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Upgrading to cleaner household stoves and reducing chronic obstructive pulmonary disease among women in rural China — A cost-benefit analysis ☆

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ABSTRACT

Exposure to fine particles ≤2.5 μm in aerodynamic diameter ($PM_{2.5}$) from incomplete combustion of solid fuels in household stoves is recognized as a major contributor to global ill health. Still there are few attempts to estimate the economic costs and health benefits of interventions to reduce exposure. The objective of this paper is to estimate costs and health benefits to women of possible interventions to replace current biomass stoves in Guizhou Province, southwest China, with cleaner burning stoves. Prevalence of chronic obstructive pulmonary disease (COPD) was measured in women ≥30 y living in households using biomass as fuel. In a sub-sample of households indoor $PM_{2.5}$ concentrations were measured. Reduced exposure from replacing stoves in individual homes and at the community level was estimated using information about stoves, concentration levels, and time-activity patterns. Annual avoided new cases of COPD were estimated. The economic value of avoided cases was compared to intervention costs. Probabilistic cost-benefit analysis was performed using Monte-Carlo simulation and the impact of uncertainty in single parameters was explored. The mean reduction in annual average $PM_{2.5}$ exposure is estimated at 127–294 μg/m^3, which corresponds to a 41–77% reduction. Annually 0.6–3.2 new cases of COPD among women may be avoided per 1000 households. The present value net benefit is 1766–22,500 Yuan (Yuan/USD ≈ 0.16) per household and mean benefit/cost-ratios (B/C) are 3.3–14.7. We conclude that policy interventions to increase access to cleaner burning stoves may bring large net benefits to rural women and their families, and to society.

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Introduction

Smoke from household stoves is a major contributor to global ill health (Lim et al., 2012). Women in developing countries may spend several hours a day near the stove, exposed to levels of household air pollution (HAP) that have large impacts on their respiratory health and may lead to COPD (Kurmi et al., 2010; Po et al., 2011). COPD is a chronic inflammatory condition of the lower airways. The basic abnormality in COPD patients is airflow limitation, which causes shortness of breath, usually accompanied by chronic cough, wheezing, chest tightness and an increasing disability over time (WHO, 2007).

A substantial share of the global disease burden linked to HAP occurs in China (Lim et al., 2012). The burden of COPD is particularly high. Reported COPD prevalence in China varies between 5% and 13% in different provinces and cities across the country. In 2008, COPD ranked third as a cause of death in rural areas. Crude prevalence of COPD in Chinese women was 3.8%–7.1% in a cross-sectional survey conducted between 2002 and 2004 and was higher in rural areas (Fang et al., 2011). A study in South China reported higher COPD prevalence among non-smoking women in rural than in urban areas (7.2% vs 2.5%) (Liu et al., 2007). Tobacco smoking and biomass smoke are the largest contributors to COPD in China (Lin et al., 2008). Few women smoke, however. The smoking rate was 2.4% among women and 52.9% among men in 2010 (Li et al., 2011).

Lin et al. (2008) estimate that halving household solid fuel use in China by 2033 would reduce the annual number of female COPD deaths by 12%. In a retrospective cohort study in Yunnan Province a significant reduction in COPD was observed among people who changed from unvented stoves to stoves with a chimney. Even though average PM_{10} (particles ≤10 μm in aerodynamic diameter) levels

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were still high near the stove (710 μg/m^3), a significant risk reduction was observed in women after installation of a chimney (Relative Risk (RR) 0.75 (95% Confidence Interval (CI): 0.62, 0.92)) (Chapman et al., 2005). The impact of improved stoves has been found to be higher when coupled with education and behavioral change (WB, 2007a).

During the 1980s and 1990s the National Improved Stove Program (NISP) was implemented in China, and a large fraction of biomass stoves were upgraded to so-called first generation improved stoves, which in practice meant that the stove had a chimney and a grate. A comprehensive assessment of NISP found that the thermal efficiency of rural stoves was only 9–14% (Sinton et al., 2004). Recently, companies have marketed better stoves, among them a range of cast iron gasifier and semi-gasifier biomass stoves (Spautz et al., 2006). If properly used and maintained, and given that they not just add to old stoves, these second generation improved stoves are expected to result in reduced HAP and significant health benefit.

In spite of the potentially large health benefit, there are few attempts to estimate the economic cost and benefit of interventions to promote cleaner burning stoves. Bruce et al. (2011) summarize previous studies of costs and benefits of biomass stove interventions, including community-based studies in Africa and Nepal (Malla et al., 2011) and a study for WHO regions (Hutton et al., 2006). All studies found benefits larger than costs. Various health and socio-economic benefits, including less time spent collecting fuels, are included in these studies and results are not directly comparable. When estimating impacts on COPD the studies treated exposure as a dichotomous variable based on fuel statistics ('exposed': household solid fuel are used versus 'not exposed': household solid fuels are not used). The fuel-based approach is a rough approximation applied when exposure measurements are not available (Smith et al., 2004).

