Community effectiveness of stove and health education interventions for reducing exposure to indoor air pollution from solid fuels in four Chinese provinces

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Abstract
Indoor air pollution (IAP) from biomass and coal is a leading cause of mortality and disease burden in the developing world. There is limited evidence of the community effectiveness of interventions for reducing IAP exposure. We conducted a community-based intervention study of stove and health education interventions in four low-income Chinese provinces: Gansu, Guizhou, Inner Mongolia, and Shaanxi. Separate townships in one county in each province were assigned to stove plus behavioral interventions, behavioral interventions alone, and control. Data on household fuel and stove use, and on concentrations of respirable particles (RPM), carbon monoxide (CO), and sulfur dioxide (SO\textsubscript{2}), were collected in peak and late heating seasons before and after interventions. The effectiveness of interventions was evaluated using difference-in-difference analysis. Pollutant concentrations were also measured in controlled tests, in which stoves were operated by expert users. In controlled tests, there was consistent and substantial reduction in concentrations of RPM (>88\%) and CO (>66\%); in the two coal-using provinces, SO\textsubscript{2} concentrations declined more in Shaanxi than in Guizhou. In community implementation, combined stove and behavioral interventions reduced the concentrations of pollutants in rooms where heating was the main purpose of stove use in the peak heating season, with smaller, non-significant, reduction in late heating season. Gansu was the only province where combined stove and behavioral interventions led to pollution reduction where cooking was the primary purpose of stove use. Compared to the control group, no significant IAP reductions were seen in groups with health education alone.

Keywords: household energy, biomass, coal, stove, indoor air pollution, particulate matter, carbon monoxide, sulfur dioxide, intervention study, global health, China

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1. Introduction

Biomass fuels (wood, charcoal, crop residues, and dung) and coal are the primary source of domestic energy for one half of the world’s population [1]. The combustion of biomass and coal, especially in open or poorly ventilated stoves, emits hundreds of health-damaging pollutants [2], that have been associated, with varying degrees of evidence, as a cause of acute respiratory infections (ARIs), chronic obstructive pulmonary disease (COPD), lung cancer (for coal smoke), asthma, nasopharyngeal and laryngeal cancers, tuberculosis, and diseases of the eye [1]. Indoor air pollution (IAP) from household use of biomass and coal resulted in more than 1.6 million deaths and nearly 3% of the global burden of disease in 2000 [1, 3]. The large disease burden associated with exposure to IAP, which primarily affects marginalized socio-demographic groups, have motivated efforts towards interventions. The proportion of the population who use solid fuels is also an indicator for measuring progress towards Goal 7 of the Millennium Development Goals (ensuring environmental sustainability).

The scientific evidence for designing effective interventions and intervention delivery programs has not kept pace with the advocacy to reduce the burden of disease associated with IAP. For example, there was a great deal of initial enthusiasm about the so-called improved (high-efficiency and low-emissions) stoves [4, 5]. However, efficiencies and emissions of alternative stoves were often measured in controlled conditions that were different from those of actual household use. The community effectiveness of stoves in reducing human exposure and disease burden has rarely been systematically evaluated: the existing evidence, although limited, indicates that their IAP reduction benefits may not reach the levels observed in controlled tests [6–10].

In this paper, we report on a study that evaluated the IAP reduction benefits of stove and behavioral interventions in a community setting. To the best of our knowledge, this study is one of two ongoing IAP intervention studies in the world, and the only one which includes both technological and behavioral interventions. We measured the efficacy of stoves under controlled conditions as well as their effectiveness under conditions of actual household use, to also assess the role of user behavior in stove performance.

