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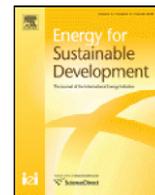
A rapid assessment randomized-controlled trial of improved cookstoves in rural Ghana

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A R T I C L E   I N F O

A B S T R A C T

We conducted a rapid assessment randomized-controlled trial to quantify changes in fuel use, exposure to smoke, and self-reported health attributable to deployment of an improved wood cookstove in the Upper West region of Ghana. Women trainers from neighboring villages taught participants to build an improved cookstove and demonstrated optimal cooking techniques on such stoves. Participants were then randomly assigned to construct improved stoves at their homes immediately (treatments) or in a few months (controls). Several weeks after the treatments built their new stoves, all participants engaged in a cooking test while wearing a carbon monoxide monitor. At that time we surveyed participants on cooking activity, fuel wood gathering, self-reported health, and socioeconomic status. At a subset of homes we also installed stove usage monitors on the improved and traditional stove for the following three weeks.

During the cooking tests, treatments used 5% less fuel wood than controls, but the difference was not statistically significant. There were no detectable reductions in a households' weekly time gathering wood or in exposure to carbon monoxide. In contrast, there was a sharp decline in participants' self-reported symptoms associated with cooking, such as burning eyes, and in respiratory symptoms, such as chest pain and a runny nose. Stove usage monitors show that treatments used their new stove on about half of the days monitored and reduced use of their old stoves by about 25%. When we returned to three of the villages eight months after project implementation, about half the improved stoves showed evidence of recent usage. Overall the new stoves were not successful, but the evaluation was. Our methods offer a rigorous modest-cost method for evaluating user uptake, field-based stove performance, and exposure to smoke.

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Introduction

Roughly half the world cooks with solid biomass fuels such as wood and charcoal, and in sub-Saharan Africa, the vast majority of rural families cook with biomass (Rehfuess, et al., 2006; Smith, et al., 2004).

Conventional biomass stoves produce air pollutants such as particulate matter and carbon monoxide (Bruce, et al., 2002; Ezzati, et al., 2000; Pope and Dokcery, 2006; WHO, 2002). The resulting household air pollution leads to approximately 1.6 million deaths per year as well as a range of health problems (Bruce, et al., 2006; Dherani, et al., 2008; Smith, et al., 2004; WHO, 2002). Exposure to these pollutants is particularly pronounced for women and for young children, as these groups spend the greatest amount of time near a stove (Balakrishnan, et al., 2002; Ezzati and Kammen, 2002; Jiang and Bell, 2008; Mestl, et al., 2007).

Because traditional cookstoves burn inefficiently, they require extra wood and other biomass fuel—contributing to deforestation and global climate change. The time required to gather fuel further deepens poverty and may lower school enrollment.

Theory of change

Improved stoves have the potential to reduce the harm that cooking with biomass does to health. For example, the RESPIRE study in Guatemala found substantial reductions in exposure to indoor air pollution and rates of respiratory illness among households with improved stoves (Diaz, et al., 2007; McCracken, et al., 2007; Smith, et al., 2010). Other recent field-based evaluations of various improved stove designs demonstrate 20–50% reductions in exposure to particulate matter and carbon monoxide during use compared to conventional stoves (Dutta, et al., 2007; Masera, et al., 2007). Further, a meta-analysis suggests that improved stoves are associated with lower levels of respiratory illness in children (Dherani, et al., 2008).

Improved stoves also have potential for substantially reducing fuel use, which reduces the environmental harms from traditional stoves. The best improved stoves can reduce fuel use by as much as two-thirds

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relative to conventional stoves (Johnson, et al., 2009; Masera, et al., 2007; Smith, et al., 2007), although current mass-produced models yield reductions closer to one-third (Adkins, et al., 2010).

Our intervention partner's theory of change began with the premise they had identified a low-cost improved cookstove with good laboratory and pilot field results showing reductions in fuel use and harmful emissions.

The inefficiency of traditional cookstoves and three-stone fires holds out the possibility that many women would like to own an efficient stove that reduces the burden of gathering fuel will be. If costs are low enough, a new stove may be adopted without the need for widespread subsidies (unlike, for example, bednets).

The intervention partner's theory of change noted that they are a trusted local NGO active in these communities. Thus, when they explained the advantages of lower fuel use and less smoke, they anticipated high demand. Women would build their stoves with help from our NGO partner.

The new stove would then reduce emissions and its chimney would move remaining smoke away from the cook and her family, reducing the sore eyes and other uncomfortable effects of cooking on a smoky cookfire (Diaz, et al., 2007). The combination of saving time and improving comfort means that cooks would use the new stove (almost) every day.

The theory of change posits that regular use of the new stove would displace almost as much use of traditional stoves or three-stone fires. The result would be lower fuel use not just when using the new stove but also lower fuel use in total.

Finally, the shift to a fuel-efficient new stove coupled with lower exposure to emissions would lead to the impacts of interest: less deforestation, lower release of greenhouse gases, and improved health.

The theory of change has many assumptions that helped drive the evaluation. For example it is possible that women do not value the savings of fuel or reduction in exposure to smoke or they may not trust our NGO partner's claims that the new stove will provide these benefits. In that case, the project will fail when women decline to build the new stove.

In other stove projects many new stoves are not used regularly (Ruiz-Mercado, et al., 2011). Thus, even if they build the new stove, the new stove may not be used because it is less flexible in terms of size of pot, size of fuel, or type of fuel than a traditional stove or three-stone fire. The new stove may be in the wrong location (e.g., outdoors on a rainy day or indoors on a day with nice weather), or its fuel may require more preparation.

Even when the new stove is used, it may add to—not replace—the use of the old stove (Ruiz-Mercado, et al., 2011). Having a new stove makes it easier for cooks to cook meals in parallel (instead of making dishes sequentially) or to cook more dishes (for example, a special meal for a diabetic or a toddler). Adding a new stove need not reduce emissions if it is used in parallel with an old stove.

The evaluation challenge

Unfortunately, it is difficult to tell what improved stoves improve users' outcomes in different settings. One study found only a third of stove programs included an evaluation, and only a minority of those evaluations measured fuel use in the field (Gifford, 2010).

The most convincing evaluations have been randomized controlled trials with multiple measures gathered in a very large number of longitudinal household visits (e.g., Masera, et al., 2007; Smith, et al., 2007). While these studies are extremely valuable, they also are extremely expensive and time-consuming, so there will never be a large number of them. In addition, long-term longitudinal data collection suffers from high costs and risks of high attrition.

