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LETTER

Adoption and use of a semi-gasifier cooking and water heating stove and fuel intervention in the Tibetan Plateau, China

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Abstract

Improved cookstoves and fuels, such as advanced gasifier stoves, carry the promise of improving health outcomes, preserving local environments, and reducing climate-forcing air pollutants. However, low adoption and use of these stoves in many settings has limited their benefits. We aimed to improve the understanding of improved stove use by describing the patterns and predictors of adoption of a semi-gasifier stove and processed biomass fuel intervention in southwestern China. Of 113 intervention homes interviewed, 79% of homes tried the stove, and the majority of these (92%) continued using it 5–10 months later. One to five months after intervention, the average proportion of days that the semi-gasifier stove was in use was modest (40.4% [95% CI 34.3–46.6]), and further declined over 13 months. Homes that received the stove in the first batch used it more frequently (67.2% [95% CI 42.1−92.3] days in use) than homes that received it in the second batch (29.3% [95% CI 13.8−44.5] days in use), likely because of stove quality and user training. Household stove use was positively associated with reported cooking needs and negatively associated with age of the main cook, household socioeconomic status, and the availability of substitute cleaner-burning stoves. Our results show that even a carefully engineered, multi-purpose semi-gasifier stove and fuel intervention contributed modestly to overall household energy use in rural China.

1. Introduction

Household burning of biomass and coal remains the primary energy source for cooking, heating, and other needs for billions of people (Bonjour *et al* 2013). This widespread practice is an important source of indoor and outdoor air pollution, and is associated with an estimated 2.8 million yearly premature deaths (GBD Risk Factors Collaborators 2016) and both global and regional climate change (Bailis *et al* 2015, Bond *et al* 2013). As a growing body of literature documents, the last four decades have seen many efforts by governments, non-governmental organizations, and for-profit companies to replace traditional biomass fuel stoves with higher efficiency fuels and biomass cookstoves (e.g. Manibog 1984, GACC 2015, Venkataraman *et al* 2010, Sinton *et al* 2004, Agarwal 1983, Dutta *et al* 2007, Mortimer *et al* 2016). Early stove programs focused on fuel supply and forest protection whereas more recent ones emphasized air pollution reductions and health. Unfortunately, low levels of adoption and poor emissions performances have limited the success of most clean stove programs in achieving their intended environmental and health goals. Reviews of stove intervention programs point to a number of technical, cultural, and socio-economic constraints that limit both the adoption of new stoves and the suspension of traditional stove use (Lewis and Pattanayak 2012, Rehfuess *et al* 2014, Malla and Timilsina 2014).

Advanced combustion semi-gasifier stoves are part of a next-generation of household energy technologies that have consistently outperformed other biomass stoves in laboratory studies, with some designs performing similarly to gaseous fuel stoves (Jetter *et al* 2012, Chen *et al* 2016, MacCarty *et al* 2010). The acceptability of semi-gasifier stoves in field settings is still largely unknown (Rehfuess *et al* 2014), with only a few studies objectively monitoring their use in different settings (Mukhopadhyay *et al* 2012, Pillarisetti *et al* 2014, Lozier *et al* 2016, Mortimer *et al* 2016), none of which evaluated the household or individual factors predicting use. Current rural energy policies in China support the production of processed biomass fuels (e.g. pellets or briquettes) (NDRC 2007, Wang *et al* 2015), which are most efficiently burned in gasifier and semi-gasifer stove designs (Shan *et al* 2016, Roth 2013). While the supply of processed biomass fuel in China is promising, the widespread acceptability and effectiveness of semi-gasifier interventions amongst China's rural population are largely unknown.

This study quantified the uptake, adoption and long-term use of a semi-gasifier cooking and water heating stove (TsingHua (THU) stove) and processed biomass fuel intervention in rural China, and evaluated the enablers and barriers of use. Notably, the THU stove underwent extensive laboratory and field testing in homes during a novel, iterative stove design process described elsewhere (Shan *et al* 2017). We conducted our study in China because it houses one-fifth of the world's solid fuel users and the government is actively involved in the development and promotion of advanced stoves (Bonjour *et al* 2013).

2. Methods

2.1. Study location and population

The study site covers approximately 6.2 km^2 in rural Beichuan County, Sichuan Province and includes 12 natural villages with ~280 households. Prior to intervention, all enrolled households cooked and heated their homes using wood and agricultural residues in traditional chimney stoves, though many also used liquefied petroleum gas (LPG), biogas, or electricity. Details on the study population and their energy use practices are presented elsewhere (Ni *et al* 2016, Shan *et al* 2014). These villages were selected for study because of a planned energy intervention program supported by China's Ministry of Science and Technology and the Ministry of Agriculture.

Eligible households cooked regularly with a traditional biomass stove and lived in one of the participating villages. We enrolled 205 primary female cooks from 204 homes into the study (Ni *et al* 2016). Most of the 85 eligible women who declined participation (71% participation rate) did so because they worked outside of the village and participation was logistically difficult. Participants provided verbal informed consent prior to participating, and were reminded at each follow-up visit that they could withdraw at any time. The study protocol and its consent procedures were approved by ethical review boards at McGill University (#A01-E01-14A), the University of Minnesota (#1304S31002), Tsinghua University, and the University of Wisconsin-Madison (#2014-0006).

2.2. Semi-gasifier stove and processed biomass fuel intervention package

2.2.1. Intervention description

The intervention package included a semi-gasifier stove (THU) for cooking and water heating and a two-year supply of pelletized biomass fuel. The stove was designed in an iterative way, undergoing extensive laboratory and field testing in village homes throughout the five-year stove development process (Shan *et al* 2017, Carter *et al* 2014). The stove featured an automatic ignition system and a small fan that produced a synthetic 'gas-like' flame that could be adjusted by the user. The adjustable flame varied the firepower and pot surface temperatures, and thus accommodated multiple styles of cooking (e.g. flash frying or slow simmer). Its other key features included a large cooking pot, stainless-steel water heater, galvanized iron chimney that vents outside the home, and an external pellet feeder that allowed the cook to add fuel during use (figure 1). The stove was classified as IWA-ISO Tier 3 with respect to thermal efficiency (41% +/−2%) and Tier 4 with respect to pollutant emissions and safety (the best performing tier) (Shan *et al* 2017). A small-scale biomass processing factory was constructed at the study site in 2012 to produce pelletized biomass fuel using locally available hardwood and agricultural waste. Additional information on the stove's design and development process, technical features, energy efficiency, and pollutant emissions performance in the laboratory and field are provided elsewhere (Shan *et al* 2017).

