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

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We conducted a rapid assesssment 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 Sissala West district of 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. Several weeks after treatments built their new stoves, all participants engaged in a controlled cooking test while wearing a carbon monoxide monitor. At that time we surveyed study participants on cooking activity, fuel wood gathering, self-reported health, and socioeconomic status. We also installed stove usage monitors on the improved and traditional stoves at a subset of households for the following three weeks. During the controlled cooking tests, treatment participants used 12% less fuel wood than controls. 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 treatments used their new stove on about half of the days monitored. When we returned to three of the villages eight months after project implementation, half the improved stoves showed evidence of recent usage. Treatments had less traditional stoves than controls at follow-up, suggesting new stoves displaced some traditional stoves. Treatment homes reduced total time cooking on their traditional stoves by approximately 25%. Out method seems to offer a rigorous, less logistically-demanding method for evaluating user uptake, field-based stove performance, and exposure to smoke.

Keywords: cookstove; technology adoption; randomized-controlled trial; indoor air pollution; biomass

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Abbreviations: CO: carbon monoxide; CCT: controlled cooking test; SUM: stove usage monitor

1 Introduction

Roughly half the world cooks with solid biomass fuels such as wood and charcoal, and in sub-Saharan Africa, 68-90% of people rely on biomass for their cooking (Rehfuess, 2006; Smith, 2004). Continuing land use change and ecological transformation present challenges to the management of increasingly scarce fuel wood resources. Field-based measurements of fuel use show that the best improved stoves can enable reductions up to two-thirds of the fuel use of conventional stoves (Johnson, 2009; Smith, 2007; Masera, 2007). Current mass-produced models may yield reductions closer to one-third of the fuel use of conventional stoves (Adkins et al., 2010).

Conventional biomass stoves also produce high indoor concentrations of air pollutants such as particulate matter and carbon monoxide, far beyond World Health Organization guidelines for ambient air quality (Pope, 2006; WHO, 2005; Gordon, 2004; Bruce, 2002; Ezzati, 2000). Exposure to these pollutants is particularly pronounced for women and for young children, as these groups spend the greatest amount of time inside the home and near a stove (Jiang, 2008; Mestl, 2007; Balakrishnan, 2002; Ezzati, 2002). It has been estimated that indoor air pollution from cooking with biomass fuels is responsible for 1.6 million deaths each year, primarily due to respiratory infections, as well as a range of other chronic health problems (Dherani, 2008; Bruce, 2006; Smith, 2004; WHO, 2002).

Improved stoves have shown potential for mitigating the negative health impacts of cooking with biomass. For example, the RESPIRE study in Guatemala found significant reductions in exposure to indoor air pollution and rates of respiratory illness among households with improved stoves (Smith, 2009; Smith, 2007; McCracken, 2007; Diaz, 2007). 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, 2007; Masera, 2007). Further, a meta-analysis of studies on respiratory illness in children suggests that improved stoves are associated with lower levels of respiratory illness (Dherani, 2008).

Field-based measurement of stove performance is crucial, as the effects of improved stoves result from a combination of stove qualities and user behavior. Also, since the impacts of improved stoves ultimately depend on users' decisions of whether to adopt and how to use them, longitudinal observation of improved stove use is critical for accurately capturing stove impacts. As it is, most stove programs lack evaluation altogether. A retrospective look at improved stove programs shows that only a third included a specific evaluation component. Of those studies that included evaluation, only a minority quantified changes in fuel use through field-based tests (Gifford, unpublished).

Longitudinal work is often logistically challenging. Each additional visit to a household increases the probability of attrition, as participants are either absent or change their mind about participation. Attrition can also introduce bias if it is systematic. Given the unpredictable nature of sampling in rural communities of developing countries, Edwards et al. (2007) suggest that an expectation of a 50% drop-out rate is not unreasonable to expect in longitudinal work. Although cross-sectional studies require relatively large sample sizes compared to longitudinal studies, they may suffer lower attrition (Edwards et al., 2007). Also, large-sample cross-sectional studies can account for the high magnitude of variance in cookstove study measurements (Saksena et al., 2003). When combined with simple equipment and protocols, cross-sectional studies may prove more rapid and cost-effective than longitudinal studies.