In contrast, the most common form of field evaluation of how a new stove affects users involves a before–after comparison of fuel use (e.g., Wallmo and Jacobson, 1998; see the discussion in Johnson, et al., 2010). This study design can be a sensible use of limited resources.

Unfortunately, this study design can give erroneous answers if unmeasured factors affected cooking during the period between the tests with the old and new cookstove.

In addition, the standard "controlled cooking tests" (which examines the fuel used to cook a standard dish) measure fuel use specifically of a new stove versus an old stove, one stove at a time. As emphasized above, measuring the effect of a new stove when used is not a good estimate of its effect in the field because the true effect depends both on how and how often cooks use the new stove and also how much they stop using their old stoves (Ruiz-Mercado, et al., 2011).

The more realistic kitchen performance test, where researchers return daily to weigh fuel remaining from the previous day's stockpile, holds the possibility of measuring the effects of using multiple stoves. Unfortunately, with stove-related measurements occurring each day, users probably feel encouraged to use their new stove and to avoid using their old ones. This "demand effect" can bias the measured effect of a new stove.

Further, both a controlled cooking tests and a kitchen performance test study users of the new stoves for a few days at most. These short-term studies can also be misleading if impacts measured at a single time do not persist.

A goal of this study was to determine if a modest-cost evaluation is feasible that provides the rigor of the long-term randomized trials cited above but with fewer measures and far lower requirements of time and money. Thus, in collaboration with the Ghanaian Council on Scientific and Industrial Research, we carried out a randomized-controlled field trial of an improved cookstove program in 2009 on behalf of Plan Ghana, an NGO.

Plan Ghana's intervention began by recruiting participants and training them in the benefits of the new stove. Plan Ghana then trained interested participants in making bricks and using the bricks to make new stoves. At this point the evaluation team randomized participants into an "early stove" group and a "late stove" group. We gave the early group the manufactured part for their stove and encouraged them to build stoves in the next 2 weeks.

We replaced the before–after design of a standard evaluation with randomization, providing the rigorous comparison group of the very best studies. To reduce costs and attrition, we did not collect a baseline but instead depend on the comparison between the treatment and control groups.

Because we care about how the stove is used over time, we installed stove usage monitors (SUMs) that recorded usage of both new stoves and traditional stoves for roughly three weeks.

To measure the effects of the stove when used for a realistic task, participants carried out a cooking test measuring fuel used while preparing a standardized meal. This test has a larger sample but a lower level of control than a standard controlled cooking test. Again, randomization implies that variation in (for example) the moisture content of wood washes out and does not bias our results.

To reduce costs, our study is not large or long enough to have statistical power to detect improvements in health such as pneumonia and bronchitis. We collected data on exposure to carbon monoxide during the cooking test as an intermediate measure correlated with exposure to particle matter and other harmful emissions.

We ended the main data collection with a household survey and retrieval of the SUMs. Plan Ghana then gave the "late group" the manufactured parts to build their stoves. Finally, eight months later we returned for a very brief medium-term follow up observation in three villages.

Setting and intervention

The improved stove

The improved cookstove model we evaluated was designed by a consultant at the Ghanaian Council on Scientific and Industrial

Fig. 1. The improved cookstove deployed in Sissala West (indoor installation featured at left; outdoor installation featured at right). Participants first produced bricks by mixing finely ground cow dung and termite mound "clay" with water and kneading the result into a consistent aggregate; they then put this aggregate in molds to produce bricks. Participants also sculpted the aggregate by hand to produce stove walls and the mortar that went between bricks. The intervention team provided a metal grate and iron rebar. The metal grate was suspended off the ground by spanning a brick base, allowing airflow through the wood that would be burned on it. The rebar was wedged between stove walls to allow cook pots to sit above the fire while recessed into the stove opening. Video of the construction process is available online at http://www.youtube.com/watch?v=gA2a3_VmJKI.

Research to increase fuel efficiency and reduce emissions by producing more complete combustion of solid fuels and venting smoke away from the user. To improve combustion efficiency, the stove used a metal grate suspended above the ground to allow air to vent through the burning biomass. To vent smoke away from the user, the stove included stove walls built to surround the family's main cooking pot and a chimney that vented through a side wall, thereby enclosing the combustion chamber and forcing air to draft through the chimney.

The stove was largely built from locally gathered materials (see Fig. 1). The Ghanaian Council of Scientific and Industrial Research reported that August 2008 water-boiling tests of the improved stove design reduced use of wood by about half. Also in August 2008, Plan Ghana pilot tested the improved stove in the village of Kupulima, in our study region. They reported high rates of adoption and, as with the water boiling tests, reductions of almost half in fuel consumption.

Area of study

Geography

The Sissala West district in the Upper West region of Ghana is a semi-arid region that receives rains from May through August. It is substantially less developed than other parts of Ghana; for example, it has almost no paved roads.

Population

Participants in the study are poor. While respondents may under-report cash income, the median respondent reports $6.00 of cash income per month. Only 10% of women and a similar share of their husbands have any formal schooling. Only 4% of respondents report owning a television, although 25% have a cell phone.

People in the Sissala West district identify primarily by ethno-linguistic group and secondarily by religion. The villages nearer to Tumu (Gorima, Jitong, and Kandia) are ethnic Sissali. Settlement in these villages is centralized and consists of 60 to 120 households; farm plots are spread over the surrounding environment. The villages near Hamale (Buo, Kaa, Kankanduale, Liero, and Foliteng) are mostly ethnic Dagaare, with a substantial ethnic Sissali minority in some villages; many ethnic Sissali in these communities are bilingual. Settlement in these villages is highly dispersed and consists of 50 to 300 households. Farm plots are interspersed among the settlements.

Men commonly have multiple wives, and each wife cares for a household (children, children-in-law, elderly family members, etc.).[2] Co-wives usually live in the same multiple-household compound. Compounds typically range from 2 to 8 households.

Geographical distribution of cookstove type and cooking practices

Traditional cookstove designs were fairly homogeneous within villages and varied across villages. For example, Gorima, Jitong, and Kandia had largely U-shaped stoves, Kaa had largely three-stone stoves, and Liero had largely L-shaped stoves (see Fig. 2 for examples). Households report only cooking with fuel wood and

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[2] The term "household" does not translate well in either of the local languages in the study villages. We clarified that by "household" we meant a group of people who eat together regularly and/or who sleep under the same roof.

occasional agricultural residues. A few households produce charcoal, but only to sell it.

Cooking practices vary by ethnic group. For example, Dagaare women often cook several days' *tisert* (boiled maize flour) in one cooking session using very large pots. They then serve this *tisert* over the following several days. This practice is uncommon in Sissali communities.

