.8	0.7	0.4	0.1
Open fire	6.3	0.7	0.4	0.3
Other	3.0	0.9	1.1	0.3
Ventilation characteristics of biomass stoves[g]				
With flue	96.7	30.3	97.1	11.6
Flue going out of the house	94.4	18.4	94.4	6.7
Flue higher than eave	22.8	8.6	82.6	6.1
Ventilation characteristics of coal stoves[g]				
With chimney	48.4	91.6	97.2	2.7
Chimneys going out of the house	46.0	14.5	93.9	2.3
Chimney higher than eaves	5.6	6.7	63.5	1.4

Numbers show % households unless otherwise stated.

[a]Biomass is the primary fuel in Inner Mongolia, and is used during the day for cooking. The bed-stove configuration is the most prevalent stove (98.7% of the study households) for heating, in which biomass fuel is used. At the same time, some households (90.8%) add coal to their biomass stove during the night since coal burns more slowly, and hence continues heating for a longer time.

[b]Multi-stove use implies that some households use more than one stove for heating or cooking, hence the numbers add to more than 100%.

[c]Biomass cooking stove in Guizhou and Shaanxi are brick or clay stoves (Fig. 3a). Most biomass stoves are ''unimproved stoves'' [i.e. without chimney or with chimney that does not go outside the house or beyond the eave (Fig. 3c)]; see also Sinton et al. (2004) for discussion of ''improved'' and ''unimproved'' stoves in China. Biomass cooking stoves in Gansu are similar in structure but larger (Fig. 3b). Most biomass stoves are without chimney or with chimney that does not go outside the house or beyond the eave. In Inner Mongolia, a cooking biomass stove is made from brick or clay and also connected to the bed acting as a bed-heating stove (Fig. 3d).

[d]In Guizhou more than 60% coal stoves are made from a simple, enclosed metal container with limited insulation and no door (Fig. 3e) and the remaining 40% are iron made ''air circular'' stoves (Fig. 3f). Most coal stoves in Guizhou have a chimney, but few have chimney that goes outside the house and beyond the eave (Figs. 3g and h). In Shaanxi, coal stoves for heating are built underground. Unimproved coal stove is an underground stove without chimney (Figs. 3i and j), and improved coal stove is the underground stove with a chimney that goes out of the house and above the eave.

[e]In Gansu a fire pan is used for either heating or cooking (Fig. 3m).

[f]Biomass heating stove is a bed stove (burning biomass under the bed) with a door opening inside or outside the room (Figs. 3k and l).

[g]All numbers given as proportion (percent) of all stoves of the specified type.

and/or anthracite, obtained from surface exposures (Finkelman, Belkin, & Zheng, 1999). In parts of the province, which include the study region, these coals have undergone mineralization, causing their enrichment in potentially toxic trace elements such as arsenic and/or fluorine (Finkelman et al., 1999). In

Shaanxi, most of the coal used for household energy is stone-coal (also called bone-coal)[3] with high concentrations of sulfur, and in some locations fluoride and/or arsenic.

Exposure behavior

In addition to the above energy–housing patterns, IAP exposure is affected by behavioral factors including energy use behavior, ventilation behavior, and time-activity patterns of household members. A summary of important exposure-related behaviors in the four Chinese study provinces is provided in Table 5.

As seen in Table 5, heating is an important source of IAP exposure in all provinces, especially in the northern provinces with colder climate, and for all household members. The role of heating as a source of IAP exposure has also created a unique epidemiological patterns in China, in which both female and male Chinese non-smokers have substantially higher rates of mortality from lung cancer and chronic respiratory disease than other populations, with those in northern, and colder, parts of the country having even higher rates (Liu et al., 1998). Cooking affects exposure above and beyond heating, and its contribution is modulated by housing and behavioral factor as described below.