The objective of this paper is to estimate the costs and health benefits among women of replacing current biomass stoves in a rural area of China with second generation improved stoves. The novelty of our analysis is that field data on HAP concentrations enables a detailed exposure assessment. Current COPD prevalence is measured. The detailed information about current exposure levels and disease prevalence together with modeled exposure levels in scenarios allow us to use exposure–response relationships from epidemiological studies to estimate health benefits. While a long-term intervention study would have been ideal, we aim in this paper to improve on the current fuel based approach by using measurement data for the pre-intervention stage. In addition, in spite of addressing only one health end-point among a range of potential health effects, our paper adds a valuable data point to the scant evidence of the social cost of stove interventions.

Material and methods

Cost-benefit analysis

The essence of cost-benefit analysis is to calculate net benefits (gross benefits less costs) of an intervention. In our case the intervention is 'replacing current biomass stoves with second generation improved stoves' at the household or community level. Cost equals the cost of purchasing and installing the stove, plus any fuel and maintenance cost over the life-time of the stove. Benefits come in many fashions, including health benefits and convenience benefits.

As noted we focus here on COPD health benefits among women. The idea is that demonstrating net benefits based on COPD benefits among women is sufficient for demonstrating net benefits in general. The unit of analysis is 'one household'. We estimate the expected annual avoided new cases of COPD in women per household and use valuation methods from economics to estimate the monetized value of the avoided cases (see detailed method below).

We assume that benefits persist for as long as the improved stove is in function. If the intervention generates net benefits over this period, a second round of the same intervention will also have net benefits etc. Demonstrating net benefits over the life time of the stove is sufficient for demonstrating net benefits for any length of time.

In order to compare benefits and costs accruing over different time periods we use a discount rate. The discount rate is higher in a high-growth economy such as the Chinese. Our real discount rate is 8%. It is applied equally to benefits and costs. However, economic growth implies growing valuation of risk. Hence the effective discount rate of benefits is in fact slightly negative.

Study area

We study villages of Guizhou Province. Guizhou is a mountainous province of 35 million inhabitants in the southwest of China. Rural households in Guizhou are poor (net income ~ 500 USD/cap), with about 50% income share for food (NBS-GZ, 2011). Traditional biomass stoves are widespread in rural areas and are previously described by Jin et al. (2006) (Fig. 1). Some households still use open fire. According to China Census data, 30% of households used coal and 32% used biomass as their main cooking fuel in 2010. Among rural households 35% use coal and 46% use biomass (NBS, 2012). During 2000–2007, biomass energy use in households increased from a total of 6.0 Mtce to 10.1 Mtce (NBS, 2010).

Data collection

An interviewer administered questionnaire was used to collect information on characteristics of 1200 rural households in 24 villages where biomass was the main fuel. The survey was carried out during the period Feb 2009–Jan 2010. Lung function was measured by spirometry. The participants had to perform at least 2 satisfactory maximum forced expiratory flow-volume curves. COPD was defined as forced expiratory volume in one second over forced vital capacity (FEV1/FVC) below 0.7 based on post-bronchodilator measurements (Celli et al., 2004). 0.6% were cigarette smokers and were excluded from the analysis. COPD prevalence and odds ratios (OR) were estimated on a sample of about 850 participating women ≥30 y of age (Alnes et al., 2011).

In a subsample of households (110 in winter and 117 in summer), measurements of indoor concentrations of $PM_{2.5}$ were carried out for 48 h using the particle and temperature monitor UCB-PATS (Edwards et al., 2006). The monitor has been used in multiple studies in developing countries (Armendariz et al., 2008; Chowdhury et al., 2007). The monitors were placed in the kitchen and living room. Details about the study on air pollution measurements are reported elsewhere (Alnes et al., 2013).

Fig. 1. Example of a traditional biomass stove often seen in rural households in Guizhou, China.

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Scenarios for two groups of households

Two groups of households were identified. In 'No-chimney' households at least one open fire and/or a stove without chimney was present. In 'Chimney' households all stoves had a chimney and usually a grate. The prevalence of COPD among women was higher in 'No-chimney' than in 'Chimney' households (OR = 3.48 (95% CI: 1.02, 11.90), p = 0.047, adjusted for age, socioeconomic status and ventilation). A prevalence of 4.6% and 1.4% for the two groups, respectively, is used below. Whereas 4.6% is the measured prevalence in No-chimney homes (the largest group), 1.4% is calculated for Chimney homes using the adjusted OR in order to compare groups with the same demographics (the measured prevalence was 1.7%). Mean $PM_{2.5}$ concentrations in 'No-chimney' household kitchens were significantly higher than in 'Chimney' household kitchens in summer, but not in winter (see Table 1 for concentration levels by room and season).

We develop two scenarios. Scenario 1 assumes that individual household upgrades to cleaner-burning stoves (henceforth second generation improved stoves). Scenario 2 assumes that whole communities upgrade to second generation improved stoves and establish a system for providing suitable biomass fuels (pellets). As described below we assume that the pellet stoves in the community level scenario have lower emission factors than stoves in the individual scenario. We assume that fuel use is constant in the scenarios. This means that any improvement in thermal efficiency will not result in lower fuel use; in other words a 100% rebound effect. This is based on the observation that mean living room temperature during the winter was low (12.0 (±4.6)°C), and we believe any fuel saved will be used for heating. To avoid speculations about the magnitude of the rebound effect in summer when heating is not needed, and the mixed evidence for fuel saving from stove efficiency improvements (Chen et al., 2006; Nepal et al., 2010), we assume no fuel saving in summer either.