2.2.2. Stove and fuel dissemination

Following two seasons of baseline (pre-intervention) environmental measurements, half of the villages and their households were randomly selected to receive the intervention during the study period (intervention group) or at the study end (control group). Several

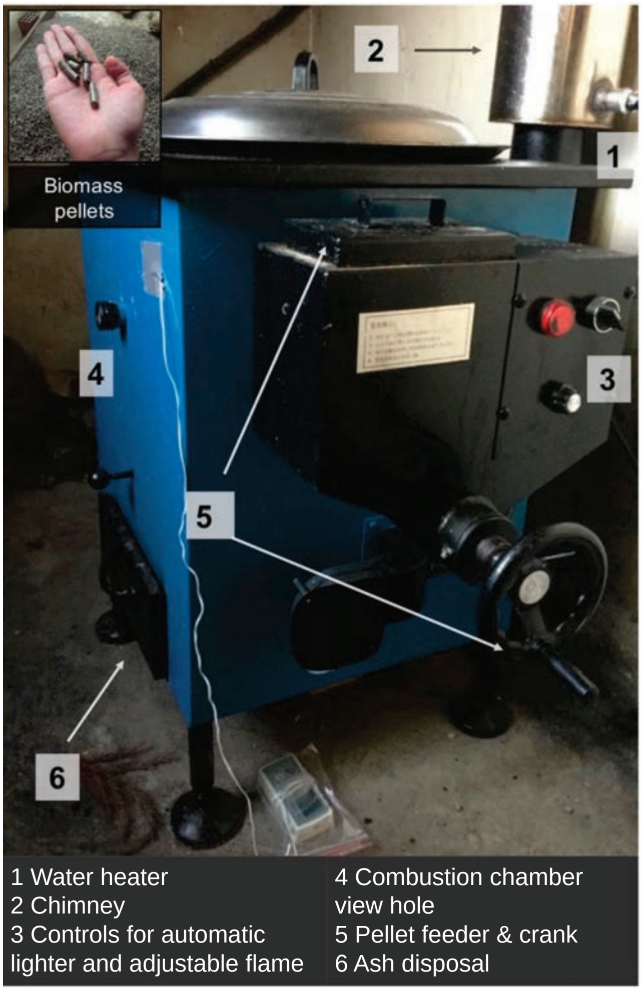

Figure 1. Key features of the Tsinghua designed THU semi-gasifier stove.

homes in intervention villages were controls because stove supply ran out ($n = 5$), they were not present to receive the stove ($n = 5$), or preferred to receive the intervention with control homes ($n = 1$). In intervention villages, 125 homes were approached to receive the intervention. Stoves were distributed in two phases: September-October 2015 (Phase 1, $n = 27$ homes) and January 2016 (Phase 2, $n = 98$ homes). Households were offered the intervention at no cost. Prior to stove installation, local technicians took home measurements to inform chimney length and stove installation location. Phase 1 households received stove use training during stove installation, while those in Phase 2 received training one month after installation due to the Spring Festival holiday (8–22 February 2016). Local technicians provided ongoing stove maintenance and repair, delivered fuel replacement, and offered ongoing training on stove use to cooks.

2.3. Study design and data collection

2.3.1. Questionnaires on stove use

The main cook in each study household completed a baseline questionnaire that included questions on household demographics, socioeconomic status (asset-based index, SES), and energy use practices (Ni *et al* 2016). A second questionnaire was administered to primary cooks at 9–10 months and 5–6 months' post-intervention for homes in Phase 1 and Phase 2, respectively. Cooks were asked about stove uptake (i.e. 'Did the household try cooking with the stove at least once?') (Ruiz-Mercado *et al* 2011) and stove adoption (i.e. 'Did the household permanently stop using the stove after they first tried it?') (Kumar and Mehta 2016), and the number of stove repairs needed since installation. Households were also asked about the most and least desirable features of the intervention and traditional stoves, and the types of local dishes typically cooked on both. Questions were adapted from previous rural energy surveys (Pattanayak *et al* 2016, Jeuland *et al* 2015), iteratively field-tested and adapted prior to implementation, and administered by field staff in the local dialect of Mandarin-Chinese.

2.3.2. Stove use monitoring and combustion event classifications

We measured 48 h stove use in 108 intervention homes and in 32 control homes at 9–10 or 5–6 months' post-intervention. In a random sample of 38 intervention homes, stove use was continuously monitored immediately following intervention installation for 13 months and for 5 months for homes in

Table 1. Metrics of short- and long-term stove use using real-time temperature data (Ruiz-Mercado *et al* 2013, Pillarisetti *et al* 2014, Lozier *et al* 2016).

Metric	Definition	48 h monitoring ($n = 108$ intervention homes)	5–13 month monitoring ($n = 38$ intervention homes)
Proportion of meals cooking with the stove	Total cooking events on each stove type was divided by the total number of meals reported by the main cook over the monitoring period	X	
Duration of cooking time	Total number of minutes that the stove was in use over the monitoring period	X	
Stove stacking	Use of more than one stove type during a 48 h monitoring period	X	
Monthly proportion of stove use	Total number of days per month when a stove was used at least once, divided by the total number of stove monitoring days in that month		X
Intensity of stove use	The average number of meals cooked on a stove in a given day, restricted to days that the stove was used		X

implementation Phase 1 and Phase 2, respectively. In seven of these homes, traditional stoves were monitored for at least a week prior to intervention. Stove use was objectively measured using real-time temperature data loggers, namely Thermochron iButtons (Models DS1922L/DS1921G, Berkeley Air, USA) and Tsinghua University Temperature Sensors (Tianjianhuayi Inc., Beijing, China). Field staff placed the temperature sensors on stoves and programmed them to record surface temperature every 10 min; pilot data showed that measurements at 5, 10, or 20 min did not change the number of combustion events detected (table S1, available at stacks.iop.org/ERL/12/075004/mmedia). Sensors were placed on all household stoves during 48 h monitoring and on the THU semi-gasifier and traditional stoves in the 38 homes with long-term monitoring. We placed control sensors on kitchen walls to measure room temperature fluctuations that were unrelated to stove use.