2. Study location and participants

The study was conducted in Gansu, Guizhou, Inner Mongolia, and Shaanxi provinces of China (see supplementary online figure S1 available at stacks.iop.org/ERL/1/014010). More than 70% of China’s households use biomass and coal for cooking, heating, and purposes such as drying and storing food [1, 11]. Indoor air pollution caused an estimated 500,000 deaths and 2.5% of disease burden 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 fourth leading cause of regional mortality and fifth leading cause of regional disease burden [1, 3]. The role of heating as a source of IAP exposure has created a unique epidemiological pattern 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 the northern, and colder, parts of the country having even higher rates [12]. In the 1980s and 1990s, China implemented an ambitious program to disseminate so-called improved stoves [5]. A recent evaluation of the program has illustrated that the design and performance of the new stoves was highly variable, with many of the stoves labelled as ‘improved’ lacking flues or other characteristics necessary for reducing IAP [10].

Our study took place in one county in each of the four provinces. In each province, three clusters of villages (two in Inner Mongolia) were selected for the study. Each cluster of villages was in a different township, except in Shaanxi where two of the three clusters were in the same township, physically separated by a mountain (see supplementary online figure S2 and table S2 available at stacks.iop.org/ERL/1/014010). We used the township as the unit of intervention for two reasons: (i) implementing stove and health education interventions requires training stove makers and health workers, who often work at the township level; and (ii) implementing health education in separate townships (or parts of a township that are physically separated) would eliminate or greatly reduce the ‘contamination’ of a control group through contacts among participants, or through interactions with the same group of health workers. Criteria for the selection of townships and households are provided in the supplementary online material (available at stacks.iop.org/ERL/1/014010).

3. Study procedure

The study procedure is presented in figure 1. Between March 2003 and January 2004, we measured the concentrations of multiple indoor pollutants, including their day-to-day, seasonal, and spatial variation, in approximately 25–30 randomly selected households in each study township, some with multiple measurements (the number of household-days of pollution measurement is given in table 2). We also documented the technological, housing, behavioral determinants of exposure through household surveys, as reported in detail elsewhere [13, 14]. This information was used to design stove and behavioral (health education) interventions specific to each of the four provinces, implemented between April and October 2004. The interventions took into account energy needs for cooking and heating, baseline fuel use and stove design, housing characteristics, and socio-cultural factors such as food types and food preparation (see supplementary online material available at stacks.iop.org/ERL/1/014010 for details of interventions). Figure 2 shows the stoves and stove ventilation in the four study provinces. The three clusters of village in each province were divided into three groups: (i) stove plus behavioral intervention (referred to as group S + B); (ii) behavioral intervention (referred to as group B); and (iii) control (referred to as group C). In Inner Mongolia, only two
Figure 1. Project timeline.

Figure 2. Stoves and stove ventilation in the four study provinces. Before interventions: (a) and (b) cooking ranges in Gansu, Guizhou, and Shaanxi; (c) chimney of a cooking range; (d) and (e) metal coal stove in Guizhou with chimney ending in the attic; (f) ground coal stove (primarily for heating) in Shaanxi; (g) heated bed in Gansu; (h) fire pan; (i) bed–stove configuration in Inner Mongolia (the bed is behind the stove and connected to it). After interventions: (j) and (k) cooking ranges in Gansu and Shaanxi; (l) chimney of a cooking range; (m) and (n) air circular stove in Guizhou with chimney ending outside; (o) ventilated ground stove in Shaanxi; (p) and (q) new heated bed construction and design in Gansu.

clusters (B and C) were included because stove improvement would have to be accompanied with changes in house design which was outside the scope of this study. Between December 2004 and April 2005 we measured the same pollutants in the same households as those in baseline measurements, and at the same points.
In addition to household measurements, we measured pollution under controlled stove use conditions, equivalent to ideal stove use behaviors, for old and new stoves in a small number of households. For each stove, the locally common fuel was used in the test (table 1). The concentrations of pollutants were measured for the duration of combustion of an approximately fixed amount of fuel.