Each scenario is divided into two sub-scenarios (a and b); depending on whether it is 'No-chimney' or 'Chimney' households that upgrade their stoves. We assume that all stoves within a household are replaced by year 1 and that the new stoves are properly used and maintained. Finally, we assume that there are no other major sources of $PM_{2.5}$ indoors apart from household fuel combustion. This assumption allows us to approximate post-intervention concentration levels from the relative emission strength of stoves.

Exposure assessment

The detailed methods and parameters to estimate $PM_{2.5}$ exposure pre- and post-interventions are as follows:

Table 1
Central estimates of concentration levels applied in the exposure assessment, μg/m^3 $PM_{2.5}$. (SE given for concentration levels based on measurements). See Table 3 for Scenario descriptions.

	Winter			Summer		
	Before intervention	Scen 1	Scen 2	Before intervention	Scen 1	Scen 2
Mean kitchen when stove in use (C_{kcook})						
No-chimney	2939 (±382)	1503	567	1470 (±224)	369	139
Chimney	2781 (±550)	1503	567	683 (±274)	369	139
Mean kitchen (C_k)						
No-chimney	783 (±96)	424	178	407 (±56)	132	71
Chimney	741 (±138)	422	178	210 (±69)	131	71
Mean living room (C_i)						
No-chimney	398 (±66)	246	126	210 (±37)	76	48
Chimney	428 (±115)	243	126	120 (±30)	75	48
Baseline ($C_{bl} = C_o$)						
No-chimney	64 (±1)	64	48	53 (±1)	53	48
Chimney	61 (±3)	61	48	52 (±2)	52	48

Following Mestl and Edwards (2011) who use time activity data from the NISP survey and Wang et al. (2008), exposure was estimated for each type of household:

$$E' = [(T_{cook} \times C_{kcook} + T_k \times C_k + T_o \times C_o + T_i \times C_i)/(T_{cook} + T_k + T_i + T_o)] \quad (1)$$

where T_{cook} is the time spent in kitchen while cooking (2.2 (SD 1.4) hours). C_{kcook} is the kitchen concentration when stove is in use, i.e. the average concentration during a cooking episode including smoldering. T_k is the time spent in kitchen when not cooking. The total time spent in kitchen is 2.5 (SD 1.9) hours. Expected time in kitchen while not cooking is therefore T_k = 0.3 h. C_k is the mean 48-hour kitchen concentration. T_o is the time spent outdoors (7.6 (SD 2.2) hours). The ambient concentration, C_o, is estimated using the kitchen time series measurements. Dwellings in the study area are drafty and it is assumed that the kitchen nighttime concentration drops to the ambient level. C_o is estimated as mean minimum kitchen concentration, which was 61(52) and 64(53) μg/m^3 in winter (summer) in Chimney and No-chimney homes, respectively. T_i is remaining time spent indoors, $T_i = 24\text{-}T_{cook}\text{-}T_k\text{-}T_o$. C_i is 48-hour mean concentration in the living room. E′ reflects 24-hour average exposure, a proxy for average longer-term exposure.

Stove use episodes (i.e. when concentrations exceed 300 μg/m^3) occur about 25% of the time. The remaining 75% of the time the kitchen concentration is conservatively assumed to equal C_0 (Supplemental material, Fig. S1). Thus, using the measured C_k for each household, C_{kcook} was estimated from:

$$C_k = 0.25{*}C_{kcook} + 0.75{*}C_0. \quad (2)$$

E′ was calculated for winter and summer months separately. When calculating the annual weighted average exposure, E, we assume that winter and summer exposure last 5 and 7 months, respectively. The pre-intervention frequency distribution for E was derived based on Eqs. (1) and (2) and measurements.

Eq. (1) is used to calculate post-intervention exposure assuming that the time activity pattern is unchanged. We assume that post-intervention C_{kcook} is a normally distributed stochastic variable. Within each scenario C_{kcook} in No-chimney homes is the same as in Chimney homes, since the new stoves introduced are identical. A change in C_{kcook} is what drives the post-intervention exposure reduction in our model. In Scenario 1 (individual upgrade) we estimate that expected C_{kcook} is reduced to 54% (95% CI: 44%, 64%) of the initial C_{kcook} of 'Chimney' households. The estimate is based on data compiled for China in the GAINS database ('UNEP_IEA09_REF' scenario) (IIASA, 2012), which shows that the ratio between $PM_{2.5}$ emission factor for 'new' versus (first generation) 'improved' cooking and heating stoves burning agricultural residues and wood is 0.54 (0.44, 0.64). The 95% CI is based on the ranges of ratios of emission factors in the GAINS database. The average emission factors for 'new' and 'improved' stoves in GAINS are 1.7 and 3.15 g $PM_{2.5}$/kg fuel, respectively, the former being close to the emission factor for the Rocket stove as estimated by MacCarty et al. (2008). We denote the expected ratio 0.54 R_{Scen1}.