Access to fuel

The mostly Dagaare villages closer to Hamale have sparse tree cover nearby, and fuel wood collection in one village competes with fuel wood collection in neighboring villages (Kaa is a notable exception). Households in these villages do not report selling fuel wood or charcoal. Some households in these villages reported buying fuel wood and charcoal from the local market.

The largely Sissali villages closer to Tumu have more access to fuel wood, as tree cover near each village is denser and neighboring villages are far enough apart that fuel wood collection zones do not overlap. Villagers near primary roads close to the major market of Tumu reported sales of fuel wood and charcoal as the largest non-transfer source of cash income. No participants reported buying fuel wood or charcoal.

Materials and methods

Intervention

Recruitment

Plan Ghana sited the project in the Sissala West district of the Upper West region in Ghana. They chose this region because it was very poor, did not have electricity, there were concerns about deforestation, and there had not been any cookstove program nearby.

Plan Ghana presented a sampling frame of 20 villages that were at least 15 km from the electrical grid as of December 2008 and had ongoing relationships with Plan Ghana. We chose 8 of the 20 villages for our randomized trial with an eye to variation in ethno-linguistic and geographic context: three villages (Gorima, Jitong, Kandia) are situated near the town of Tumu and primarily Sissali, and five villages (Foliteng, Liero, Kankanduale, Kaa, and Buo) are situated near the town of Hamale and primarily Dagaare. We tested protocols and recruited women trainers in the pilot village of Kupulima. The study ran from February to May 2009.

In February 2009 we presented the stove program at village meetings. We recruited women to attend the meeting by contacting the chief and other local leaders in each village and requesting them to notify the rest of the village. Once a group of women assembled, we explained the intent of the study and eligibility for participation. Eligibility was restricted to one woman per household, and to the women most frequently responsible for cooking. Following a question and answer session, we enrolled volunteers. Translators on our team read out an informed consent letter and explained that only one group would receive stove materials at first, and the second group would receive stove materials approximately a month or two later.

Training

Approximately two weeks after the first village meetings, women from our pilot village who were experienced in building the new stoves trained participants in stove construction. The trainings occurred over two separate days. On the first day, trainers taught participants to use brick molds we distributed. We recruited several members in each village, mostly women but some men, to act as group leaders, responsible for organizing and motivating women to make bricks and build their stoves. There was then a gap of roughly two weeks so women could make bricks. On the second day, trainers showed participants to build the stoves using the bricks they had made along with the iron grate and rebar we provided.

At the end of the second training day, we used a lottery to randomly assign participants to control and treatment groups. We divided lottery tickets such that participants had a 55% chance of drawing treatment group status; participants drew tickets without replacement. The treatment group received materials to build their stoves immediately, and the control group was told they would receive their stove materials in one month.

Stove building

In the two weeks following randomization, (most of) the treatment group of each village built their improved stoves, assisting each other on an ad hoc basis and motivated by their group leaders. Our staff oversaw improved stove construction and measured the dimensions of each improved stove, directing participants to rebuild their stoves if construction was of particularly poor quality. Our staff also demonstrated the construction of proper chimneys to participants, as well as adding a ventilation hole to each indoor kitchen to provide a proper outlet for chimneys.

Between three and four weeks following random assignment, experienced women from Kupulima village demonstrated fuel-efficient cooking on an improved stove in each village. Both treatment and control group members attended the demonstrations.

Data

Stove usage monitors

We installed stove usage monitors (SUMs) a few weeks after construction of the improved stoves. Following Ruiz-Mercado et al. (2008), we employed Thermochron 1921G iButtons, a digital sensor enclosed in a 16 mm thick stainless steel case that can measure and record temperature between −40 °C and 85 °C. We programmed the SUMs to measure temperature every 15 min and left them on the stoves for three weeks.

We placed stove usage monitors in almost all participant homes in two villages (Gorima and Kaa). In two other villages (Jitong and Kandia) field staff started from the village center, walked in different directions and distributed SUMs at study households they encountered along their trajectory. At households chosen, we placed a SUM in each stove the respondent reported using in the prior month. In two villages (Gorima and Jitong) we placed SUMs one week after improved stove construction; in Kandia and Kaa, we placed SUMs five weeks after improved stove construction.

We used conventions for the placement of SUMs on each stove type (Figs. 2 and 3). For three-stone fires, we buried SUMs approximately 2 cm below the largest of the three stones and instructed households not to relocate the stove during our study. For other stoves, we carved a shallow depression into the wall of each stove and sealed in a SUM using clay.

Cooking test

Roughly five weeks following randomization (three to five weeks after most treatment homes built their improved stoves) we carried out cooking tests in each village. We asked participants to cook the common meal of a pot of *tisert* (boiled maize flour) and a pot of stew, cooking pots sequentially on the same stove. We gave participants a bag of maize flour (700–900 g), but only if they presented an equal amount at the outset of the cooking test, thereby ensuring each participant would make a full pot of *tisert* to match realistic cooking conditions. We instructed treatment group participants to cook with improved stoves and control group participants to cook on their primary traditional stove. Prior to cooking, we weighed the total flour, the cooking pots, and an estimate of how much water participants planned to use. Following cooking, we weighed the *tisert*, the stew, and any leftover flour.

We also instructed the participants to present the amount of wood they considered necessary for cooking the *tisert* meal. We weighed
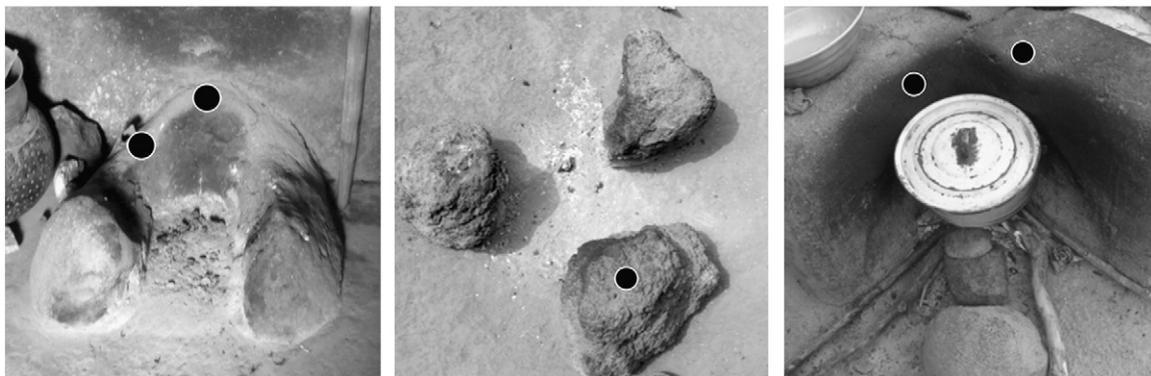
Fig. 2. Examples of traditional stoves in Sissala West. Dots indicate convention for placement of stove usage monitors.

this wood prior to cooking and weighed remaining wood following cooking. To calculate wood use during the cooking test, we subtracted the weight of the remaining wood from the weight of the wood respondents presented prior to cooking.[3]

Carbon monoxide tubes

We measured exposure to carbon monoxide during the cooking test with Gastec 1DL Carbon Monoxide Passive Diffusion Tubes (hereafter referred to as CO tubes). Using the principles of gas diffusion and colorimetric reaction, the CO tubes measure concentrations of carbon monoxide between 0.4 and 400 ppm·hours. In our analyses we normalize by sampling time to estimate exposure to carbon monoxide (parts per million, ppm).