The number and duration of stove combustion events were identified from the temperature data using an algorithm adapted from Ruiz-Mercado *et al* (2013) and described in the SI text (S2). Briefly, a 'stove combustion event' was defined as a time period over which the stove surface temperature exceeded the wall control temperature by $\geq 10\,°C$ and met other conditions of peak shape to distinguish it from room temperature changes. If multiple combustion events were identified within a 60 min period, they were classified as a single 'cooking event', which was the metric we used in the analysis. Stove use metrics applied to the short and long-term monitoring data are defined in table 1.

2.4. Statistical analysis

We first examined the distribution of questionnaire and stove use data using summary statistics (means, proportions, and 95% confidence intervals [95% CI]) and graphical plots. To evaluate the enablers and barriers to intervention uptake and use, we defined outcomes as (1) *uptake* as 'tried ever (yes/no)', (2) *use* as 'stove was used at least once during 48 h monitoring (yes/no)', and (3) *duration of use* as the number of minutes that the stove was in use during 48 h monitoring. We then examined associations of these stove use outcomes with a number of independent variables selected based on the stove adoption literature. These variables included demographic characteristics of the household and primary cook, household SES (Ni *et al* 2016), pre-intervention stove practices, stove implementation phase, and the number of dishes typically cooked on the intervention stove. We tested the unadjusted bivariate associations using t-tests and χ^2 (chi-squared) tests. Co-linearity between independent variables was evaluated using Pearson and Spearman correlations. A multivariable probit regression model with a random intercept for natural village was used to model the association between uptake (yes/no) of the intervention and the selected independent variables. We next evaluated the association between 48 h stove use (yes/no), duration of use (minutes), and the independent variables using a hurdle model that was robust to clustering of standard errors within villages (Cragg 1971). In this model, the determinants of household stove use ($p(y > 0)$) and the total time (minutes) of stove use during the 48 h measurement period, conditional on use ($E(y \mid y > 0)$), were modeled using probit and linear regressions, respectively. Model fit was assessed by visually inspecting model residuals. We also tested for influential variables which may have driven the observed associations by iteratively inserting and removing them from the models and looking for a change >25% in the covariate effects.

3. Results

Household demographics were similar between intervention and control homes, between homes that participated in the post-intervention measurements and homes that did not, and between homes that

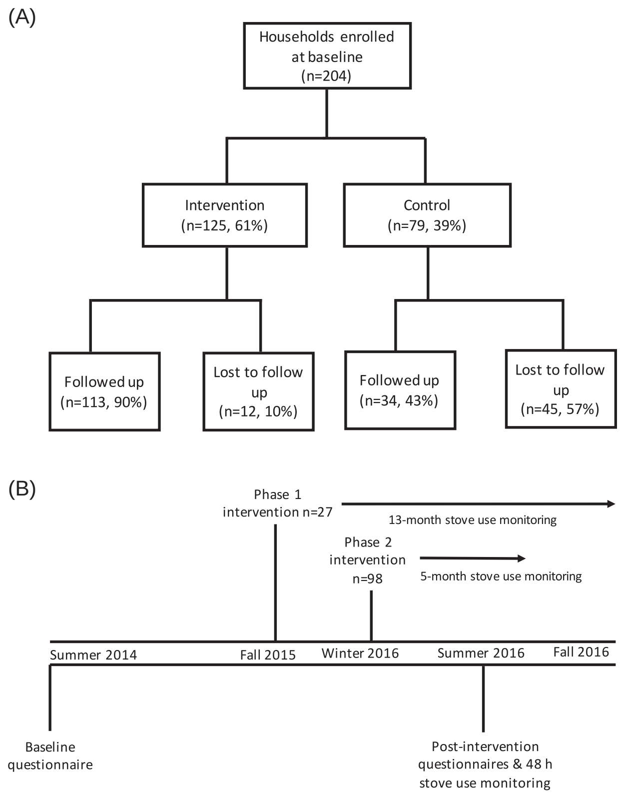

Figure 2. (*a*) Flow diagram of participation by intervention and control households, and (*b*) study timeline.

received the intervention in Phase 1 versus Phase 2 (tables S3 and S4).

Post-intervention interviews were conducted in 113 of the 125 intervention homes (90%) and 34 of the 79 control homes (43%) (figure 2). Reasons for loss to follow-up were household relocation to an urban area ($n = 7$ intervention, 24 control), refusal ($n = 2$ intervention, 18 control), sick (i.e. common cold) ($n = 3$ intervention, 1 control), and death ($n = 1$ control). Complete 48 h stove use information with SUMs was obtained from 108 intervention homes (86%) and 32 control homes (41%).

3.1. Intervention uptake and adoption

Uptake and adoption are defined previously (section 2.3) as whether a household tried the stove at least once (uptake), and whether they had not permanently stopped using it at the time of the survey (adoption). Among intervention homes interviewed, 79% (n = 89) reported using the THU stove at least once (uptake) (figure S5) and, among these, 92% ($n = 82$) reported still regularly cooking on the stove 5–10 months post-installation (adoption). Homes in Phase 1 had higher uptake and adoption of the THU stove compared with homes in Phase 2 (88% vs 77% (uptake) and 100% versus 90% (adoption), respectively). The percentage of homes that reported stove repairs was less frequent among Phase 1 homes than Phase 2 homes (27% versus 48%). The most commonly reported repair need was the stove's automated ignition (table S6).