In Scenario 2 (community upgrade) we estimate that expected C_{kcook} is reduced to 20% (95% CI: 10%, 30%) of the initial C_{kcook} of 'Chimney' households. This is based on the ratio of 0.20 (0.10–0.30) between the $PM_{2.5}$ emission factor for 'pellet' stoves in the GAINS database (0.64 g $PM_{2.5}$/kg fuel) versus 'improved' stoves. We denote the expected ratio 0.20 R_{Scen2}. The use of emission factors to derive R_{Scen} estimates is obviously a rough approximation, and the uncertainties involved are discussed below.

In Scenario 1 C_0 is unchanged as individual stove switching does not affect ambient pollution levels. In Scenario 2 we assume that ambient pollution is reduced due to the ubiquitous stove replacement, and C_0 is set to 48 μg/m^3 $PM_{2.5}$. This level is the median kitchen minimum

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concentration in summer when stoves are not in use. We believe that it represents the ambient concentration without major household fuel pollution sources (note that rural background levels of $PM_{2.5}$ in China typically exceed 40 μg/m^3 (Yang et al., 2011)). C_k, the mean concentration in kitchen, is estimated using Eq. (2), and C_i, the mean concentration in living room, is estimated assuming the same percentage reduction in the living room as obtained for C_k. Concentration levels applied in the exposure assessment are shown in Table 1 (see Supplemental material, Table S1, for $PM_{2.5}$ measurement data).

Health damage assessment

We use the relative risk (*RR*) function to estimate the expected annual avoided new cases of COPD in women of reducing exposure:

$$RR = exp(\beta \Delta E). \quad (3)$$

ΔE is current E minus E after intervention and β is the exposure–response (E–R) coefficient. We use a β of 0.0048 (95%CI: 0.0040–0.0056) estimated for long-term PM_{10} levels and prevalence of chronic bronchitis (CB) in adults based on cross-sectional questionnaire surveys in urban and suburban areas in China (Aunan and Pan, 2004). We assume that the effect estimates for CB are similar to the effect estimates for COPD (see discussion below). A similar β of 0.0045 (95% CI: 0.0015–0.0074) is estimated for CB in Kan et al. (2005). Due to the limited sample size we choose not to use the considerably higher β that may be derived from the observations in the current study. Note that our RR is stochastic since both β and ΔE are stochastic. We convert $PM_{2.5}$ exposure to PM_{10} using the measured ratio between the two components in wood burning homes, 0.89 (95%CI: 0.80–0.98) (Zhang et al., 2011).

By definition

$$RR = p/p_0. \quad (4)$$

p is the annual incidence rate in a polluted environment, p_0 is the annual incidence rate in a cleaner environment. Given p Eqs. (3) and (4) give p_0.

$$AC = (p - p_0) * P \quad (5)$$

Given p, p_0 and P Eq. (5) gives *AC* (attributable cases), the number of cases attributable to ΔE. P is the average number of women per household in Guizhou, 1.39 (GSB, 2008). *AC* therefore indicates the number of cases per household.

To estimate p we assume steady-state pre-intervention conditions and divide current prevalence (4.6 or 1.4%, see above) with the average duration of 'aged chronic bronchitis' cases in people > 25 years of age in China, 16 years, to obtain an annual incidence rate of 0.0029 and 0.0009 for women in 'No-chimney' and 'Chimney' households, respectively. Duration was estimated from data for the Chinese population for 2003, see WB (2007b). Including only people > 35, average duration is reduced to 14 years.

COPD is a progressive disease perceived to be irreversible, and the relationship between exposure and incidence is complicated. Given a stable annual incidence rate a simplified model consistent with instantaneous impact in the population is the following: Assume that T years of exposure lead to COPD. Assume that the intervention is implemented following T-1 years of exposure for individuals who are on the brink of developing the disease (the annual incidence population). The impact will then be instantaneous for this group. Backed by this argument and in line with others (Wilkinson et al., 2009) we assume an instantaneous reduction of incidence in response to improved stoves.

If health status reacts more strongly to recent exposure our model will underestimate the true response to improved stoves. On the other hand, if health status reacts with a lag as if some threshold is needed for a discernible effect, our model will overestimate the true response, see Rabl (2006). Discounting also matters for the question of over- versus underestimation. If the true effect of an intervention in year one is postponed to year two or three, the error of assuming the effect in year one will be proportional to the real discount rate (r–g in the language below). Chapman et al. (2005) found that the risk of COPD was reduced unequivocally about 10 years after installation of a chimney. However, they also found that there was an increased risk just after the chimney was installed, which they speculate could be related to a biased selection of people choosing to install a chimney. Thus, while indicating a delayed effect, their results do not provide a quantification of this delay. Below we present sensitivity estimates for a simple alternative model where the response is delayed. Note that we do not include the likely benefit from HAP reductions in women who already have COPD. Studies of tobacco smoke cessation show that lung function decline in COPD patients is attenuated in quitters and symptoms of cough, phlegm and wheeze are reduced. Improvements are found from year one after quitting (Scanlon et al., 2001).

Monetized benefits

The individual benefit of lowering the incidence of COPD consists of two kinds. One is treatment expenses saved. The other is the benefit of lowering the individual risk of contracting COPD. Treatment expenses are incurred in order to reduce the cost of living with COPD. In this sense they are second order in nature.

Contracting and living with COPD reduce physical capabilities and increase the risk of premature death. The risk of contracting and living with COPD is therefore similar in kind to the risk of premature mortality. The valuation literature in economics makes use of this property.