While the CO tubes directly measure exposure to carbon monoxide, they also proxy for exposure to particulate matter (Northcross et al., 2010; Smith, 1994). Fischer and Koshland (2007) find that 1-hour CO tube exposures correlate moderately with both 1-hour and 24-hour exposures to PM2.5, and Northcross et al. (2010) finds that time-weighted CO tube readings correlate highly to time-weighted exposure to $PM_{2.5}$.

After weighing participants' cooking materials during the cooking test, we attached the CO tubes to the lapels of the participants' shirts with the exposed end facing down and unobstructed to ambient airflow, and we recorded the time. Once the participants finished cooking and returned to the weighing station, we noted the time and removed the CO tubes. We photographed the CO tubes and then coded the highest exposure band that turned darker (where the bans are marked 0 to 10 ppm, 10–30 ppm, and so forth). Details of the coding procedure are in the Web Appendix.

Household survey

Roughly eight weeks after randomization we surveyed both control and treatment group participants on self-reported recent cooking activity, frequency and duration of wood collection, perceptions of the improved cookstove, and socioeconomic status. The survey also asked participants about their symptoms related to exposure to smoke when cooking (sore eyes, and so forth) and about a variety of respiratory ailments they or their children suffer from (cough, runny nose, and so forth).

We provided materials for the control group to build their stoves after the household survey.

Follow-up stove usage observations

Field staff returned to three villages (Gorima, Jitong, and Kandia) eight months following program implementation. Field staff walked

through each village to observe the conditions of the improved stoves and determine whether or not stoves evidenced recent use— determined affirmatively if the stoves were observed in use, warm to the touch, or contained significant amounts of ash.

Statistical methods

Our basic method is to compare the treatment and control groups. As in most randomized trials, our experiment had non-compliers (treatments who did not build a stove and controls who did). Our intention-to-treat estimates avoid the endogeneity of the decision to comply and give unbiased estimates of the effect of the intervention; that is, of being taught how to build the stove, after agreeing to learn.

For wood use we also estimated "treatment-on-the treated" estimates that used treatment status as an instrumental variable for having a new stove. This procedure estimates the effect of the stove program on those who are affected by it (that is, not treatments without a new stove or controls who built one). As the rate of non-compliers is low, results with the simple comparison and with the instrumental variable estimator are very similar.

We cluster standard errors for all statistical tests at the village level.

Results

Randomization check, pipeline, and attrition

The random assignment process resulted in 402 treatment group participants and 366 control group participants. Adherence to randomization was fairly high: 331 treatment households (82%) built an improved cookstove, while 33 controls (9%) procured the

Fig. 3. Conventional placement of SUM on improved stove.

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[3] We also weighed remaining coals and ash. For the purpose of our analysis, we consider coals as burned, although they are often placed in small metal containers for keeping pots of food warm. Results are similar if we treat coals and ash as 100% re-used.

metal grate on their own and built an improved cookstove during our study period. Our analysis is based on the randomized intention-to-treat, not on adherence to the randomization; thus, our results are not biased by self-selection among those who did or did not build a stove.

The treatments and controls are similar on baseline characteristics (Table 1). A probit regression of treatment status on baseline characteristics shows no joint significance.

Substantial attrition occurred during the course of the study. Of the 768 study participants, 572 (74%) completed the cooking test almost all of whom (539) provided CO tube readings. Data collection rates for the cooking test and CO tube readings were similar for treatments and controls.

The survey completion rate was somewhat lower, 64% (N = 498). Owing to difficulty in locating respondents for follow-up, only 53% of treatments completed the survey, versus 73% controls.

Attrition was largely due to participants' absence from the villages, owing to weddings, funerals, and market days. We used a number of our surveyed characteristics in a probit regression to predict attrition; results showed no statistically significant predictors of attrition.

We placed SUMs on a subsample of study participants' households, covering 295 stoves in 114 treatment households and 159 stoves in 77 control households. There were more treatment

Table 1
Summary statistics.

	Treatment (stdev)	Control (stdev)	Difference (z-stat/t-stat)
A) From the household survey			
Number of members in household	6.3 (2)	6.5 (2.6)	0.2 (0.71)
Number of wives her husband has	1.7 (0.9)	1.7 (0.9)	0 (0.27)
Primary language Dagaare (vs. Sissali)	0.56	0.58	0.02 (0.31)
HH Std adult equivalents (1 = man, 0.7 = woman, 0.5 = child under 16)	4.6 (1.6)	4.5 (1.9)	0.1 (0.11)
Number of overall stoves	2.3 (0.7)	1.9 (0.6)	0.4*** (7.28)
Number of traditional stoves	1.4 (0.7)	1.9 (0.6)	0.5*** (7.77)
Share of traditional stoves outdoors	0.64 (0.43)	0.59 (0.36)	0.05 (1.44)
Pct that buy wood	0.03 (0.17)	0.03 (0.17)	0 (0.03)
Pct that sell wood	0.05 (0.22)	0.05 (0.21)	0 (0.36)
Pct that sell charcoal	0.06 (0.23)	0.04 (0.19)	0.02 (1.01)
N	225	263	
B) From the cooking test			
Fuel wood use (grams)	1434 (519)	1621 (705)	187** (3.53)
Proportion of participants cooking outdoors	0.43	0.48	0.05 (1.04)
Initial fuel wood presented at cooking test (grams)	2366 (671)	2758 (954)	392** (5.46)
Weight of pot and cooked tisert (grams)	6679 (1542)	6576 (1713)	103 (0.72)
Carbon monoxide tube exposure band (1 to 8, coding 0, 0.1–10, 10–30, 30–50, 50–100, 100–150, 150–200, 200–400, and over 400 ppm)	5.2 (2.7)	5.2 (2.6)	0 (0.17)
Minutes wearing carbon monoxide tubes	89 (26)	85 (26)	4*** (0.7)
N	278	239	

* = p<0.1; ** = p<0.05; *** = p<0.01 for differences of treatment and control, with t-tests of differences in means for continuous variables and proportions test for discrete variables. Tests adjust for clustering by village. Three cooking test observations were dropped due to duration<0 (due to measurement error).

households primarily because field staff identified study participants more readily when an improved stove was present. High heat destroyed 28% of the SUMs, leaving data from 217 (74%) of the SUMs on treatment household stoves and 108 (68%) of the SUMs on control stoves. Attrition was comparable for improved and traditional stoves.