3.2. Frequency and patterns of stove use among adopters

Prior to intervention, all study homes regularly (three or more times a week) cooked with a traditional chimney stove and 39% also regularly cooked with an electric (induction) or gaseous stove (figure 3). Post-intervention, the percentage of homes that used electric or gaseous stoves during 48 h of stove monitoring was 40% for intervention homes and 59.5% for control homes. Exclusive use of electric and gaseous stoves increased from 0% (pre-intervention) to 11% of intervention homes and 23% of control homes, which may reflect a shift to cleaner stoves that was independent of the intervention. While 43% of intervention homes used the THU stove during 48 h post-intervention monitoring, only 4% used it exclusively and the rest combined use with other stoves. Further, the majority of intervention homes (77%) continued to use traditional stoves in the post-intervention 48 h monitoring period.

Desirable features of the THU stove reported by cooks included its ability to reach high temperatures (51% of women), its ease of operation (43% of women), and that less smoke was generated from the cooking pot (40% of women). Desirable features of the traditional stove included the larger pot size and ability to cook more food (85% of women), and the taste of food (71% of women). Cooks also reported that the THU and traditional stoves were used to prepare different local dishes: 54% and 46% of cooks reported

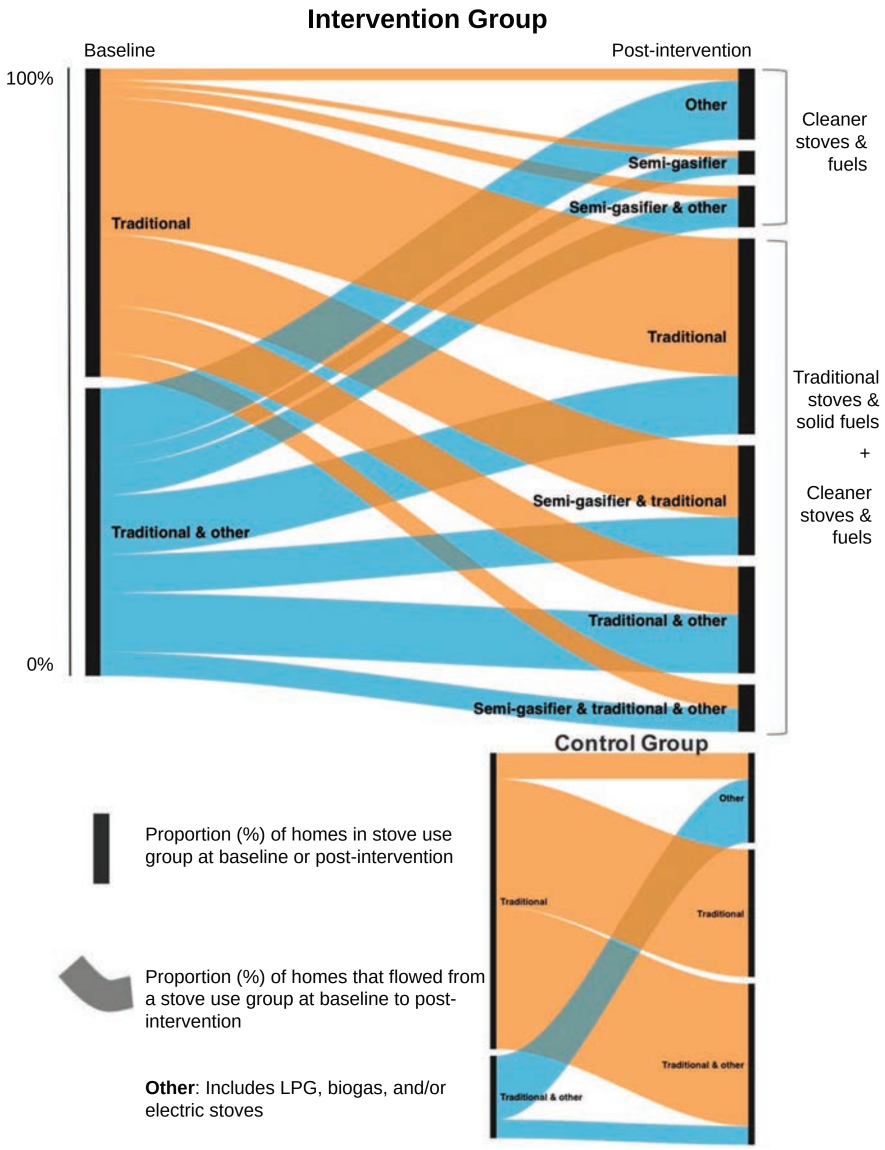

Figure 3. Proportion of homes using different stoves and stove combinations, before and after intervention. The y-axis represents the proportion of homes that regularly used different combinations of stoves, either at baseline or post-intervention. Stove use at baseline was classified as self-reported regular (3 or more times per week) use of stoves and post-intervention if the stove was classified to be in use at least once in the 48 h period of stove use monitoring. The flows from baseline to post-intervention stove use are proportional and include all homes. Estimates are from 80 intervention and 31 control homes that were followed up post-intervention with stove use monitoring on all household stoves.

using both stoves to prepare fried dishes and stews, respectively, while 62%, 62%, and 70% reported using the traditional stove for porridges, soups, and steamed dishes, respectively. Less than 3% of participants reported using the THU stove to cook the latter set of foods (figure S7).

3.3. Long-term stove use monitoring with temperature sensors

3.3.1. Five-month monitoring

Among intervention homes, the average percentage of days that THU and traditional stoves were in use over a five-month post-intervention monitoring period was 40.4% [95% CI 34.3–46.6] and 45.2% [95% CI 38.3–52.0], respectively (figure 4), with a small decline in traditional stove use from pre-intervention levels (63.0% [95% CI 43.8–82.2] days in use). The average proportion of THU stove use over five months post-intervention differed for homes in Phase 1 and Phase 2 implementation groups (67.2% [95% CI 42.1–92.3] and 29.3% [95% CI 13.8–44.5] of days, respectively), though the rates of decline in use from the first to fifth month post-intervention were similar (−6.7% and −6.0% days in use, respectively). When used, the average intensity of use was identical for the THU and traditional stoves (1.7 [95% CI 1.6–1.7] meals per day, on average). The average daily number of cooking events on the THU stove was similar when it was used exclusively (1.7 events [95% CI 1.6–1.7]) or on the same day as the traditional stove (stove-stacking) (1.7 events [95% CI 1.6–1.8]). We found a moderate to high degree of correlation between our 48 h short- and long-term measures of stove use (S8).