To monetize *AC* we use the present value (PV) formula:

$$Benefit = \sum_{t=0}^{N} \frac{AC\gamma \ VSL_o\left(1+g^t\right)}{(1+r)^t}. \quad (6)$$

VSL is value of statistical life, a metric of the willingness to pay for lower mortality risk. g is the growth in VSL over time. r is the discount rate. N is the number of years the stove is expected to last given normal maintenance. We assume that the risk of contracting COPD is valued at $\gamma = 32\%$ of mortality risk (VSL) (Viscusi et al., 1991). The original article asked for risk-risk valuation of a case of severe chronic bronchitis. Note that this is the value of living with the disease for the rest of one's life. Values are in 2010 price level.

There is a sizable literature on the VSL in Europe and the U.S.A, and some from China. Guo and Hammitt (2009) study risk preferences of 10,000 urban workers in China as revealed from their willingness to take on risky work in return for a higher wage. They find VSL to be 33–150 times annual earnings. Hammitt and Zhou (2006) do a contingent valuation survey of 3200 residents of Beijing and Anhui Province and find VSL to be 10–200 of earnings. Wang and Mullahy (2006) perform a contingent valuation survey of 500 residents of Chongqing and find VSL to be 70 times earnings. Based on evidence like this and the international literature Aunan et al. (2004) and Vennemo et al. (2009) have suggested that a Chinese VSL is approximately 50–150 times earnings, with 100 as a middle estimate.

Our analysis assumes a normal distribution for VSL with mean 100 (95% CI: 50, 100). For GDP/capita we consider two alternatives, national GDP/capita (30,000 Yuan in 2010) and Guizhou Province GDP/capita (13,000 Yuan). Yuan/USD ≈ 0.16. There are arguments for using the national value (e.g., all inhabitants should be treated equal) but also for using the province value (e.g., consistency with provincial prices and incomes). We assume a binominal distribution with p = 0.5 for 13,000 and (1-p) = 0.5 for 30,000. The expected value of VSL is 2.15 million Yuan.

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There is reason to believe that VSL grows faster than income (Hammitt and Robinson, 2011). We use an income elasticity of 1.5 (95% CI: 1.0, 2.0). Given 6.5% annual growth in GDP/capita, which is planned for the 12th five year plan period the parameter g is 9.8%. The discount rate r is 8%.

Our estimate of benefit excludes convenience benefits from improved stoves. By restricting the analysis to women we exclude the benefit to men and children. The estimate excludes treatment expenses. A sensitivity analysis examines the impact of valuing COPD risk in terms of treatment expenses *only*.

Intervention costs

Data and parameters used to calculate investment and maintenance costs of stoves are as follows. Based on own survey data we assume that biomass fuel is free. We do not include any value of savings in time searching for fuel as we assume 100% rebound (see above). A single household upgrading its stove (Scenario 1) must use a stove with simple fuel input requirements. Examples are the Shengchang and Guanglei CSX series (Dou, 2011; Zhou, 2009). These stoves sell for 200 (100–300) Yuan, a range also reported elsewhere (WB, 2007a). Due to the low capacity of such stoves a household will need two stoves. An estimated 100% surcharge covers costs of transportation, installation and maintenance, thus full cost per household is estimated at 800 (400–1200) Yuan. The stoves are assumed to have a life time of 6 (4–8) years (Zhou, 2009).

In a community program households may use a stove with higher operational requirements. An example is the Daxu stove of Beijing Shenzhou Daxu Bio-energy Technology Company that won the Shell/CAREI competition and the Ashden Awards for Sustainable Energy (Ashden, 2013). It requires a stable supply of pellets, most commonly organized by establishing a pelleting plant in the community; and is fitted to the home by a company representative. The Daxu stove comes in different varieties. We use a 1300 Yuan (650–1950) stove for cooking and household supply of hot water as our example (Han, 2010). One such stove is needed. Its life time is 10 (8–12) years. An estimated 30% surcharge to cover transport, maintenance, the household share of the pelleting plant investment, and program costs are added, thus full cost per household is estimated at 1690 (845–2535) Yuan.

Monte Carlo simulation and sensitivities

We estimate net benefits and B/C-ratios of interventions using Monte Carlo simulations and the distributional assumptions given above. The number of random draws in the Monte Carlo simulation is one million.

By testing the sensitivity of results to a ±20% change in key input parameters we also explore the impact of uncertainty in single parameters.

Results

Pre-intervention mean exposure is 381 (SE 29) and 308 (SE 40) $\mu g/m^3$ $PM_{2.5}$ in No-chimney and Chimney homes, respectively (Table 2). The mean reduction in $PM_{2.5}$ exposure in the scenarios (ΔE) ranges from 41% to 77% of pre-intervention exposure (Table 2). Annual avoided new cases of COPD among women, in physical and monetary terms, are given in Table 3. Net benefit and B/C ratios are given in Table 4. The present value net benefit is in the range 1766–22,500 Yuan per household across the four scenarios (Yuan/USD = 0.16). The simultaneous probability for positive net benefit is 99.0–99.99% depending on scenario (Supplemental material, Fig. S2). Net benefit is higher when the intervention targets No-chimney homes (a scenarios) than Chimney homes (b scenarios). This is reasonable since the pre-intervention status is much worse in No-chimney homes. Net benefit is higher in the community level scenario (Scenario 2) than the individual stove switch scenario (Scenario 1). This is less evident: Benefits are higher in Scenario 2 since the new stoves have lower emissions, but on the other hand, costs are higher. The highest B/C ratio is found in Scenario 1a.