4. Methods

4.1. Pollution measurement

We used three main indicator pollutants: respirable particles (RPM), carbon monoxide (CO), and sulfur dioxide (SO2). Epidemiological and toxicological evidence has established RPM as a key indicator pollutant for health effects of combustion products. In addition to health effects such as poisoning, CO is an indicator of total combustion. CO concentrations in these homes were closer to international standards and guidelines than those of RPM and SO2 [14]; hence, the observed changes are less likely to have important health implications. SO2 is an important pollutant in provinces where coal is commonly used (Guizhou and Shaanxi) and measured primarily in those provinces; low SO2 levels in Gansu and Inner Mongolia were confirmed in our pilot and baseline studies [14, 15]. Detailed measurement methods and equipment are described in the supplementary online material (available at stacks.iop.org/ERL/1/014010).

4.2. Statistical analysis

The change in the concentrations of pollutants before and after intervention within each group (C, B, and S + B) was estimated using two-sided, two-sample, independent \( t \)-tests; change between groups (i.e. difference-in-difference) was
estimated using the following regression:

\[ C = \beta_0 + \beta_1 \text{Group} + \beta_2 \text{Time} + \beta_3 \text{Group} \times \text{Time} \] (1)

where \( C \) is the measured concentration of pollutant; \( \text{Group} \) refers to one of the three groups (C, B, and S + B); \( \text{Time} \) refers to pre- or post-intervention; and \( \beta \) denotes statistical interaction. In this regression equation, \( \beta_1 \) measures the average difference in pollution between any pair of control or intervention groups; \( \beta_2 \) measures the average change in pollution after intervention, and \( \beta_3 \) measures the difference in pollution change between the two groups (e.g. between control and intervention). We compared each intervention group to the control group separately, and also compared the control and intervention. We compared each intervention in pollution change between the two groups (e.g. between 

\[ \Delta \]

All analyses were conducted in Intercooled Stata, version 8.0.

5. Results

5.1. Housing, fuel, and stove

Information on housing in the participant households, with emphasis on kitchen characteristics and location of cooking, is provided in supplementary online tables S5 (available at stacks.iop.org/ERL/1/014010). Supplementary online tables S6 to S8 (available at stacks.iop.org/ERL/1/014010) show the summary of fuel and stove use in the study households, before and after intervention. Multi-fuel use and multi-stove use are common features of household energy in China because of fuel availability and multiple uses of energy (e.g. cooking and heating) (see also Sinton et al [10]). In particular, although coal is the nearly universal fuel for heating in Guizhou and Shaanxi, some households in Shaanxi and in the S+B group in Guizhou used biomass for cooking. Conversely, biomass was the main cooking fuel in Gansu and Inner Mongolia; but in both provinces coal had an important role for heating, as the main fuel or in addition to biomass. There were improvements in stove technical characteristics (i.e. whether the stove had a chimney; and whether the chimney went outside the house, and its length) in group S + B, as intended in the intervention design. There were also some improvements in stove ventilation among group B, such as improvements in chimney design and construction in Guizhou and Shaanxi or reduced reliance on a stove-bed device in Inner Mongolia.

5.2. Concentrations of pollutants

In controlled tests (table 1), new stoves showed consistent and substantial reduction in concentrations of RPM (>88%) and CO (>66%); most reductions were statistically significant despite the small number of tests. For SO$_2$, there was larger reduction in Shaanxi, where the SO$_2$ concentration is higher due to the type of coal used [14], than in Guizhou. These figures show the performance of stoves under ideal conditions, or the potential for improvement in indoor air quality (i.e. equivalent to stove efficacy).

The levels and changes in concentrations of pollutants under conditions of household use (table 2) show substantially more heterogeneous stove performance than in controlled tests. Note that the proportional reduction in 24 h household
those in controlled tests for two possible reasons: (i) the user skills and behaviors may lower the pollution-reducing efficacy of a stove; and (ii) 24 h measurements consist of periods when the stove is burning intermittently with those when the stove is off (see table 4 in Jin et al [14]). Therefore the proportional reduction in 24 h concentration may be less than those observed in controlled tests, which consisted only of burning periods.