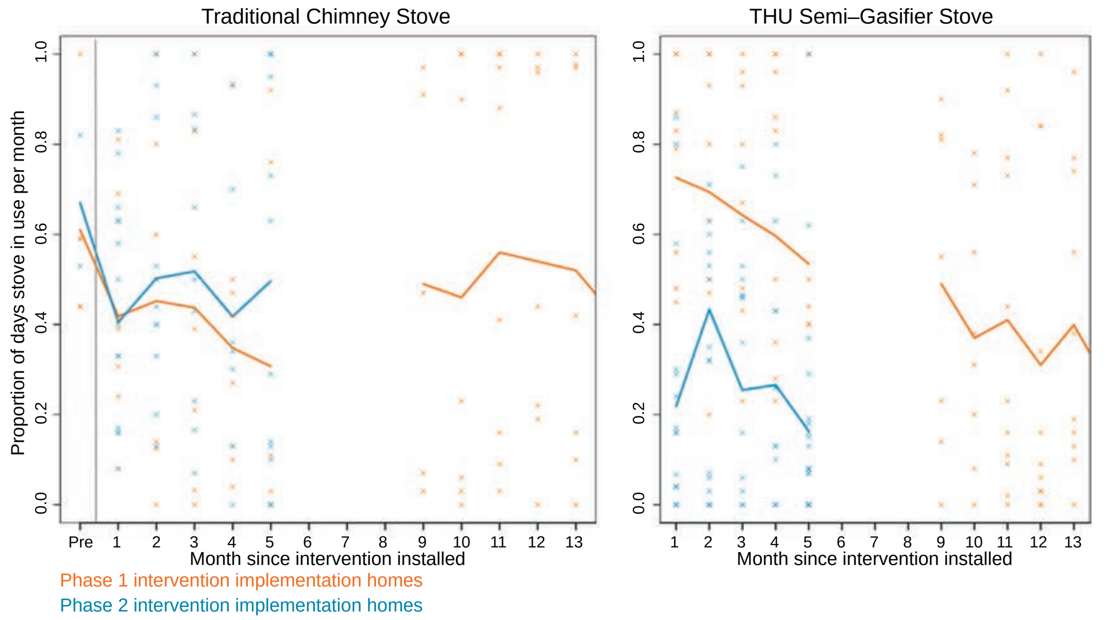

Figure 4. Average monthly proportion of days that the intervention and traditional stoves were used, pre- and up to 13 months post-intervention, in a random sample of 38 homes. Individual data points (x) represent the proportion of days that the stove was used per month for each home. Lines represent the monthly average across all homes. Seven homes contributed to pre-intervention traditional stove estimates (pre). Days were omitted if homes did not have fuel, the stove needed repairs, participants were temporally living outside of the village, or the sensors failed.

3.3.2. Thirteen-month monitoring

Among homes in Phase 1, the average proportion of days the THU and traditional stoves were in use over a 13 month period was 51.4% [95% CI 45.1−59.8] and 45.6% [95% CI 36.7−36.7], respectively (figure 4). However, THU stove use declined considerably from one (74% of days) to 13 (39% of days) months post-intervention.

3.4. Socio-demographic and behavioral predictors of THU stove uptake and use

The multi-level multivariable probit model did not identify any variables that were associated with intervention uptake. However, the proportion of homes with uptake was not randomly distributed across the study region and, rather, clustered in certain villages (p-value from likelihood ratio test of standard and multi-level probit model difference = 0.05; intra-class correlation coefficient = 0.13). In contrast, a number of factors were associated with 48 h intervention use (yes/no) and the duration of use (minutes per 48 h) (table 2). If a cook reported that the THU stove was suitable to cook one or more local dishes, the probability of stove use in the home increased significantly ($p < 0.01$). If the stove was implemented in Phase 2, the THU stove was less likely to be used ($p = 0.05$). Conditional on the THU stove being used, age of the primary cook ($p < 0.01$), household SES ($p = 0.05$), and ownership of either a gaseous or electric stove at baseline ($p < 0.01$), were all negatively associated with minutes of THU stove use.

In robustness checks, we evaluated the proportion of daily meals cooked on the THU gasifier stove as an alternate outcome to duration of use, and estimated two-part models that assumed independence in each stage of the model, and standard truncated models (tobit). The results were similar across models. The hurdle model was selected for the main analysis because the estimations of stove use and duration of use were most in line with the process from which the data arose, and it had the lowest Akaike Information Criterion value (Xu *et al* 2015). We also calculated the degree of correlation between 48 h average cooking events during periods of 48 h observation and those of non-observation in a random sample of 17 homes, and did not find evidence of observer bias (S8).

4. Discussion

Though hundreds of millions of improved cookstoves have been disseminated globally (Sinton *et al* 2004, Venkataraman *et al* 2010), low levels of uptake and sustained exclusive use have limited their effectiveness (Manibog 1984, Pillarisetti *et al* 2014, Lozier *et al* 2016, Mukhopadhyay *et al* 2012, Mortimer *et al* 2016, Pine *et al* 2011). We found that even a high-preforming cookstove and fuel intervention, designed to meet local cooking needs and preferences, failed to replace traditional stoves or reach the uptake and use levels needed to achieve measureable air pollution reductions (Johnson and Chiang 2015). Compared with recent improved stove evaluations, the level of uptake in our study (79% of homes) was similar to that observed in Guatemala with a chimney biomass stove (Ruiz-Mercado *et al* 2013), in Malawi and India with Philips HD4012 gasifier stoves (Mortimer *et al* 2016, Mukhopadhyay *et al* 2012), in India with an electric

Table 2. Results from the multivariable hurdle regression model[a] of THU semi-gasifier stove use, and duration of use (minutes), from 48 h stove use monitoring.