We tested the value of input parameters that would result in zero net benefit (other parameters unchanged), and found that for all parameters this value was outside their 95% CI. R_{Scen1} and R_{Scen2} are core input parameters as they directly affect ΔE. We find that applying the upper 95% CI (i.e. lowest effect of intervention) while keeping other parameters constant, results in only moderate reductions in net benefit, maximum 24% (in Scenario 1b). ΔE may in fact be as low as 9 $\mu g/m^3$ in Scenarios 1a and 2a, 32 $\mu g/m^3$ in Scenario 1b, and 39 $\mu g/m^3$ in Scenario 2b before net benefit becomes zero, much lower than the lower 95% CI of ΔE in our simulation (Table 2). The VSL value that gives zero net benefit was maximum 31% of the central estimate in all scenarios. Correspondingly, the E–R coefficient that gives zero net benefit was 4–24% of the central estimate depending on scenario. The sensitivity of net benefit estimates was largest for life-time of intervention, VSL, and baseline COPD prevalence. Sensitivities were largest for the Chimney home Scenarios 1b and 2b. See Supplemental material, Fig. S3, for one-way-sensitivity tests.

We investigate whether the stove intervention could be justified in terms of saved treatment expenses only. Fang et al. (2011) estimate direct and indirect expenses of a case of COPD in China to be 1964 USD/yr. In discounted terms this equals 176,000 Yuan per case (average duration of a case is 16 years, see above). Expenses included are direct medical expenses, dietary supplements, transportation, and end-of-life care. Applying this estimate (while not changing other

Table 3
Expected health benefit in the scenarios (number of annual cases and present value (PV) in 2010 Yuan). 95% CI in parenthesis. (1 Yuan ≈ 0.16 US$).

	Annual avoided new cases of COPD in women per 1000 households	PV of avoided cases per household (2010 Yuan)
Scen 1a[a]	2.63 (2.23, 2.99)	11,551 (4735, 21,000)
Scen 1b[b]	0.58 (0.43, 0.73)	2566 (1012, 4807)
Scen 2a[c]	3.18 (2.85, 3.46)	24,189 (10,685, 41,485)
Scen 2b[d]	0.82 (0.67, 0.95)	6241 (2719, 10,849)

[a] Scenario 1a: Individual households switch from No-chimney stove to Second generation improved stove.
[b] Scenario 1b: Individual households switch from Chimney stove to Second generation improved stove.
[c] Scenario 2a: Community level switch from No-chimney stove to Second generation improved stove (pellets).
[d] Scenario 2b: Community level switch from Chimney stove to Second generation improved stove (pellets).

Table 2
Annual mean $PM_{2.5}$ exposure (SE) for women living in 'No-chimney' and 'Chimney' homes and estimated reduced exposure (ΔE) after individual (Scenario 1) or community level (Scenario 2) upgrade to 'Second generation improved stove' ($\mu g/m^3$).

E before intervention		ΔE Scenario 1		ΔE Scenario 2	
No-chimney	Chimney	No-chimney (a)	Chimney (b)	No-chimney (a)	Chimney (b)
381 (±29)	308 (±40)	198 (±21)	127 (±22)	294 (±25)	221 (±31)

Table 4
Expected present value of net benefit (PV) per household (2010 Yuan) and B/C ratios for the scenarios. 95% CI in parenthesis. Scenario descriptions, see Table 3.

	Net benefit (2010 Yuan)	B/C-ratio
Scen 1a	10,751 (3931, 20,203)	14.7 (5.8, 28.0)
Scen 1b	1766 (195, 4015)	3.3 (1.2, 6.4)
Scen 2a	22,500 (8983, 39,800)	14.5 (6.2, 26.0)
Scen 2b	4551 (1004, 9173)	3.7 (1.6, 6.8)

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parameters) we obtain slightly positive net benefit estimates in the scenarios addressing No-chimney homes, but negative estimates for Chimney homes. Net benefit in Scenario 1a becomes 150 Yuan (B/C ratio 1.19); in Scenario 2a 299 Yuan (B/C ratio 1.18).

We investigated how an alternative simple model assuming a delayed impact on annual incidence rate from instantaneous exposure reductions affects our results. If the estimated reduced annual incidence rate as calculated in the main model is reached not after one year but after 10 years, and the realization of annually avoided new cases is linearly distributed from year 1–10, the net benefit is reduced by 69%, 94%, 47%, and 60% in Scenarios 1a, 1b, 2a, and 2b, respectively. B/C ratios become 5.1, 1.1, 8.0, and 2.1, respectively. Note that as the life-time of Scenarios 1a and 1b is six years, full effect is not reached over the course of the project period. If full effect is reached after 5 years and the effect is linearly distributed from years 1–5, the net benefit is reduced by 35%, 47%, 20%, and 26% in Scenarios 1a, 1b, 2a, and 2b, respectively. B/C ratios become 9.7, 2.2, 11.5, and 3.0, respectively.