Summary statistics

The household survey shows no systematic difference in study groups other than number of stoves (Table 1). The sample is fairly evenly split between those who speak Dagaare (56%) and those who speak Sissali (44%), and these proportions are almost the same across treatment and control groups. Polygamy is common: 43% of respondents are married to a man with more than one wife. Average household size is 6.4 people.

Most control homes have more than one wood-burning stove, with a mean of 1.9 wood-burning stoves. Many participants also employ a charcoal-based stove that utilizes embers from other stoves, primarily for the purpose of heating water or soup in smaller pots; we have not included these stoves in any figures. Nearly all participants cook with wood that the household gathers.

Stove usage

Improved stoves may have precipitated a movement of some cooking activity indoors. Over the entire sample, a minority (38%) of traditional stoves at control homes are indoors. However, the ethno-linguistic groups differ in this respect: only 20% of traditional stoves among Sissali controls were indoors, versus 61% among Dagaare controls. We found that participants in the treatment group built 58% of improved stoves indoors. Group differences persist: 43% of Sissali participants built their improved stoves indoors versus 72% of Dagaare participants.

Improved stoves may also have displaced some traditional stoves. In the household survey following the intervention, treatment group participants reported using an average of 1.4 traditional stoves, whereas control group participants reported using an average of 1.9 traditional stoves (Table 1). Given that treatment group participants report using an average of 2.3 stoves overall—improved plus traditional—this suggests that treatment group participants ceased using an average of 0.4 traditional stoves per household. The subgroup of households observed during SUM placement show an almost identical decrease in traditional stoves among treatment group participants (0.4), although both groups report more traditional stoves than the general survey (1.8 traditional stoves for treatments vs. 2.2 traditional stoves for controls).

SUM data

Households reporting more stoves had higher SUM over-heating than those reporting fewer stoves. 48 compliant treatment households and 38 compliant control households had all their reported stoves successfully monitored by SUMs over the monitoring period. Participants reporting more stoves had more opportunity to damage a SUM; as expected, households with overheated SUMs reported an average of 2.5 stoves, a bit above those with no overheated SUM (2.2, P<.05). Therefore, the fully monitored households tend to have fewer stoves than do households with incomplete surviving SUMs. Self-reported characteristics of recent stove usage do not systematically affect likelihood of SUM overheating.

Adoption of the improved stove appears to be reasonably high. Eight of the 78 improved stoves monitored were used two or fewer times over the three-week monitoring period, representing a lack of adoption. The 70 improved stoves that were used more than two times over the monitoring period registered temperatures in excess of 50 °C on average 60% of the days in the monitoring period. During

Table 2
Usage of improved and traditional stoves (minutes over 50 °C).

	Treatment			Control
	Traditional	Improved	All	Traditional
All surviving SUMs				
Hours of stove usage per home	7.1	2.5	9.6	10.7
n homes	103	103	103	48
n SUMs	139	69	208	95
Only households with 100% coverage by SUMs				
Hours of stove usage per home	9.2	2.6	11.8	8.6
n homes	48	48	48	38
n SUMs	79	44	123	65

Note: 9 control-group improved stoves (due to non-compliance) not included in the table. Inclusion does not significantly alter full control group averages or comparisons to treatment group.

this time, these improved stoves show an average of 185 min (and median of 136 min) over 50 °C per day. In contrast, at both control and treatment homes, the typical traditional stove registered temperatures in excess of 50 °C on average 74% of days monitored (difference P<0.01).

If we assume SUMs overheated at random, then we can multiply SUM readings on individual stoves by the mean number of stoves to estimate household-level usage. Control homes average almost 11 stove-hours per day over 50 °C across all traditional stoves (Table 2); this number is greater than total time cooking because most control homes have multiple stoves and sometimes heated two or more stoves at once. Treatment homes used their traditional stoves a total of about 7 stove-hours a day on average and their improved stoves about 2 1/2 hours per day. Thus, being in a treatment home reduced use of traditional stoves (P<.05), but did not necessarily reduce overall stove use (10.72 h total for controls, 9.59 h for treatments, difference not statistically significant).

The subset of fully-covered households (that is, those with no SUM attrition) tells a different story. For reasons we do not fully understand, treatment households do not show a reduction in the number of traditional stoves that we see in the survey (treatments have 1.65 traditional stoves and controls have 1.71, difference not significant). Such treatment households also show no reduction in minutes per day they use their traditional stoves compared to controls.

In short, there is some, but not always consistent, evidence that the new cookstoves reduced usage of the traditional stoves.

Participants commonly employ multiple stoves. Of the 23 completely monitored control group participants reporting two stoves, the median most-used stove accounts for only 52% of time over 50 °C.

The improved stove was heated a smaller share of time than traditional stoves. Of the 15 completely monitored treatment group participants reporting two stoves, on average the improved stove accounts for 36% of time over 50 °C; of the 22 completely monitored treatment group participants reporting three stoves, the improved stove represents only 25% of time over 50 °C. Multiple stoves register temperatures over 50 °C about a third of the time when at least one stove is in use, suggesting that simultaneous use of multiple stoves is common.

Besides temperatures over 50 °C, we examined several methods for translating SUM readings into indicators of stove usage, including an increase in temperature of over 5 °C in one hour, and a reduction in temperature of over 3 °C in one hour. Results remained robust to the measure we used.

The non-random survival of SUMs may under-report use of old stoves if, as is likely, SUMs overheated more often when placed on stoves that were used more intensively. At the same tine, improved stoves' walls were thin compared to traditional stoves; the decreased

thermal mass means improved stoves were likely to cool faster than traditional stoves—and so SUMs might record less usage than traditional stoves.

Eight-month follow-up observations

Approximately half of improved stoves appear to remain in regular use eight months after implementation (Table 3).

Fuel use

Fuel use during the cooking test

Our intention to treat analysis of fuel use of household *i* in village *v* is:

$$\text{Fuel use}_{vi} = \beta_0 + \beta_1 \text{treatment}_{vi} + \Sigma_v \delta_v \text{village}_v + \varepsilon_{vi}. \qquad (1)$$

Results are in the first column of Table 4. The point estimate indicates that treatments use 92 g (about 5% of the mean) less than controls, but the coefficient is not statistically significant (SE=64).