	Stove use					
	Probit regression (use > 0)			Linear regression (E(time in use ∣ use > 0))		
Individual and household characteristics	Average change in the probability of stove being used	95% confidence interval	*p*-value	Average change in minutes of stove use over 48 h	95% confidence interval	*p*-value
Age of primary cook at baseline	0.00	−0.01, 0.01	0.48	−3.85	−6.29, −1.39	<0.01
Household socioeconomic status	−0.01	−0.06, 0.04	0.60	−34.92	−73.27, −1.23	0.05
Number of inhabitants	0.01	−0.03, 0.06	0.59	16.72	−15.82, 49.25	0.31
Own LPG, biogas, or electric stove?						
No	Ref			Ref		
Yes	0.11	−0.18, 0.39	0.47	−86.20	−142.54, −29.86	<0.01
Adult child living in home?						
No	Ref			Ref		
Yes	0.08	−0.04, 0.19	0.19	26.23	−68.91, 121.34	0.59
Stove implementation phase[b]						
Phase 1	Ref			Ref		
Phase 2	−0.11	−0.22, 0.00	0.05	5.73	−60.55, 72.01	0.86
Able to cook one or more local dishes with the semi-gasifier stove?						
No	Ref			Ref		
Yes	0.41	0.31, 0.51	<0.01	30.43	−11.23, 72.34	0.52

[a] Standard errors of the model were robust to clustering of the outcome within natural village ($n = 12$).
[b] The variable indicating if the THU stove needed repairs ever (1) or never (0) was removed from the model due to co-linearity with stove implementation phase.

stove (Pattanayak *et al* 2016, Jeuland *et al* 2015), and in Ghana and Rwanda with rocket stoves (Piedrahita *et al* 2016, Barstow *et al* 2014). The percentage of days the THU stove was in use over a five month period was modest (~40% of days in use per month), and gradually declined over time, similar to what was observed in studies of ISO Tier 3 and Tier 4 gasifier stoves in India and Sub-Saharan Africa (Piedrahita *et al* 2016, Pillarisetti *et al* 2014, Mukhopadhyay *et al* 2012, Lozier *et al* 2016, Mortimer *et al* 2016, Lotter *et al* 2015).

While most study homes continued to cook with their traditional stoves, increased periods of exclusive use of modern-fuel stoves was observed from pre- to post-intervention. For example, pre-intervention, none of the study homes exclusively used modern fuel stoves, such as electric or gaseous stoves, to meet their energy needs but 14% exclusively used them during post-intervention 48 h stove use monitoring. At baseline, all study homes regularly cooked with solid fuels in traditional stoves, but only 77% used them during short-term post-intervention monitoring. This trend in increased electric and gaseous stove use, independent of the intervention, may be partly attributable to recent economic growth and development (i.e. improved roads and other infrastructure) in the study region during recent post-earthquake reconstruction, and also reflects the gradual shift away from solid fuel cooking occurring throughout China (Bonjour *et al* 2013, Chen *et al* 2016, Pachauri and Jiang 2008, Masera *et al* 2000). A similar trend occurred during an intervention study in India when, compared with the intervention advanced biomass stove, more study homes gained access to and adopted LPG due to improved fuel availability and decreased costs during the study period (Thurber *et al* 2014).

In contrast to the laboratory-based design process of most biomass stoves, the THU stove was iteratively engineered through a process where local cooking requirements and user preferences informed each stage of its design (Shan *et al* 2017). Still, a third of cooks (38%) reported that they regularly did not use the THU to cook many local dishes, and this variable was a significant predictor of stove use in the two-stage hurdle regression model. Further, most participants preferred the taste of food prepared on a traditional stove and its capacity to prepare larger quantities of food than the THU stove. These results further highlight the challenge of designing contextually appropriate stoves that adequately meet or exceed the functionality of traditional cookstoves that, in most settings, have been used for lifetimes (Bielecki and Wingenbach 2014, Bhojvaid *et al* 2014, Pant *et al* 2014, Jeuland *et al* 2015).

Overall adoption and use of the THU stove were considerably higher among homes in Phase 1 compared with Phase 2, despite similar household and primary cook demographics (table S4). Notably, the timing of stove use training and stove repair needs were different between the Phases, though not originally planned. In Phase 1, the number of intervention homes receiving stoves was smaller ($n = 27$ versus $n = 98$) and households received training on stove use immediately after installation. Also, the Phase 2 group received stove use training a month after installation due to the Spring Festival holiday. The need to provide training on stove use within a critical time window of installation may be important for adoption (Martin *et al* 2013, Stanistreet *et al* 2014, Rosenbaum *et al* 2015). In addition, stoves implemented in Phase 2 were manufactured as a separate batch and under different company management, which appears to have impacted stove quality; in particular, stove breakage was considerably more common. The nuisance of constant repairs likely inhibited reliance on, and confidence in, the THU stove to meet household energy needs (Rehfuess *et al* 2014, Stanistreet *et al* 2014).

Households that never tried the intervention (no uptake) were significantly clustered in certain villages. Because we lacked statistical power for village level analysis, we cannot identify what village-level factors were associated with the clustering. Previous studies from low and middle-income countries identified village-level peer effects and influence from leader's opinion as important drivers of adoption (Jagger and Jumbe 2016, Martin *et al* 2013, Beltramo *et al* 2015). Other studies in Guatemala and Mexico found that differences between individual preferences for improved cookstoves were greater than the differences between communities (Troncoso *et al* 2013, Bielecki and Wingenbach 2014). It is also possible that residents of the same village were more similar in behaviors and other characteristics, and that this clustering was due to peer effects (Pattanayak and Pfaff 2009).