The health benefits per household in Scenarios 2a and 2b may be scaled up to a province level. In 2010, 3.47 million households in Guizhou Province had biomass fuels as their main cooking fuel (94% of these are in rural villages) (NBS, 2012). We do not know the distribution of 'No-chimney' and 'Chimney' households in Guizhou and can only roughly estimate the range of total health benefit. For the lower bound we assume that all are 'Chimney' households. For the upper bound we assume that 85% are 'Chimney' households. This yields a range of 2870–4100 avoided new cases of COPD annually in Guizhou Province. The estimated net benefit is 12–25 billion Yuan, corresponding to 2%–4% of Guizhou's Regional Domestic Product in 2011.

Discussion

We find that upgrading current stoves in both No-chimney and Chimney households to second generation improved stoves would yield net benefits to society. The conclusion is robust to major alterations in input parameters and confirms previous studies in other settings using other methods and data (Bruce et al., 2011). The fact that we only include avoided COPD in women in our analysis implies that the health benefit may be substantially underestimated as there is evidence for effects of indoor air pollution in a range of other end-points and also in men and children (Po et al., 2011; Smith and Peel, 2010).

Expected exposure reductions (41%–77%) are comparable to previous estimates. Jiang and Bell (2008) find that personal $PM_{2.5}$ exposure for urban cooks in homes using a combination of electricity and natural gas on average was 69% lower than for rural cooks in homes using biomass. Practical intervention studies indicate a 35–50% reduction in personal $PM_{2.5}$ exposure from stove interventions (switch to biogas stoves excluded). In these studies the percentage reduction in personal exposure is typically about half the percentage reduction in indoor $PM_{2.5}$ concentration (Armendariz et al., 2008; Hutton et al., 2006; Malla et al., 2011; Naeher et al., 2000). A possible explanation for the discrepancy in effect (exposure vs concentration) could be that there are other important sources of PM exposure, e.g., outdoor sources. As noted by Johnson et al. (2011), outdoor sources have only little impact on indoor concentrations for traditional stove users, but the relative contribution is likely to increase in homes using cleaner stoves. Regarding CO, for which there may be fewer large outdoor sources, Armendariz et al. (2008), Malla et al. (2011), and Naeher et al. (2000) all find that the percentage reduction in personal exposure from stove interventions is close to the percentage reduction in kitchen concentration.

R_{Scen1} (44%–64%) and R_{Scen2} (10%–30%) are derived from emission factor ratios and used to estimate the reduction in kitchen concentration during cooking. We acknowledge the large uncertainties in emission factors for biomass stoves (Zhang et al., 2009). The emission factors applied in the current paper are taken from the widely applied model GAINS, and are mainly derived from laboratory studies. Whether laboratory studies reflect a field setting is uncertain and difficult to fully take into account in the analysis. Further complicating the matter, a range of test protocols exist that may give diverging estimates (Johnson et al., 2007). Equally important as the emission factors per se, and also adding uncertainty which is not explicitly quantified in our analysis, is the fraction of stove emissions that is vented outdoors through the chimney, eave gaps or other leakages in the house before they mix throughout the room. Regarding the kitchen concentration reductions obtained by our model, these may be compared with the model experiment by Johnson et al. (2011), in which it is also assumed that stoves are the only source of $PM_{2.5}$. They estimate that for a defined cooking task, kitchen 24-h mean $PM_{2.5}$ concentration (comparable to our C_k) is 36–83% lower when a Rocket stove is used compared to an open fire (the range depends on test conditions for input data). In our model we arrive at a 48% and 68% reduction in C_k in winter and summer, respectively, for No-chimney homes in Scenario1 (i.e. switch to a stove with emissions similar to a Rocket stove), thus in the middle of the model results of Johnson et al. (2011). In absolute terms, both measured and modeled C_k for No-chimney and Rocket type stove homes are lower in our study than in Johnson et al. (2011). An intervention study in Nepal replacing traditional mud stoves with improved mud stoves found that mean kitchen $PM_{2.5}$ concentration was reduced by 52–71% across the regions included (Singh et al., 2012). In a previous field based study in Guizhou Province we found that during biogas burning, kitchen concentrations were around 70% lower than during no-chimney wood combustion (Wang et al., 2010). Our model renders an 81–91% reduction in C_{kcook} for a switch from No-chimney to pellet stove in winter and summer, respectively. This may seem high compared to the field based results for biogas, but on the other hand applies to ideal setting with no other major $PM_{2.5}$ sources. Note that the $PM_{2.5}$ emission factor for pellet stoves in GAINS is 91% lower than the average emission factor for biomass burned in old stoves ('No control') and open pits.

The assumption that time-activity is constant before and after intervention may be questioned. If women spend less time collecting fuel wood, the rebound effect is lower, but more time may be spent indoors. Use of second generation stoves may require a more active attending of the fire (Barnes et al., 1994). This implies that women spend more time close to the stove, where the exposure is highest. If that is the case, assuming constant time-activity could lead to overstated health benefits.