Energy–housing–behavior interactions and intervention options

Main IAP exposure mechanisms and interventions options, involving the interactions of energy technology, housing, and energy use behavior, in these four Chinese provinces with diverse socio-cultural and geographical characteristics, include:

- In homes with separate cooking and living/sleeping areas, and different cooking and heating stoves (many households in Gansu and Shaanxi), cooking stove is a source of exposure throughout the year for women and young children who may spend time near their mothers. In such cases, the duration of exposure from cooking is a few hours per day, and stove improvement alone can reduce exposure.[4] Even in these households, smaller cooking tasks (e.g. making tea) take place in the living area, for example on a fire pan or ground stove, which results in IAP exposure for all household members. In these households heating is a source of exposure, possibly to a larger extent than cooking, for all household members in winter (He et al., 2005; Jin et al., 2005). Therefore, reducing exposure requires improvements in heating stove above and beyond that used for cooking. Improving the heating stove may indeed be more difficult or costly because, maintaining the heating function while achieving better stove insulation and ventilation of stove requires more sophisticated stove design.
- In households where cooking and living areas are the same, and cooking and heating stoves are the same (most households in Inner Mongolia), cooking activities are a source of exposure throughout the year for all household members. Exposure from cooking also depends on time-activity budgets (amount of time spent inside when cooking takes place), and is likely to be highest for women. In winter, heating requires stove use, and hence causes exposure, for a period as long as or longer than cooking. In principle, stove improvement can reduce indoor concentrations and exposure. When cooking and/or heating stoves use biomass (wood or crop residues), fuel size may prevent stove door from closing, and hence result in smoke leaking into the cooking/living area. Therefore, stove improvements would have to be accompanied with housing changes that separate the main stove body from the living area (i.e. create a specialized kitchen) (Fig. 3n).[5]
- Most households in Guizhou have a separate cooking area and stove, which are used only occasionally (mostly for animal food). Rather, most cooking takes place in the living area, combined with heating in winter. These households in practice have the same exposure patterns as those with combined cooking/living areas and cooking/heating stoves. The type of stove in

[3]The terms "bone-coal" and "stone-coal" are generally used for carbonaceous shales, organic-rich rocks with more than 50 weight percent ash yield. Shaanxi is a major coal producer. The use of stone-coal, which is generally considered lower quality, is nonetheless common in the poorest households including those in the study area.

[4]In the poorest households in both Gansu and Shaanxi, the cooking and living/sleeping areas are connected without a door (Table 3). In such cases, cooking affects other household members as well, with exposure depending on their time-activity budgets (time spent inside during cooking).

[5]An additional benefit of separating the main stove body from the living area is reductions in burns among young children from contact with the stove, a major hazard in Inner Mongolia.

Table 5
Energy behavior and time-activity budgets as determinants of exposure

	Gansu	Guizhou	Inner Mongolia	Shaanxi
Cooking	• Affects primarily women who spend > 2 h per day cooking human and animal food. • Some cooking and making tea takes place on fire pan in the living and sleeping area in morning and night time (Fig. 3m), affecting other household members.	• Affects primarily women who spend 2.5–3 h per day cooking human and animal food. • Cooking the main meal takes place in the living area, affecting other household members.	• Affects all household members since all cooking takes place in the same room as living and sleeping. • Women, who spend > 2 h per day cooking human and animal food, are particularly affected because during the day other household members may be away.	• Affects primarily women who spend 2.5–3 h per day cooking human and animal food. • Some cooking and heating water takes place on the ground-stove in the living area, affecting other household members.
Heating[a]	• Affects all household members who spend time around the fire pan or on the heated bed, especially children and the elderly who spend most time in the living area. • Seasonal pattern (approximately 4–6 months).	• Affects all household members who spend time around the heating stove in the living area. • Because the chimney in most houses only goes to the attic area, smoke disperses in the house through the porous separation of main floor and attic. • Seasonal pattern (approximately 6–7 months).	• Affects all household members who spend time on the heated bed, especially children and the elderly who spend most time inside, and women who use the same stove for cooking. • Seasonal pattern (approximately 6–7 months).	• Affects all household members who spend time around the ground-stove heating stove in the living area. • With no chimney, smoke disperses in the house directly from the stove. • Seasonal pattern (approximately 5–6 months). • Most residents stated that the ground-stoves in bedrooms were no longer used for heating, because of concerns about CO poisoning.
Food drying and storage	N/A	• Food is dried directly above the stove or in the attic above the chimney outlet (58% corn and 85% chili) (Fig. 3g). Most of the rice (68%) is stored in bags during drying. • 54% of households do not wash corn, and 81% do not wash chili, before eating. • Corn is mainly used for animal feed in the study households.	N/A	• In the past, food was stored over the stove. Public health programs have promoted alternative behaviors to store food in bags and/or away from the stove.

[a]Although the provinces have relatively similar heating seasons, the "intensity" of home heating is higher in the colder provinces (Table 1), particularly in Inner Mongolia. In Guizhou for example, increased humidity and cloudiness is the main feature of heating season. Therefore, stove is used for shorter daily durations and with less intensity than in Inner Mongolia. Similarly, windows may be left open in Guizhou during the heating season but they are closed and sealed in Inner Mongolia.