The RPM concentrations declined (Δ1 in table 2) in both of the intervention groups (S + B and B) as well as in the control group (C) after the interventions were implemented, concentrations after stove intervention may be lower than those in controlled tests for two possible reasons: (i) the user skills and behaviors may lower the pollution-reducing efficacy of a stove; and (ii) 24 h measurements consist of periods when the stove is burning intermittently with those when the stove is off (see table 4 in Jin et al [14]). Therefore the proportional reduction in 24 h concentration may be less than those observed in controlled tests, which consisted only of burning periods.

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with few exceptions (e.g. group B in Guizhou in the Dec–
Jan measurement period where there was a 9% non-significant
increase). Given the physical separation of the three clusters
of villages, it is unlikely that the decline in group C is a
consequence of a contamination effect. Rather, this may
represent determinants of pollution that are external to the
To evaluate the effectiveness of interventions, the reduction in pollution should be compared between intervention and control groups (Δ2 and Δ3 in table 2). In Gansu, group S + B consistently had a larger decline in concentrations of RPM and CO than group C, in both cooking and living/bed rooms. The patterns in the two rooms and in the Dec–Jan period versus in the Mar–Apr period were related to multiple purposes of energy use. The S + B group interventions led to larger pollution reduction in the peak heating season (Dec–Jan) than in the late heating period (Mar–Apr) in the living/bed room (Δ2 was −367 μg m⁻³ for RPM and −22.1 ppm for CO in Dec–Jan versus −70 μg m⁻³ for RPM and 1.7 ppm in Mar–Apr); the reductions were more similar across seasons in the cooking room (e.g. −298 and −230 μg m⁻³ for RPM in Dec–Jan and Mar–Apr, respectively). The reduction in the living/bed room were larger than those in the cooking room in Dec–Jan and smaller in Mar–Apr.

With few exceptions, in Guizhou, group S + B had larger reductions than group C for all three measured pollutants in Dec–Jan, but smaller reduction in Mar–Apr, especially for RPM; none of the results in Mar–Apr were statistically significant. The finding in Mar–Apr is largely caused by the unusually high concentrations in the baseline measurements for group C (621 μg m⁻³ in the cooking/living room and 552 μg m⁻³ in the bedroom) which led to very large observed post-intervention reductions in this group. Of the 33 baseline measurements, 9 were above 1000 μg m⁻³, with relatively large influence on the mean; 6 of these were measured in the same village within a 2-day period (see table 2).

The effects of group S + B interventions on different pollutants and in different months were least consistent in Shaanxi, with the only noticeable reduction compared to group C being for RPM and SO₂ (but not CO) in the bedroom. This finding may be because the new stoves in bedrooms lowered the concentrations of RPM and SO₂ through better combustion/ventilation, but not that of CO which is a crude indicator of total combustion. The reductions in the bedroom were larger in Dec–Jan than in Mar–Apr, reflecting the seasonal nature of heating. In this province, group C did better than group S + B in terms of change in the concentrations of all three pollutants in the living room in Dec–Jan, although sample sizes were smaller because fewer households used their living room stove. The cooking room results had no consistent patterns or statistical significance.

In Inner Mongolia, where only behavioral interventions (B) were implemented, the concentrations of RPM and CO were reduced more in the intervention group than in the control group (differences not statistically significant). No reductions were observed in group B compared to group C in the other provinces; in fact the comparison of the two groups resulted in as many observed reductions in group B compared to group C as there were opposite results, almost none being statistically significant.

In pooled analyses for Gansu, Guizhou, and Shaanxi (the three provinces with both S + B and B) and all rooms, none of the IAQ reductions in group B compared to group C were statistically significant. Reductions in RPM and CO concentrations in group S + B, compared to group C, were statistically significant in Dec–Jan; the findings on SO₂ were consistent with the other two pollutants but non-significant.