That older cooks used the intervention less is perhaps not surprising, considering that cooking behaviors and habits become entrenched over time, and that older cooks may be less inclined to modify these long-developed behaviors (Rehfuess *et al* 2014, Lewis and Pattanayak 2012, Bielecki and Wingenbach 2014). The negative association between household SES and intervention use is inconsistent with the literature (Lewis and Pattanayak 2012, Rehfuess *et al* 2016, Stanistreet *et al* 2014). However, since households were provided the stove at no charge, cost may not drive our results because there are lower returns from intense use for wealthy households who are already using improved fuels. This might also explain why households that already owned and used other cleaner stoves (i.e. LPG, biogas, electricity) did not use the intervention stoves as intensely—there is no novelty or additional benefit to use.

Our study has a number of limitations to consider for future studies on this topic. First, recent peri-urban development in our study region caused increased migration and a higher than expected loss to follow-up. Though, baseline socio-demographic and energy use characteristics were similar between homes that remained in the study and those lost to follow-up, indicating that the intervention adoption behaviors may have been similar for homes that left the study. Second, self-reported information on stove preferences and use can be subject to recall bias if participants felt inclined to respond in a systematically more positive or negative way (Coughlin 1990, Piedrahita *et al* 2016). However, our field staff continually encouraged participants to report their true experiences and, overall, self-reported information on stove adoption and use was consistent with objectively measured stove use metrics, suggesting that recall bias did not impact our results. Finally, traditional stoves have large surface areas and highly insulated combustion chambers that made it difficult to distinguish traditional stove use from room temperature change in a small number of cases ($n = 5$). While traditional stove use may thus be slightly underestimated (Simons *et al* 2014, Hankey *et al* 2015) as a result, we tried to avoid incorrect classifications by visually analyzing these cases.

5. Conclusion

Low-polluting gasifier stoves have the potential to fill critical clean cooking needs, particularly in places where raw biomass is abundant and where access to gaseous fuel or electricity is limited. We found that a low-polluting semi-gasifier stove and fuel intervention, designed to meet the local community's preferences and energy use needs, failed to replace traditional stove use in a rural Chinese setting. Though most households tried the stove and many continued cooking with it for at least 5–13 months post-intervention, the levels of use were modest and likely insufficient for achieving large air pollution reductions. Factors including stove breakage, delayed user training, and the inability of the stove to meet household's diverse cooking needs were associated with lower levels of use. These results can inform future stove design and implementation programs, and assist researchers, stove developers, and practitioners in prioritizing efforts to formulate and test hypotheses about how to promote and accelerate exclusive use of clean technologies because household energy transitions have typically occurred over long periods (Pachauri and Jiang 2008). In the very near term, clean-burning LPG and electric stoves may be most suitable for replacing traditional biomass cookstoves since they are the least polluting cooking stoves and already exclusively used by millions of rural homes in China (Smith 2002, Pattanayak *et al* 2016, Pachauri and Jiang 2008).

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References

Agarwal B 1983 Diffusion of rural innovations: some analytical issues and the case of wood-burning stoves *World Dev.* **11** 359–76

Bailis R *et al* 2015 The carbon footprint of traditional woodfuels *Nat. Clim. Change* **5** 266–72

Barstow C K *et al* 2014 Designing and piloting a program to provide water filters and improved cookstoves in Rwanda *PLoS ONE* **9** e92403

Beltramo T *et al* 2015 Does peer use influence adoption of efficient cookstoves? Evidence from a randomized controlled trial in Uganda *J. Health Commun.* **20** 55–66

Bhojvaid V *et al* 2014 How do people in rural India perceive improved stoves and clean fuel? Evidence from Uttar Pradesh and Uttarakhand *Int. J. Environ. Res. Public Health* **11** 1341–58

Bielecki C and Wingenbach G 2014 Rethinking improved cookstove diffusion programs: a case study of social perceptions and cooking choices in rural Guatemala *Energy Policy* **66** 350–58

Bond T C *et al* 2013 Bounding the role of black carbon in the climate system: a scientific assessment *J. Geophys. Res. Atmos.* **118** 5380–552

Bonjour S *et al* 2013 Solid fuel use for household cooking: country and regional estimates for 1980−2010 *Environ. Health Perspect.* **121** 784–91

Carter E M *et al* 2014 Pollutant emissions and energy efficiency of Chinese gasifier cooking stoves and implications for future intervention studies *Environ. Sci. Technol.* **48** 6461–67

Chen Y *et al* 2016 Efficiencies and pollutant emissions from forced-draft biomass-pellet semi-gasifier stoves: comparison of international and Chinese water boiling test protocols *Energy Sustain. Dev.* **32** 22–30

Chen Y *et al* 2016 Transition of household cookfuels in China from 2010 to 2012 *Appl. Energy* **184** 800–809

Coughlin S S 1990 Recall bias in epidemiologic studies *J. Clin. Epidemiol.* **43** 87–91

Cragg J G 1971 Some statistical models for limited dependent variables with application to the demand of durable goods *Econometrica* **39** 829–44

Dutta K *et al* 2007 Impact of improved biomass cookstoves on indoor air quality near Pune, India *Energy Sustain. Dev.* **11** 19–32

GACC 2015 *Five years of impact 2010–2015 report* (Washington, DC: GACC)

GBD Risk Factors Collaborators 2016 Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risk, 1990−2015: a systematic analysis for the global burden of disease study 2015 *Lancet* **388** 1659–724

Hankey S *et al* 2015 Using objective measures of stove use and indoor air quality to evaluate a cookstove intervention in rural Uganda *Energy Sustain. Dev.* **25** 67–74

Jagger P and Jumbe C 2016 Stoves or sugar? Willingness to adopt improved cookstoves in Malawi *Energy Policy* **92** 409–19

Jetter J *et al* 2012 Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards *Environ. Sci. Technol.* **46** 10827–34

Jeuland M *et al* 2015 Preferences for improved cookstoves: evidence from rural villages in north India *Energy Econ.* **52** 287–98

Johnson M A and Chiang R A 2015 Quantitative guidance for stove usage and performance to achieve health and environmental targets *Environ. Health Perspect.* **123** 820–26

Kumar P and Mehta S 2016 Poverty, gender, and empowerment in sustained adoption of cleaner cooking systems: making the case for refined measurement *Energy Res. Soc. Sci.* **19** 48–52

Lewis J J and Pattanayak S K 2012 Who adopts improved fuels and cookstoves? A systematic review *Environ. Health Perspect.* **120** 637–45