One may question the use of the E–R relationship for CB and ambient particulate air pollution to estimate impacts of HAP on COPD. We deem the application of the E–R relationship justifiable in the current paper based on the following. Whereas no studies have established the E–R relationship for COPD prevalence and particulate pollution in China, the odds ratios for COPD and CB prevalence are shown to be quantitatively similar in studies of solid fuels (Kurmi et al., 2010). The close link between the two health end-points is indicated by the fact that most people who have COPD also have chronic bronchitis (US-NIH, 2010). A study of the 30-year cumulative incidence of CB and COPD related to tobacco smoking showed that half of the smokers who had CB also acquired COPD over time (Pelkonen et al., 2006). Regarding the use of ambient air pollution epidemiology, we rely on WHO (2010) stating that there is "no convincing evidence of a difference in the hazardous nature of particulate matter from indoor sources as compared with the outdoors". Transferring the E–R coefficient for ambient air in Chinese settings (where $PM_{2.5}$ levels were up to about 200–250 $\mu g/m^3$) to the integrated indoor and ambient exposure may thus be justified if a proper exposure assessment is carried out.

Some studies of cardiopulmonary mortality impacts of $PM_{2.5}$ exposure suggest a nonlinear exposure–response function that is relatively steep at low exposures and levels off at higher exposures (Pope et al., 2009). An E–R relationship that flattens renders smaller health benefits of interventions in very polluted environments compared to a similar

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intervention in less polluted environments. While no studies are available to directly verify a flattening E–R curve for COPD, E–R coefficients for CB reported in Western countries, where air pollution levels are much lower than in China, are considerably higher than the coefficient used in the current paper (see Aunan and Pan (2004) for comparisons). In a cohort study in Germany, Schikowski et al. (2010) report that the prevalence of mild and moderate COPD (diagnosed from lung function measurements) in non-smoking elderly women was reduced by about 3.0% per μg/m^3 reduction in PM_{10} (5 year mean). PM_{10} was 47 μg/m^3 in the baseline period and 27 μg/m^3 in the follow-up period. As a comparison, the β applied in the current paper renders a change in prevalence of 0.5% per μg/m^3 PM_{10}. This β results in mean RR estimates in Scenarios 1a (switch from No-chimney to new improved stove) and 2a (switch from No-chimney to pellet stove) of 2.94 [95% CI 2.24–3.91] and 4.96 [95% CI 3.43–7.20], respectively. These values seem low compared with the empirical adjusted OR between 'No-chimney' and 'Chimney' groups (see above) of 3.48 [95% CI 1.02–11.90], particularly for Scenario 1a. Consequently, we may in fact have underestimated risk reductions.

Pre-intervention prevalence rates in our study are low compared to the literature, and we suspect that a possible selection bias may have led to an underestimation of prevalence (Alnes et al., 2011). The assumption of 100% rebound is conservative, i.e. we may underestimate the benefit of stove interventions. The assumption that old stoves are abandoned and new stoves are properly maintained may on the other hand overestimate the real world benefit.

In lack of verified models to treat the time-dependency of the response in COPD incidence rate to reduced $PM_{2.5}$ on a population level, we assume that the reduced incidence rate is obtained from year 1. This is based on the assumption that the intervention may prevent individuals who are on the brink of developing the disease actually doing so. While this model entails a crude simplification, and a compromised lung function will continue to decline, lung function decline in individuals who do not yet fulfill the COPD diagnosis criteria is likely to happen at a slower rate given reduced exposure, as has been shown to be the case in patients with a COPD diagnosis (Scanlon et al., 2001).

In the current paper we model health benefits from stove interventions in an idealized setting. Still, given the above discussion, there is in our view no convincing evidence for a bias in either direction when it comes to the estimated costs and benefits. To confirm how improved stoves affect indoor PM concentrations and exposure, monitoring over the lifetime of an intervention is needed. Issues of compliance (i.e., to what extent old stoves are abandoned), mode of stove use, type of food cooked, and properties of fuel used, will affect actual exposure. As pointed out by others, "fuel stacking", in which new technologies and fuels are added to base, is a realistic possibility unless countermeasures are taken (Ruiz-Mercado et al., 2011; Sinton et al., 2004). Costs and technical problems as well as cultural preferences may hamper the uptake of cleaner technologies and must be carefully addressed (Peng et al., 2010; Pine et al., 2011). Stove and fuel switch programs need to be carefully designed to take into account local conditions regarding cooking and heating practices, fuels available, and levels of affordability. Practical field intervention studies are required to better understand and quantify feasible exposure reductions and health benefits in poor rural biomass dependent households.

Conclusions

There are large net benefits to be gained from upgrading household stoves in rural areas in Guizhou Province. We find that annually 0.6–2.6 new cases of COPD in women can be avoided per 1000 households in individual households that upgrade to second-generation improved stoves a la Rocket stove or similar. Correspondingly, 0.8–3.2 new cases of COPD in women can be avoided per 1000 households given community level upgrade to pellet stoves or other stove types with similar emissions. For the quantitative results to be valid, new stoves have to yield exposure reductions as described in the scenarios, i.e. reduce the $PM_{2.5}$ exposure with 41% to 77% of pre-intervention exposure. Considerably smaller reductions still yield B/C ratios above unity. While there are inherently large uncertainties in the calculations, the tendency of the results is robust as shown by the Monte Carlo lower confidence interval and with respect to changes in individual key parameters.

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