Guizhou lends itself to improvement without changes to housing (Fig. 3f). Because the porous ceiling between the ground floor and the attic allows pollutant dispersion back into the main floor, stove improvements must be accompanied with increased chimney length to limit the dispersion of pollutants inside the house and reduce exposure.

- A route of exposure unique to Guizhou, a relatively humid region, is food drying and storage. The role of current food drying practices is two-fold: First, drying food over smoke (Fig. 3g) results in bioaccumulation of pollutants like fluoride or arsenic in dried food (Finkelman et al., 1999), which is often not washed before consumption (Table 5); and second, keeping the end of chimney inside the house, results in dispersion of smoke in the house (He et al., 2005; Jin et al., 2005). Alternative food drying techniques and arrangements (e.g. drying food under the sun in the summer prior to storage or shared community food storage space) are needed to reduce exposure through ingestion, and to provide an alternative to current chimney arrangement.

Knowledge and perception of IAP risks and interventions

Knowledge and perceptions of risk and interventions are important determinants of, or obstacles to, adoption of interventions. Risk knowledge, in turn, may depend on socio-demographic factors such as age or education which affect access to, and utilization of, information. Table 6 presents the respondents' knowledge of IAP as a health hazard stratified on province and socio-demographic characteristics. The questions focused on health as a broad concept rather than on specific diseases caused by IAP. This was because perceiving an exposure as hazardous should contribute to intervention adoption, even without specialized knowledge on the etiology of specific diseases affected by it (Fisher, Fisher, & Harman, 2003). Questions were also asked about smoking and environmental tobacco smoke (ETS) for two reasons: First, more than 60% of adult Chinese males are smokers (WHO, 1997) and many pollutants and hazards are shared, at varying concentrations, between biomass and coal smoke and direct or environmental exposure to tobacco smoke; and second, although much of the tobacco consumed in China is produced domestically, there has been little effort on tobacco control, providing a broadly parallel subject for evaluating risk knowledge.

Table 6 shows that in all provinces and socio-demographic groups, the majority of respondents were aware that smoke from cooking and heating is a health hazard. Guizhou, a poor province with a high proportion of population from ethnic minorities and limited health education for most health risks, and a tobacco growing region, had the lowest knowledge of health risks associated with respirable pollutants from any source. The younger respondents (those below the age of 40 years) had the highest knowledge of health hazards. There was a slight gradient by education and income, with those in higher socioeconomic status generally having higher knowledge of risk.

Knowledge of risk and hazard associated with energy use may exist in forms other than direct linkages with health, including perceptions about how energy use may affect the quality of air inside the home. Table 7 shows the knowledge of the causes of IAP. Further, 16%, 12% and 5% of interviewees knew that smoke from fuel combustion contains harmful components, including dust, carbon monoxide (CO), sulfur dioxide (SO_2), fluoride, arsenic and/or "other chemicals" in Guizhou, Shaanxi and Gansu, respectively. The proportions in Table 7 are generally lower than those in Table 6, which indicates that, while people may be aware of the health hazards of cigarette or stove smoke, they do not necessarily link this hazard with indoor air quality, per se. The only exception was Inner Mongolia, where there have been recent efforts to encourage the installation of ventilation fans in homes to "improve indoor air quality".

Even if knowledge about health risks exists, it should be coupled with knowledge about effective interventions (or solutions) for individuals and households to choose alternative energy, housing, or behavioral options; see also Fisher et al. (2003). Table 8 illustrates that awareness about interventions for reducing indoor smoke was relatively low, except for "improving stove and chimney" in Shaanxi province, where an improved stove program has been in place, and in Inner Mongolia, where new efforts are under way to improve the design of the bed-stove configuration in newly constructed homes. In particular, in all provinces, small proportions of respondents thought that improving stove handling skill would reduce indoor smoke from energy use. A total of 49%, 77% and

Table 6
Knowledge of the health effects of "respirable pollutants"