6. Discussion

The results of this study on community effectiveness of stove and behavioral interventions demonstrate that heating stove interventions were effective in reducing indoor air pollution from coal and biomass fuels. When energy is used for heating, fuel combustion takes place with a more stable pattern and with less intensity. Therefore, the new heating stoves, which separated the combustion chamber from the
in the indoor environment and/or ventilated smoke outdoors, seem to have been effective in reducing indoor air pollution, and less sensitive to user behaviors (e.g. the new heated bed in Gansu or underground heating stove in Shaanxi). Because heating is an important use of energy for much of China’s population, well-designed and well-constructed stove improvements can result in significant reductions in IAP exposure and the associated disease burden.

Stove interventions had more mixed performance when they were used for cooking, possibly because during cooking users modify the combustion process actively and regularly, leading to relatively large fluctuations in combustion intensity. The inconsistent findings on pollution reduction in Guizhou, where the same coal stove is used for cooking or heating, may be related to this factor. Further, one of the main aims of interventions in Guizhou was reducing exposure to fluorine deposited onto food dried/stored over chimneys in attics. Hence these interventions may have put less emphasis on the ambient concentrations of the three indicator pollutants used in this analysis. A small number of measurements in the attics in Guizhou found that reductions in the concentrations of all three pollutants in group S + B were about 10 times those in group C.

This study found no IAP reduction benefits from health education and behavioral interventions alone, despite the relatively extensive program. The introduction of alternative stove-handling behaviors as a part of the health education program led to changes in specific behavioral indicators (e.g. covering the stove door or top after fuel is added) based on self-reported data (results not shown), but these changes

### Table 2. (Continued.)

| Inner Mongolia | Control (C) | Behavioral intervention (B) | Stove and behavioral intervention (S + B) |
|----------------|------------|-----------------------------|------------------------------------------|
|                | Dec–Jan 2004–05 | Dec–Jan 2004–05 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 | Dec–Jan 2004–05 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 | Dec–Jan 2004–05 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 |
| Time (°C)      | 4.0        | –11.3          | 2.0          | –4.9         |
|                | 14.7       | 11.4           | 14.7         | 13.1         |
| CO (ppm)       |            |                |              |              |
| RPM (μg m⁻³)   |            |                |              |              |
|                |            |                |              |              |
| CO (ppm)       | 30         | 25             | 35           | 15           |
| Level          | 7.12       | 5.87           | 7.62         | 5.32         |
|                | (6.09, 8.15) | (4.67, 7.07) | (6.59, 8.66) | (4.01, 6.62) |
| Δ1             | –1.25      | (–18%)         | –2.30        | (–30%)       |
|                | (p₁ = 0.11) |                | (p₁ = 0.01)  |              |
| Δ2             | –1.05      | (p₂ = 0.36)    | –3.10        | (p₂ = 0.33)  |
| CO (ppm)       |            |                |              |              |
| RPM (μg m⁻³)   |            |                |              |              |
|                |            |                |              |              |
| CO (ppm)       | 30         | 25             | 35           | 16           |
| Level          | 6.53       | 5.50           | 7.92         | 5.46         |
|                | (5.67, 7.40) | (4.50, 6.51) | (6.98, 8.85) | (4.13, 6.79) |
| Δ1             | –1.03      | (–16%)         | –2.46        | (–51%)       |
|                | (p₁ = 0.12) |                | (p₁ = 0.00)  |              |
| Δ2             | –1.43      | (P₂ = 0.17)    |              |              |

a Of the 23 household-days of measurements, 3 measurements were dropped because the duration of measurements was < 900 min (16 h).
b Of the 16 household-days of measurements, 1 measurement was dropped because the duration of measurement was < 900 min (16 h).
c Of the 23 household-days of measurements, 1 measurement was dropped because the duration of measurement was < 900 min (16 h).
d Of the 16 household-days of measurements, 2 measurements were dropped because the duration of measurements were < 900 min (16 h).
Table 2. (Continued.)