Given the logistical difficulties of obtaining longitudinal measures, as well as the perennial resource constraints and limited technical capacities of many organizations that implement improved stove programs, we sought to demonstrate that a quantitative evaluation adequately capturing both stove usage and impacts on fuel use and exposure to emissions can be carried out rapidly at scale using simple methods. To this end, in collaboration with the Ghanaian Council on Scientific and Industrial Research, we carried out a randomized-control field trial of an improved cookstove program in 2009 on behalf of Plan Ghana, an NGO.

Of the several methods for measuring stove performance, we chose to use a controlled cooking test since it enables rapid, large-scale implementation while maintaining a measure of field-based realism. The kitchen performance test, in which total household fuel use is measured over a period of days, more accurately quantifies the impact of an improved stove on a household. However, because it measures fuel use at the household level, the kitchen performance test cannot determine the performance of a particular stove and does not directly observe behaviors that affect household fuel use. Furthermore, kitchen performance tests remain uncommon due to their substantial logistical burden. A common alternative is the water boiling test, in which a single stove’s fuel use is measured over the course of boiling a defined amount of water. However methods that measure fuel use of individual stoves in highly controlled environments, such as in water-boiling tests, do not reflect actual cooking behavior and often overstate fuel use reductions (Bailis, 2007). The controlled cooking test, in which fuel use is measured over the course of a single conventional cooking task, provides the realism of actual cooking behavior and the ability to examine the performance of an improved stove by itself.

Since the impacts of stoves ultimately depend on users’ decisions of whether and how to use stoves, observing stove use over time is critical for fully and accurately capturing stove impacts. Many factors affect the stove adoption and use; among the most obvious characteristics are the compatibility of stoves with current practices, perceptions of stove benefits, durability of stoves, ease of stove use, and affordability of stoves. Improved stoves are often inferior to conventional stoves on at least one of these parameters (Wallmo, 1998), and therefore adoption cannot be assumed. In addition, greater sociocultural factors and household decision-making can affect rates of stove adoption and use (Troncoso et al., 2007; El Tayeb Muneer and Mukhtar Mohamed, 2003). Studies that do not evaluate stove use over time are of limited value, as impacts measured at a single point in time do not necessarily persist. Since the controlled cooking test measures fuel use at the level of a single stove at a single point in time, we made complementary observations of cooking behavior over time to adequately describe overall stove performance.

This article presents results from our rapid assessment randomized-controlled trial of an improved cookstove program in rural northern Ghana. We measured adoption and use of the improved cookstove, changes in fuel wood use, and changes in carbon monoxide exposure among women that use the improved cookstoves.

1.1 The improved stove

The improved cookstove model we evaluated was designed by a consultant at the Ghanaian Council on Scientific and Industrial 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 a chimney and walls that fully enveloped cook pots, thereby enclosing the combustion chamber and forcing air to draft through the chimney.

The stove was largely built from locally gathered materials (see Figure 1). The Ghanaian Council of Scientific and Industrial Research reported that August 2008 water-boiling tests of the improved stove design found significant reductions in fuel wood use. Also in August 2008, Plan Ghana pilot tested the improved stove in the village of Kupulima, in our study region. Their results reportedly indicated high rates of adoption and sizeable reductions in fuel wood use.

Figure 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. Stove dimensions, along with observed dimensions of built stoves, are listed in **Error! Reference source not found.**. Video of the construction process is available online at http://www.youtube.com/watch?v=gA2a3_VmJKI.

1.2)

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

A singificant majority of households depend on subsistence farming. Literacy rates are extremely low among people over the age of 30. 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).[3] All wives usually live in the same multiple-household compound together; compounds typically range from 2 to 8 households.