In column 4 we shift from intention-to-treat to a treatment-on-the-treated analysis. We instrument for whether the cooking test was on an improved stove using treatment status as an instrument and conduct two-stage least squares. The first stage of this estimate is very strong as treatment has a t-statistic of 38 in predicting using an improved stove on the cooking test. As expected, estimated fuel savings are slightly higher (107 g, SE=76, n.s.) when we focus solely on participants who built an improved stove, but the point estimate remains not statistically significant.

Returning to OLS we examined if covariates (though potentially endogenous) change this result. During the cooking test, treatments and controls cooked indoors in equal proportions and cooked the same weight of food on average (Table 1B). Treatment group participants brought less fuel wood to the cooking test than controls (2.4 vs. 2.8 kg., P<0.05). Controlling for the weight of the pot and cooked food left the point estimate similar and insignificant (col. 3).

We hypothesized that treatment might be most helpful for those who attended the educational program on proper use of the new stove, subject to the caution that attending the educational program is endogenous. The point estimate on education is small, statistically significant and negative (−43 g, SE=64, n.s.), but the point estimate of the interaction of treatment and education is small and positive (the opposite of the expected sign, 52 g, SE=93, n.s.). Surprisingly, if we look only at those who did not attend training the treatment group now has statistically significantly lower fuel use (by 133 g, SE=42, P<0.01), but as this subgroup is not one we initially focused on we do not want to over-emphasize this result.

Survey measures of fuel use and fuel collection activity

Treatment group participants report spending about the same time collecting wood per week as do control group participants (Table 5). This equality arises from two offsetting small effects: Treatments spend about 10% more time per trip to collect wood but collect wood about 10% less often. It is plausible that these effects are just sampling error.

Table 3
Field observations of improved stoves in three villages after 8 months.

	Observed	Broken (not in use)		Appear in use		Unclear if in use	
		N	%	N	%	N	%
Gorima	53	10	19%	32	60%	11	21%
Kandia	81	12	15%	41	51%	28	34%
Jitong	88	35	40%	35	40%	18	20%

Emissions and health

Exposure to carbon monoxide

We present the histogram of carbon monoxide exposure for treatments and controls in Fig. 4. On average, treatments and controls showed statistically indistinguishable readings of carbon monoxide·hours. At the same time, the treatments wore the CO tubes slightly longer than controls (89 vs. 85 min, P<0.01, Table 1B).

Given the nature of our CO data, we ran an interval regression to examine exposure to carbon monoxide. We use the following regression specification:

$$b \text{ and}_i \text{ (lower − bound and upper − bound) of CO exposure} \qquad (2)$$
$$\text{(in ppm·hr)} = F(\beta_0 + \beta_1 \text{ minutes of exposure}_i$$
$$+ \beta_2 \text{ minutes of exposure}_i^2 + \beta_3 \text{ treatment}_i + \varepsilon_i),$$

where $band_i$ is as a range (e.g., 100 to 150 ppm·hour).

Exposure to carbon monoxide during the cooking test of the treatment and control groups was not statistically significantly or substantively different (Table 5, col. 1).

In column 2 we adjust for whether the cook was outdoors—an endogenous factor. Outdoor cooking lowered CO exposure substantially for controls, but there is no strong evidence that treatment was beneficial for those cooking indoors. The point estimate for treatment when cooking indoors is −15 ppm, with a P value of 11%, weakly supportive of lower emissions for the new stove when cooking indoors. The treatment was less effective outdoors than indoors (point estimate on treatment * outdoors = 35.9, SE 16, P<0.05), but the total effect for treatments outdoors (35.9–15.5) is not statistically significantly different from zero.

Self-reported symptoms

Table 6 shows self-reported recent health from the household survey. Control group participants reported experiencing irritated eyes following cooking over twice as many days during the preceding week as treatment group participants. Differences were almost as large for symptoms of headache, bad cough and sore throat. Similarly, control group participants averaged a larger number of respiratory symptoms from the previous week (sore throat, bad cough, difficulty breathing, chest pain, excessive mucus) than treatments. Over the five symptoms we surveyed, 34% of controls reported at least one symptom in the previous week versus 17% of treatments (P<0.01).

Table 4
Fuel wood use during the cooking test.

	1	2	3	4
	OLS	IV	OLS	OLS
Treatment group	−92		−107	−33**
	(66)		(68)	(42)
Used an improved stove (instrumented with Treatment group)		−107		
		(76)		
Weight of pot and cooked tisert (grams)			.22**	.22**
			(.10)	(.09)
Attended stove use educational session				−43
				(64)
Education × Treatment				52
				(93)
Village intercepts	Yes	Yes	Yes	Yes
N	515	515	514	514
R²	.096	.097	.121	0.122
F				–

* = p<0.1; ** = p<0.05; *** = p<0.01. Standard errors adjust for clustering by village. Sample drops outliers on time for the cooking test (<30 min), very low fuel use (<200 g), very low weight of tisert (<500 g), and fuel use less than 20% of fuel brought to be weighed.

Table 5
Self-reported wood collection activity.

	Treatment	Control	Difference
			(t-stat/z-stat)
Number of days of wood collection in past week			
Mean	1.73	2.02	0.29**
SD	(1.27)	(1.47)	(2.24)
Median	2	2	0++
Duration of most recent wood collection (min)			
Mean	183	165	18*
SD	(87)	(96)	(1.85)
Median	180	180	0++
Number of days of wood collection in past week × duration of most recent wood collection (min)			
Mean (minutes/week)	349	358	9
SD	(328)	(386)	(0.24)
Median	240	240	0
Number of days since most recent wood collection			
Mean	6.25	5.30	0.95*
SD	(5.74)	(5.00)	(1.95)
Median	5	4	1+++
Number of days wood collected lasts "in general"			
Mean	11.27	9.77	1.50*
SD	(9.21)	(10.00)	(1.71)
Median	7	7	0+++
N	227	255	

* = p<0.1; ** = p<0.05; *** = p<0.01. t-tests adjust for clustering by village. Pearson chi-square for median-comparison test: + = z<0.1; ++ = z<0.05; +++ = z<0.01

In contrast, there was no difference in the proportion of control and treatment groups reporting children becoming sick in the preceding week (Table 7).