By province	Gansu ($n = 463$)	Guizhou ($n = 476$)	Inner Mongolia ($n = 323$)	Shaanxi ($n = 479$)
Smoking is a health hazard	93.3	60.1	90.4	80.1
ETS is a health hazard	76.0	47.7	83.3	74.9
Smoke from burning fuel or from cooking is a health hazard	74.5	53.8	77.3	59.7
By age	$<$ 40 years ($n = 1226$)	40–59 years ($n = 455$)	$\geqslant$60 years ($n = 60$)	
Smoking is a health hazard	82.2	76.9	60.3	
ETS is a health hazard	71.7	65.0	52.5	
Smoke from fuel use for cooking or heating is a health hazard	67.5	60.3	58.3	
By education	Illiterate ($n = 472$)	Elementary school ($n = 760$)	Junior High school ($n = 387$)	Senior High School and higher ($n = 63$)
Smoking is a health hazard	71.5	82.2	85.4	92.1
ETS is a health hazard	60.2	70.0	76.9	82.3
Smoke from fuel use for cooking or heating is a health hazard	53.6	68.6	70.8	85.5
By income (*combined value of cash income and subsistence food in RMB*)	$<$1500 ($n = 137$)	1500–2999 ($n = 442$)	3000–4499 ($n = 452$)	$\geqslant$4500 ($n = 684$)
Smoking is a health hazard	62.2	75.6	79.2	86.8
ETS is a health hazard	50.4	63.1	67.6	77.8
Smoke from fuel use for cooking or heating is a health hazard	55.6	65.0	61.9	62.2

Numbers show % respondents in each province or age/education/income category.

79% of respondents could not identify alternative fuels in Gansu, Guizhou and Shaanxi, respectively.

Discussion

This comparative study of four Chinese provinces illustrates that exposure to indoor smoke results from interactions of housing, energy technology, and energy use behavior, themselves determined by the diverse socio-cultural and geographical characteristics, and energy infrastructures. Multiple uses of energy—for cooking, heating and purposes such as food drying—result in multiple routes of exposure to IAP, which vary considerably from one province to another. This variation in energy use and exposure in turn requires more integrated energy technology and energy behavior interventions that fulfill the original purpose of energy use while reducing exposure.

Because the focus of the study was on the interactions of technology and behavior in IAP exposure and interventions, our data on the knowledge and perceptions of IAP risks are limited to small number of targeted questions. The results of the simple analysis nonetheless indicate that knowledge of health hazards of an exposure, while likely to be a necessary factor in behavior change, is not sufficient when (i) exposure behaviors are closely linked to day-to-day activities of households such as cooking and heating, or have other welfare effects (e.g. food drying or maintaining constant temperature for raising silk worms) and (ii) alternative technologies and behaviors that reduce exposure and fulfill the original purpose of energy use, without substantial additional cost and effort are not readily available, or are not perceived to be available by users. This may be in contrast to those interventions offered through formal health services

Table 7
Knowledge of the sources of "indoor air pollution" by province

	Gansu ($n = 463$)	Guizhou ($n = 476$)	Inner Mongolia ($n = 323$)	Shaanxi ($n = 479$)
Cooking	36.7	51.6	77.7	63.1
Heating	16.8	38.3	57.6	54.1
Smoking	16.0	42.4	71.5	55.7
Poor/limited ventilation	23.3	49.0	63.8	42.3

Numbers show % respondents in each province.
Indoor air pollution was defined as "contaminated/polluted/bad air inside the house" in the question.

Table 8
Knowledge of methods for reducing smoke from energy use

	Gansu ($n = 463$)	Guizhou ($n = 476$)	Inner Mongolia ($n = 323$)	Shaanxi ($n = 479$)
Improving stove	29.2	32.4	61.9	71.6
Improving chimney	21.4	29.7	26.0	68.4
Improving the skills of stove handling[a]	12.5	19.4	19.8	13.9
Improving ventilation[b]	57.7	34.8	65.9	46.6
No smoking indoors	4.5	22.4	44.3	15.7
Spending less time using stove	6.9	17.6	10.8	8.3

Numbers show % respondents in each province.
[a]Examples of behaviors given to respondents included splitting wood into small pieces, cleaning the ash regularly to allow better burning, etc.
[b]Examples include opening windows and doors.

(e.g. child immunization or case management of specific diseases) where intervention adoption may be encouraged through health education or those interventions whose outcomes do not jeopardize other welfare generating activities (e.g. smoking for which the desired alternative behavior is cessation).