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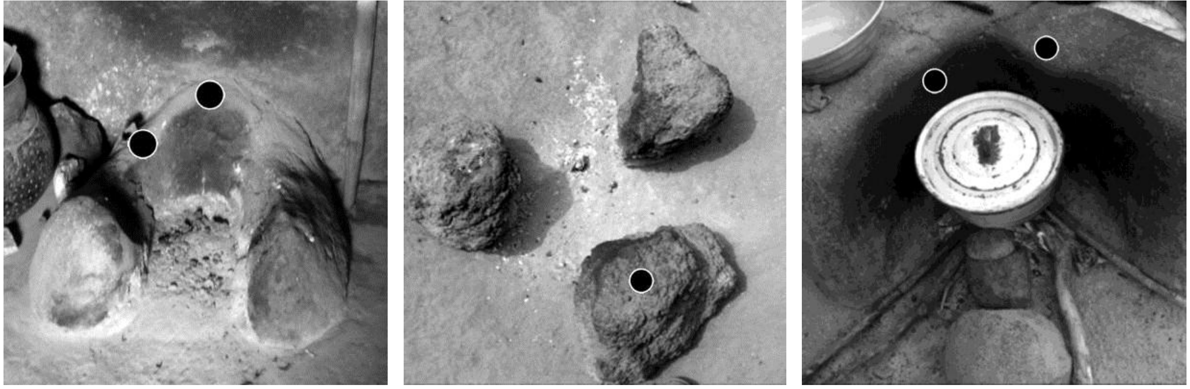
[3] The term "household" does not translate well in either of the local languages used during this study. We clarified that by "household" we meant a group of people who eat together regularly and/or who sleep under the same roof together.

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 Figure 2 for examples). Households report only cooking with fuel wood and occasional agricultural residues; charcoal, when produced, is reportedly always intended for sale. Cooking practices appear to vary by ethnic group. For example, Dagaare women often cook several days' *tisert* (boiled maize flour) in one cooking session using very large pots; this *tisert* is then consumed over the following several days. This practice is reportedly uncommon in Sissali communities.

Figure 2 | Examples of traditional stoves in Sissala West

Dots indicate convention for placement of stove usage monitors



Geographical Fuel Access

The 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 fuel wood products. Some households in these villages reported buying fuel wood and charcoal from the local market. The 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 households in these villages reported buying fuel wood or charcoal.

2 Materials and Methods

2.1 Study design

2.1.1 Recruitment

Plan Ghana sited the project in the Sissala West district of the Upper West region in Ghana. 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 one month later.

2.1.2 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.

2.1.3 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.

2.2 Data Collection Methods

2.2.1 Stove Usage Monitors

We installed stove usage monitors (SUMs) a few weeks after construction of the improved stoves. Modeled on the work of Mercado et al. (2008), we employed Thermochron 1921G iButtons, a programmable digital temperature sensor and memory enclosed in a 16mm thick stainless steel case, capable of measuring temperatures between -40˚C and 85˚C at user-specified intervals. We programmed the SUMs to measure temperature every 15 minutes, and SUMs operated for three weeks before being recovered.

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 (see Figure 2 and Figure 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.

Figure 3 | Conventional placement of SUM on improved stove

2.2.2 Controlled cooking test

Roughly five weeks following randomization (3-5 weeks after most treatment homes built their improved stoves) we carried out controlled 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 grams), 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 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.[4]

2.2.3 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 the time-weighted average concentrations of carbon monoxide between 0.4 and 400 ppm. While the CO tubes directly measure exposure to carbon monoxide, they also proxy for exposure to particulate matter (Smith 2009; Northcross 2010). 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 research by Northcross (2010) shows 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. These CO tubes were immediately sealed with duct tape and kept in an airtight bag until they could be digitally photographed in controlled fluorescent lighting conditions, usually within 48 hours. CO tubes of identical manufacturing specifications were photographed in batches with an unexposed reference tube in each image.

Each tube has a reactive strip bounded by non-reactive layers. A longer length of the reactive strip darkened in tubes exposed to more carbon monoxide. The tubes also had 7 rings dividing the tube into six discrete bands, where each band represented a range of parts per million per hour (ppm-hr): 0-10, 10-30, 30-50, 50-100, 100-150, 150-200.

We worked with three separate batches of CO tubes, which were manufactured to different specifications. We categorized exposure by the highest discrete band of the reactive strip that darkened. To determine the highest darkened band, we converted the digital photographs to black and white and compared the brightness of pixels inside the reactive strip with adjacent pixels in the adjacent non-reactive layers (see Figure 4). We repeated this comparison at the midpoint of the 6 discrete bands as well as just after the final ppm-hr marking (which we coded as 200-400 ppm-hr) and midway between the final marking and the very end of the reactive strip (which we coded as "over 400 ppm-hr"). We coded the reactive portion of a band as "darkened" if its RGB values were 10 or more units greater than the adjacent non-reactive portion's RGB values; RGB values range from 0 (pure black) to 255 (pure white).