|         | Control (C)                  | Behavioral intervention (B)                      | Stove and behavioral intervention (S + B) |
|---------|------------------------------|--------------------------------------------------|------------------------------------------|
|         | Dec–Jan 2003–04 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 | Dec–Jan 2003–04 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 | Dec–Jan 2003–04 | Dec–Jan 2004–05 | Mar–Apr 2003 | Mar–Apr 2005 |
| $T_f$ (°C) | 3.0                      | –1.4               | 22.2          | 4.7          | 3.8           | 21.4          | 22.8         | 23.4          | 5.0          | –0.2          | 18.6          | 16.9        |
| $T_h$ (°C) | 4.3                      | 3.8               | 15.9          | 5.7          | 7.0           | 15.3          | 21.0         | 21.0          | 3.7          | 4.0           | 18.6          | 16.7        |

Cooking room

|         | RPM (μg m$^{-3}$) |
|---------|------------------|
| $n$     |                  |
| Level   |                  |
| Δ1      |                  |
| Δ2      |                  |
| Δ3      |                  |

|         | CO (ppm)         |
|---------|------------------|
| $n$     |                  |
| Level   |                  |
| Δ1      |                  |
| Δ2      |                  |
| Δ3      |                  |

SO$_2$ (ppm)

|         |                  |
|---------|------------------|
| $n$     |                  |
| Level   |                  |
| Δ1      |                  |
| Δ2      |                  |
| Δ3      |                  |

Living room

|         | RPM (μg m$^{-3}$) |
|---------|------------------|
| $n$     |                  |
| Level   |                  |
| Δ1      |                  |
| Δ2      |                  |
| Δ3      |                  |

CO (ppm)

|         |                  |
|---------|------------------|
| $n$     |                  |
| Level   |                  |
| Δ1      |                  |
| Δ2      |                  |
| Δ3      |                  |

Though table 2 is not visible, the text seems to have no measurable benefits for indoor air quality. There are two possible reasons for this finding: first, awareness of health risks and interventions cannot lead to changes in fuel and stove choices when there is insufficient physical and financial access to alternative fuels and stoves [13]. Second, given the central role of cooking and heating in daily life, the specific behavioral changes reported by participants may not have been enough to lead to reduction in emissions. 

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There are, nonetheless, reasons to use health education as a part of a comprehensive intervention program: first, health education may help encourage the uptake of interventions such as cleaner fuels/stoves, or affect how these technologies are used; second, health education may help reduce IAP exposure through specific routes (e.g., bioaccumulation of fluorine in food dried over a fire) even if the ambient concentrations remain unchanged.

This study has a number of limitations and uncertainties, described in the supplementary online material (available at stacks.iop.org/ERL/1/014010). Despite these uncertainties, the findings in this study are consistent with studies from China and Kenya which found that the alternative cooking stoves had relatively variable performance in reducing IAP, especially compared to stoves that used cleaner fuels [10, 16, and with a study that documented health benefits of ventilated heating stoves in China [17, 18]. This emerging evidence has two implications for scaling up interventions: first, stov programs must put emphasis on stove design and construction to ensure that, to the extent possible, solid fuel combustion is isolated from living and working environments, and that the stoves are robust to user behavior. This in turn requires identifying the multiple purposes of energy use, including cooking and heating, and how they affect stove operation and emissions. Second, the evidence on limitations of alternative stoves shows that sustained and robust exposure reduction requires programs to develop and disseminate alternative fuels. Macroeconomic and infrastructure factors are limits to the large-scale switch to petroleum-based fuels in the short run. Therefore an area of emphasis for future research must be pre-processing solid fuels into cleaner fuels, including charcoal or gaseous and liquid fuels [16, 19–24].