Lotter D *et al* 2015 Microgasification cookstoves and pellet fuels from waste biomass: a cost and performance comparison with charcoal and natural gas in Tanzania *Afr. J. Environ. Sci. Technol.* **9** 573–83

Lozier M J *et al* 2016 Use of temperature sensors to determine exclusivity of improved stove use and associated household air pollution reductions in Kenya *Environ. Sci. Technol.* **50** 4564–71

MacCarty N, Still D and Ogle D 2010 Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance *Energy Sustain. Dev.* **14** 161–71

Malla S and Timilsina G R 2014 Household cooking fuel choice and adoption of improved cookstoves in developing countries: a review, *Report* (Washington, DC: World Bank) (https://openknowledge.worldbank.org/handle/10986/18775)

Manibog F 1984 Improved cooking stoves in developing countries: problems and opportunities *Annu. Rev. Energy* **9** 199–227

Martin S L *et al* 2013 Using formative research to design a behavior change strategy to increase the use of improved cookstoves in peri-urban Kampala, Uganda *Int. J. Environ. Res. Public Health* **10** 6920–38

Masera O R, Saatkamp B D and Kammen D M 2000 From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model *World Dev.* **28** 2083–2103

Mortimer K *et al* 2016 A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the cooking and pneumonia study): a cluster randomised controlled trial *Lancet* **389** 167–75

Mukhopadhyay R *et al* 2012 Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: an exploratory study to inform large-scale interventions *Glob. Health Action* **5** 19016

NDRC, ND and RC 2007 *Medium and Long-term Development Plan for Renewable Energy in China* (www.martinot.info/China_RE_Plan_to_2020_Sep-2007.pdf)

Ni K *et al* 2016 Seasonal variation in outdoor, indoor, and personal air pollution exposures of women using wood stoves in the Tibetan Plateau: baseline assessment for an energy intervention study *Environ. Int.* **94** 449–57

Pachauri S and Jiang L 2008 The household energy transition in India and China *Energy Policy* **36** 4022–35

Pant K, Pattanayak S and Thakuri M 2014 Climate change, cook stove, and coughs and colds: thinking global and acting local in rural Nepal *Environment and Development Economics: Essays in Honor of Sir Partha Dasgupta* ed S Barrett, K Maler and E S Maskin (Oxford: Oxford University Press) pp 145–68

Pattanayak S and Pfaff A 2009 Behavior, environment and health in developing countries: evaluation and valuation *Annu. Rev. Resour. Economics* **1** 183–222

Pattanayak S K *et al* 2016 Cooking up change in the Himalayas: experimental evidence on cookstove promotion *Duke Environmental and Energy Economics Working Paper Series EE 16-03*

Piedrahita R *et al* 2016 Assessment of cookstove stacking in Northern Ghana using surveys and stove use monitors *Energy Sustain. Dev.* **34** 67–76

Pillarisetti A *et al* 2014 Patterns of stove usage after introduction of an advanced cookstove: the long-term application of household sensors *Environ. Sci. Technol.* **48** 14525–33

Pine K *et al* 2011 Adoption and use of improved biomass stoves in rural Mexico *Energy Sustain. Dev.* **15** 176–83

Rehfuess E *et al* 2016 Assessing household solid fuel use: multiple implications for the millennium development goals *Environ. Health Perspect.* **114** 373–78

Rehfuess E *et al* 2014 Enablers and barriers to large-scale uptake of improved solid-fuel stoves: a systematic review *Environ. Health Perspect.* **122** 120–30

Rosenbaum J, Derby E and Dutta K 2015 Understanding consumer preference and willingness to pay for improved cookstoves in Bangladesh *J. Health Commun.* **20** 20–27 (April 2016)

Roth C 2013 *Micro-gasification: Cooking with gas from dry biomass* (http://seachar.org/wp-content/uploads/2014/04/2014-03_Micro-gasification_manual_GIZ_HERA_Roth_med.pdf)

Ruiz-Mercado I *et al* 2011 Adoption and sustained use of improved cookstoves *Energy Policy* **39** 7557–66

Ruiz-Mercado I *et al* 2013 Quantitative metrics of stove adoption using stove use monitors (SUMs) *Biomass Bioenergy* **57** 136–48

Shan M *et al* 2014 A feasibility study of the association of exposure to biomass smoke with vascular function, inflammation, and cellular aging *Environ. Res.* **135** 165–72

Shan M *et al* 2017 A user-centered iterative engineering approach for advanced biomass cookstove design and development *Environ. Res. Lett.* submitted

Shan M *et al* 2016 Re-thinking China's densified biomass fuel policies: large or small scale? *Energy Policy* **93** 119–26

Simons A M *et al* 2014 Comparing methods for signal analysis of temperature readings from stove use monitors *Biomass Bioenergy* **70** 476–488

Sinton J E *et al* 2004 An assessment of programs to promote improved household stoves in China *Energy Sustain. Dev.* **8** 33–52

Smith K 2002 In praise of petroleum *Science* **298** 1847

Stanistreet D *et al* 2014 Factors influencing household uptake of improved solid fuel stoves in low-and middle-income countries: a qualitative systematic review *Int. J. Environ. Res. Public Health* **11** 8228–50

Thurber M C *et al* 2014 'Oorja' in India: assessing a large-scale commercial distribution of advanced biomass stoves to households *Energy Sustain. Dev.* **19** 138–50

Troncoso K, Armendáriz C and Alatorre S 2013 Improved cook stove adoption and impact assessment: a proposed methodology *Energy Policy* **62** 637–45

Venkataraman C *et al* 2010 The Indian National Initiative for advanced biomass cookstoves: the benefits of clean combustion *Energy Sustain. Dev.* **14** 63–72

Wang W, Ouyang W and Hao F 2015 A supply-chain analysis framework for assessing densified biomass solid fuel utilization policies in China *Energies* **8** 7122–39

Xu L *et al* 2015 Assessment and selection of competing models for zero-inflated microbiome data *PLoS ONE* **10** e0129606