Therefore, although the finding of this study is compatible with the general health behavior models such as the information–motivation–behavioral skills model (Fisher et al., 2003), the important roles of technology–behavior interface and other welfare consequences of technology use require careful specification of the "motivation" and "behavioral skills" components of this model. In particular, a better understanding of the technology–behavior interface would allow designing technological interventions that account for, and are robust to, behavioral factors or to provide individuals and households with alternative behaviors that fulfill the original purpose of energy use while reducing exposure (Barnes et al., 2004). Future research on risk perception and mitigation should also consider (i) the individual, household, and contextual determinants of risk perception and behavior as has been conducted for environmental risk management in the industrialized nations or for behavioral risks such tobacco smoking (Krimsky & Golding, 1992; Slovic, 1987), and (ii) the determinants of technology diffusion as has been examined in the case of agricultural technologies (Antle & Crissman, 1990; Barnett, Payne, & Steiner, 1995; Conley & Udry, 2001; Feder & Umali, 1993; Frossard, 1994).

There are a number of implications from this study for IAP intervention technologies and programs in China. First, design and evaluation of new technologies should account for all purposes for which it is used, and for how alternative technologies would be used to serve all these needs. For example, a better stove in Guizhou would not reduce exposure to fluoride and arsenic if food is dried over the smoke; neither would it reduce exposure to inhaled pollutants if the chimney remains inside the attic for the purpose of food drying. On the other hand, an improved stove with a longer chimney, coupled with drying food in the sun during the summer harvest season and food washing can reduce exposure through inhalation and ingestion. Second, above and beyond household level knowledge, behavior, and economic

Table 9
Household fuel choices and barriers; adopted from Kammen, Bailis, and Herzog (2001) and Leach (1992)

Energy source	Selected determinants of adoption		
	Equipment costs	Nature of payments for fuel	Nature of access[a]
Electricity	Very high	Lumpy	Restricted
Bottled gas (LPG, butane, natural gas)	High	Lumpy	Often restricted; bulky and specialized transport
Kerosene	Medium	Small	Often restricted in low income areas
Charcoal	Low	Small	Good; dispersed markets and reliable supplies though prices and supplies can vary seasonally
Coal	Low-medium	Small; zero if gathered	Good; dispersed markets and reliable supplies
Fuelwood	Low or Zero	Small; zero if gathered	Good; dispersed markets and reliable supplies though prices and supplies can vary seasonally
Crop residues, animal dung	Low or Zero	Small; zero if gathered	Variable: depends on local crops and livestock holding; high opportunity cost where residues are used as fodder and/or dung is used as fertilizer

[a]Nature of access refers to ease at which households can choose the fuel if they are willing to pay for it, determined by physical and institutional infrastructure (Ezzati et al., 2005).

resources, community-level and regional physical and institutional energy infrastructures are important, but often overlooked, components of successful intervention programs (Ezzati, Utzinger, Cairncross, Cohen, & Singer, 2005) (Table 9). In particular, geological and ecological characteristics as well as the spread of coal briquette and stove markets are important determinants of fuel choice. Regionally, cleaner coal (e.g. with lower arsenic and fluorine concentrations) and better stoves would be difficult to sustain in the absence of a delivery and marketing system that facilitates household access. Similarly, trained workers to construct improved stoves are essential to diffusion of new technologies. At the community level, food drying and storage can take place in community-operated shared spaces, which would remove households' perceived need for terminating the stove chimney inside the attic.

There is a great deal of interest in interventions to reduce the health hazards associated with indoor smoke from household use of solid fuels in international development and public health arenas, possibly paralleling those of water and sanitation in the last quarter of the 20th century. Examples include the inclusion of solid fuel use and its health risks for children and women in the MDGs and in numerous child and maternal health programs. Limited economic resources and lack of political or individual resolve are the commonly cited reasons for the low coverage or community effectiveness of IAP interventions, appropriately leading to public health advocacy (Warwick & Doig, 2004). Public health research continues to play an important role for strengthening the scientific evidence for advocacy, as it did in the case of clean water and sanitation. Early experiences of improved stove programs (Agarwal, 1983; Kammen, 1995a; Krugmann, 1987; Manibog, 1984), as well as those of agricultural technologies (Antle & Crissman, 1990; Barnett et al., 1995; Feder & Umali, 1993; Frossard, 1994) and water and sanitation (Drangert, 1993) illustrate that technology diffusion and utilization may be hindered by social and behavioral factors. Therefore, beyond advocacy, scientific research must contribute to designing new technologies and implementation strategies that recognize and are robust to, the existing limits in economic resources, social norms, and human behavior, as described here in the case of four poor provinces in China.

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