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References

[1] Smith K R, Mehta S and Maeusezahl-Feuz M 2004 Indoor air pollution from household solid fuel use Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors ed M Ezzati, A D Lopez, A Rodgers and C J L Murray (Geneva: World Health Organization) pp 1435–93

[2] Smith K R 1987 Biofuels, Air Pollution, and Health: A Global Review (New York: Plenum)

[3] Ezzati M, Lopez A D, Rodgers A, Vander Hoorn S, Murray C JL and Comparative Risk Assessment Collaborative Group 2002 Selected major risk factors and global and regional burden of disease Lancet 360 1347–60

[4] Barnes D F, Openshaw K, Smith K R and van der Plas R 1994 What Makes People Cook with Improved Biomass Stoves? A Comparative International Review of Stove Programs (Washington, DC: The World Bank)

[5] Smith K R, Gu S, Huang K and Qui D 1993 One hundred million improved cookstoves in China: how was it done? World Dev. 21 941–61

[6] Kammen D M 1995 From energy efficiency to social utility: improved cookstoves and the small is beautiful model of development Energy as an Instrument for Social Change ed J Goldemberg and T B Johansson (New York: United Nations Development Programme)

[7] Krugmann H 1987 Review of Issues and Research Relating to Improved Cookstoves (Ottawa: International Development Research Centre) Report No. IDRC-MR152e

[8] Manibog F R 1984 Improved cooking stoves in developing countries: problems and opportunities Ann. Rev. Energy 9 199–227

[9] Agarwal B 1983 Diffusion of rural innovations: some analytical issues and the case of wood-burning stoves World Dev. 11 359–376

[10] Sinton J et al 2004 An assessment of programs to promote improved household stoves in China Energy Sustainable Dev. VIII 33–52

[11] Florig H K 1997 China’s air pollution risks Environ. Sci. Technol. 31 274A–79A

[12] Liu B Q et al 1998 Emerging tobacco hazards in China: 1. Retrospective proportional mortality study of one million deaths Br. Med. J. 317 1411–22

[13] Jin Y, Ma X, Chen X, Cheng Y, Baris E and Ezzati M 2006 Exposure to indoor air pollution from household energy use in rural China: the interactions of technology, behavior, and knowledge in health risk management Soc. Sci. Med. 62 3161–76

[14] Jin Y et al 2005 Geographical, spatial, and temporal distributions of multiple indoor air pollutants in four Chinese provinces Environ. Sci. Technol. 39 9431–9

[15] He G et al 2005 Patterns of household concentrations of multiple indoor air pollutants in China Environ. Sci. Technol. 39 991–8

[16] Ezzati M, Mbinda B M and Kammen D M 2000 Comparison of emissions and residential exposure from traditional and improved biofuel stoves in rural Kenya Environ. Sci. Technol. 34 578–83

[17] Chapman R S, He X, Blair A E and Lan Q 2005 Improvement in household stoves and risk of chronic obstructive pulmonary disease in Xuanwei, China: retrospective cohort study BMJ 331 1050

[18] Lan Q, Chapman R S, Schreinemachers D M, Tian L and He X 2002 Household stove improvement and risk of lung cancer in Xuanwei, China J. Natl Cancer. Inst. 94 826–35

[19] Fischer S L 2001 Biomass-derived liquid cooking fuels for household use in rural China: potential for reducing health costs and mitigating greenhouse gas emissions Energy Sustainable Dev. IV (1)

[20] Henderick P and Williams R H 2000 Trigeneration in a northern Chinese village using crop residues Energy Sustainable Dev. IV (3)

[21] Larson E D and Yang H 2004 Dimethyl ether (DME) from coal as a household cooking fuel in China Energy Sustainable Dev. VIII 124

[22] Larson E D and Jin H 1999 A preliminary assessment of biomass conversion to Fischer-Tropsch cooking fuels for rural China Proc. 4 the Biomass Conf. of the Americas, 1999 p 1999

[23] Williams R H 2001 Toward zero emissions from coal in China Energy Sustainable Dev. V (4)

[24] Bailis R, Ezzati M and Kammen D M 2005 Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa Science 308 98–103