Casting doubt on the validity of the self-reports' relation to the new stove, in results not shown, neither self-reported recent use of the improved stove nor CO tube readings recorded during the cooking test show any significant relationship to self-reported recent health. Further suggesting bias in the self-reported symptoms, eighteen percent of treatments and 31% of controls reported chest pain in the previous week (P<0.01). As chest pain is unlikely to respond to a few weeks' improvement in households air quality, it is likely that most of this 13 percentage point decline in self-reported symptoms is largely due to a courtesy bias or demand effect.[4] As 13 percentage points is the average decline across the five self-reported respiratory symptoms, we have little confidence that these encouraging results indicate true improvements in health.

Discussion

Summary

Stove adoption and usage

Our stove usage monitors showed that on average improved stoves were used at least half of all days in the three-week monitoring period, indicating continuing use past construction. In addition, treatment group participants reported fewer traditional stoves in regular use than controls, suggesting some displacement of traditional stoves. At the same time, treatment participants usually continued to use one or more traditional stoves. On average, traditional stoves were also used more often and for longer periods than improved stoves. The net result is that treatment and control households do not register significantly different durations of overall stove activity, and there was mixed evidence for decline in use of

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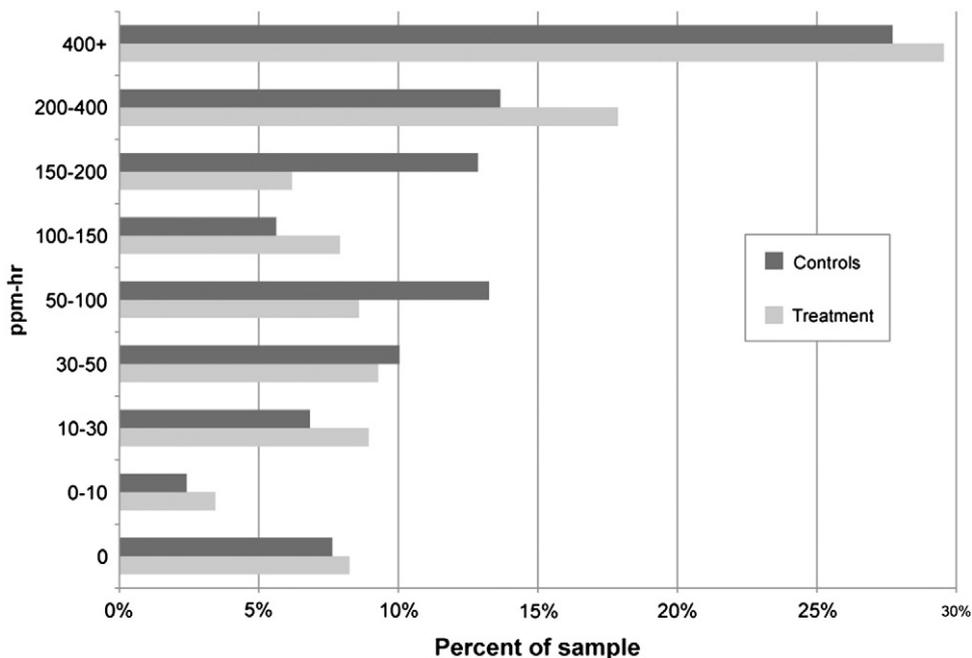[4] We appreciate an anonymous referee for making this point.

Fig. 4. Exposure to carbon monoxide during cooking test.

traditional stoves among treatments. Although our SUMs readings are subject to a number of cautions (for example, due to attrition of SUMs through over-heating), it is clear that continued use of old stoves limits the benefits of the new stove.

In addition, usage of the improved stoves appears to have declined over time; by the eighth month following construction, perhaps 50% of improved stoves remained in use.

Although SUMs provide real-time objective monitoring, our results remain less than conclusive. The lack of standardized placement of temperature sensors, the variation in thermal mass, and the partial coverage of households due to sensor attrition all add error to the stove usage measures. In addition, cooks use multiple stoves and stoves are used by multiple cooks, making it difficult to measure who is cooking where. For example, 25 of the 31 participants identifying only a single stove for SUM placement report multiple stoves in the survey. Furthermore, some participants reporting only a single stove show very little time over 50 °C on that stove, suggesting some degree of misreporting of number of stoves and/or inaccurate monitoring of stove activity.

Regardless of these concerns, clear adoption of a new stove does not imply that the household uses the new stove, and adopting or using a new stove does not always directly reduce usage of an old stove. Furthermore, even if new stoves are used and substitute for old stoves, some measure may fall into disuse from breakage. To accurately assess the impact of improved stove programs, future evaluations must focus on all four, separable behaviors associated with new technology uptake: adoption, usage, substitution, and upkeep.

Table 6
Interval regression for CO exposure (ppm·h).

	1	2
Treatment	2.9	− 15.5
	(12.2)	(9.5)
Minutes of CO tube exposure	2.42*	2.4**
	(1.37)	(1.33)
Minutes of CO tube exposure^2	− 0.011*	− 0.011**
	(.006)	(.006)
Cooked outdoors during cooking test		− 50**
		(20)
Treatment∗Outdoors		35.9***
		(16.5)
Constant	38.4	28.4
	(64)	(64)
N	458	455

* = p<0.1; ** = p<0.05; *** = p<0.01.
Standard errors account for clustering by village. This regression treated each band of the CO tube as an interval such as 10–30 ppm·h, 30–50 ppm·h, and so forth.

Table 7
Self-reported recent health.

	Treatment	Control	Difference
	(stdev)	(stdev)	(z-stat/t-stat)
Number of days in previous week respondent reported problem following cooking			
Irritated eyes	1	2.7	1.7***
	(2.1)	(2.6)	(7.63)
Headache	1	2.2	1.2***
	(2)	(2.4)	(5.75)
A bad cough or sore throat	0.7	1.6	0.9***
	(1.6)	(2.4)	(4.91)
Self-reported respiratory symptoms in previous week (1 = yes)			
Sore throat outside of cooking	0.1	0.19	0.09***
	(.02)	(.02)	(2.75)
Bad cough outside of cooking	0.16	0.27	0.11***
	(.02)	(.03)	(3.13)
Difficulty breathing	0.12	0.27	0.15***
	(.02)	(.03)	(4.32)
Chest pain	0.18	0.31	0.13***
	(.03)	(.03)	(3.35)
Excessive mucus	0.13	0.19	0.06
	(.02)	(.03)	(1.71)
Number of above symptoms (out of 5)	0.68	1.22	0.54
	(1.29)	(1.63)	(4)
Report sick child in previous week (1 = yes)	0.21	0.24	0.03
	(.03)	(.03)	(.82)
N	225	255	

* = p<0.1; ** = p<0.05; *** = p<0.01.
Standard errors account for clustering by village.

Exposure to emissions

We found no detectable decline in exposure to carbon monoxide among treatment group participants during the cooking test. Most of our treatments and controls exceeded the WHO (2006) guideline of 26 ppm as the average limit for 1-hour exposure to carbon monoxide indoors.

In contrast, cooking outdoors produces a significant decrease in exposure to smoke for controls; the same, however, cannot be said for treatments.

At the same time, women in the treatment group self-reported far fewer symptoms related to cooking (e.g., irritated eyes) and respiratory symptoms (e.g., runny nose and chest pain). The findings of the survey may reflect a "courtesy bias" by participants, who have existing relationships with our partner Plan Ghana and might want to encourage future activities.

The indoor stoves had a chimney to remove smoke, which made it more attractive to locate it indoors. However, moving indoors could offset any emissions reductions improved cookstoves might have. In addition, we observed many improved stoves that emitted some smoke, whether due to physical failures of the chimneys (cracking of mortar seal around bricks, chimney outlet too low to create strong vacuum effect), improper use of the improved cookstove (e.g., by blocking the chimney inlet by pushing fuel wood too far into the stove), or cooking behavior different than the new stove was optimized for (such as removing a pot from the fire for some time or use of a small pot that leaves a gap between the pot side and the wall where smoke escapes).

Fuel use

The point estimate suggests slightly lower fuel use on the stove during the cooking test, but never by a statistically significant amount. Although our estimate's 95% confidence interval is consistent with some savings, is clear the stove did not achieve savings as large as those claimed for many improved stoves or compared to the aspirations for this stove. The estimated treatment effect was not larger for those attending an educational program (although the endogenous nature of attending the program reduces our confidence in this null result).

Implications

Implications for stove programs

An improved cookstove program has to account for the heterogeneity of cooking situations. For example, in Dagaare communities women commonly cook large amounts of *tisert* in one cooking session using very large pots and then consume the food over the following several days. The improved stoves we studied cannot accommodate pots of this size. Similarly, Dagaare architecture posed an additional obstacle, as traditional Dagaare multi-family compounds include buildings with internal rooms. Chimneys for these improved stoves were designed to vent through a wall to the outdoors, which was ill-suited to interior kitchens. This stove program had extensive piloting, but more extensive piloting would have discovered these concerns and either changed the design of the stove or selected different villages for rolling out the program.

These concerns highlight a disadvantage of subsidized dissemination of cookstoves; lack of self-targeting. When a stove is only appropriate for some uses or users, it is important that those disseminating the stove inform consumers of those constraints so consumers can self-select appropriately.

A new stove with a chimney, such as the one in this intervention, is well suited for indoor cooking, which many cooks appreciate. At the same time, the health benefits of a new stove are much more difficult to achieve if the old stove was in a well-ventilated space and the new stove is in a poorly ventilated space. Thus, stove programs attempting to improve health should focus on regions with indoor cooking and also create systems of monitoring and maintenance to ensure that chimneys continue to work well to draw smoke out of the cooking area.

The relative advantages of a stove—what makes it "improved," often according to engineers—are not sufficient to entail adoption and use. Improved cookstoves need to have some compatibility with local cooking and architectural norms to be widely adopted— or possess such large perceived advantage that cooks and families change cooking practices. The stove we studied was attractive enough for adoption, but usually not for replacement of existing stoves.

We studied a very low-cost stove largely constructed with locally-produced bricks. A more advanced stove design might have led to larger reductions in emissions and fuel use. The challenge remains in coupling affordability, consumer acceptance, and meaningful improvements in health.

Implications for stove evaluations

A key point of this evaluation, as others have found, is the importance of measuring an intervention, not just a new stove (Ruiz-Mercado, et al., 2011). The differences are that (1) a new stove is not usually used for each meal; and (2) old stoves usually continue to be used.

Thus, it is crucial to have ways to monitor use of each stove over a period of time, as we do with our Stove Usage Monitors (SUMs). Because SUMs are measuring temperature, there is always a risk of them over-heating. Thus, evaluations should plan for SUM attrition when choosing sample sizes. In addition, additional hardware may be needed to protect SUMs for first, especially three-stone fires (as their heat output can vary so widely).

We collected self-reported respiratory symptoms, but found that they did not correlate with CO measurement or self-reported use of the new stove. Thus, we suspect experimenter demand effects and courtesy bias may drive the lower rates of self-reported symptoms for women with a new stove. These results are a cautionary tale for any intervention that touts health benefits, emphasizing the importance of objective measures of exposure and of physiological functioning in future evaluations.

Fuel use in a stove versus a household versus an economy

An improved cookstove that cuts in half the wood needed to cook a specified dish may not cut household wood use by half. There may be a "rebound effect" in which the lower "cost" of cooking increases fuel consumption, as Davis (2008) found for clothes dryers in the United States. Similarly, if the space-heating of inefficient stoves is useful, then efficient improved stoves could end up stimulating greater overall fuel use. Furthermore, many cooks continue to use traditional stoves, limiting the contribution of a single improved stove to household fuel use.

Improved stove programs aim to scale up, but reductions in household wood demand may not impact economy-wide demand. By freeing up wood for sale, either as wood or charcoal—a source of income for villages near good roads—improved stoves in rural communities may have only small effects on wood harvesting, instead resulting in greater wood sales and increasing income flow from urban centers to the countryside. From a general equilibrium standpoint, lower overall demand for wood resulting from widespread use of improved stoves could also lower wood prices, which would lower the effective "wage" for wood gathering and so discourage it. However, these lower wood prices could also slow the shift away from solid fuels for other households (Dufournaud, et al., 1994).

Conclusion

We have undertaken a rapid assessment randomized-controlled trial of improved cookstoves using methods less demanding than

current longitudinal experimental studies. While our methods sacrificed some precision, they sufficed to meaningful adoption of the new stove, but even higher continued use of old stoves. Even when used, the new stoves did not reduce fuel use or exposure to emissions by a large amount (if at all).

By identifying simply whether a stove project has substantial impacts or not, our approach should prove useful for non-profit organizations and others attempting to discern whether or not a stove project is cost-effective at achieving its goals. Follow-up studies can then refine estimates in fuel and exposure reductions if such estimates are critical for scientific or policy purposes.

The reductions in wood use we find are insufficient to warrant scaling up the stove-building program we studied—at least using the current design of the stove and its roll-out program. It is plausible that a different stove design, coupled with policies that discouraged use of traditional cookstoves, would show better results. We hope a future stove design and cookstove program can offer more encouraging pilot results, so that the citizens of rural Ghana and elsewhere can reduce fuel needs and can have better health as part of the fight against global climate change.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2012.04.001.

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