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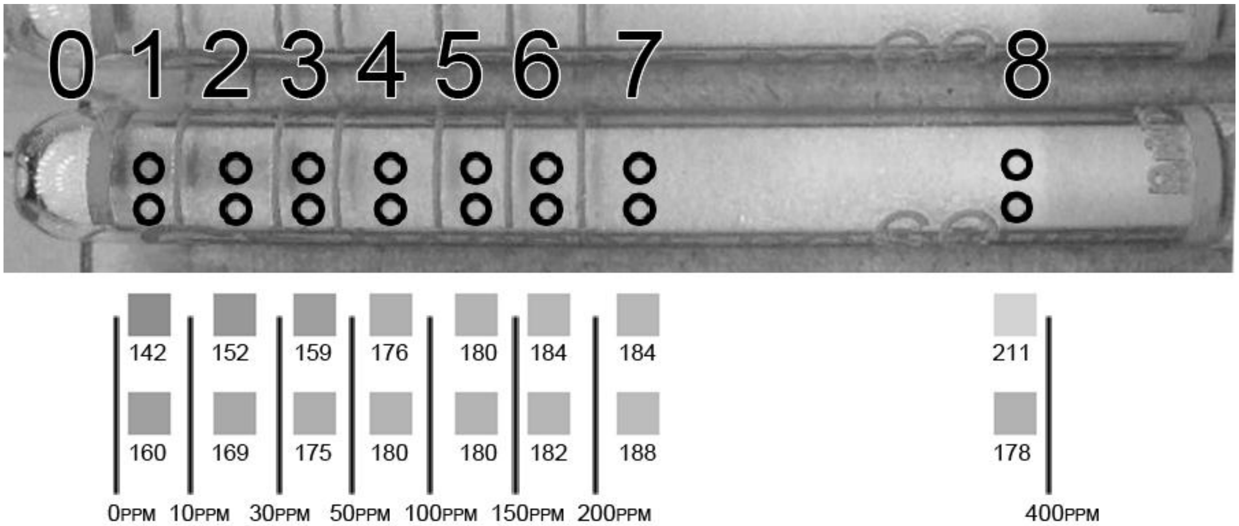
[4] We also weighed remaining coals and ash. For the purpose of our analysis, we consider coals as "burned," although they are often placed in small metal containers for keeping pots of food warm.

Figure 4 | Measurement of pixel values inside and outside of CO tube reactive strip
We converted digital images from RGB color to black and white using the “desaturate” function of Adobe Photoshop CS3 software. We read RGB unit values by using the Photoshop Navigator information pane while scrolling the cursor to a midpoint in each band. Results were robust to using other thresholds ranging from 2 to 15 RGB unit values.



In this example, band 3 is the highest band with a more than 10 “RGB” unit value difference (as measured by Adobe Photoshop CS3 software) between the reactive and non-reactive parts of the CO tube. We code this reading as 30-50 ppm.

2.2.4 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).

2.2.5 Follow-up stove usage observations

Field staff returned to Gorima, Jitong, and Kandia villages eight months following program implementation. Field staff completed walkthroughs of the villages 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.

3 Results

3.1 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 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 (see Table 1). A probit regression of treatment status on baseline characteristics shows no joint significance.

Significant attrition occurred during the course of the study. Of the 768 study participants, 572 (74%) completed the controlled cooking test, 539 (70%) provided CO tube readings, and 498 (64%) completed the survey. Data collection rates for the cooking test and CO tube readings were similar for treatments and controls. Owing to difficulty in locating households for follow-up, only 53% of treatments completed the survey, versus 73% controls. See Appendix C for pipeline tabulations. Attrition was largley due to participants' absence from the villages on days that we scheduled intervention activities and data collection, 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 households covered 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.

3.2 Summary Statistics

The household survey shows no systematic difference in study groups other than number of stoves (see Table 1). The sample is fairly evenly split between those who speak Dagaare (56%) and those who speak Sissali (44%), and these proportions remain 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. Participants in the study are poor. While respondents may under-report of cash income, the median respondent reports 8 GHS ($5.60) of cash income per month. Only 10% of both women and their husbands report any formal schooling, and of those with schooling, only half proceeded beyond primary education. Only 4% of respondents report owning a television, although 25% have a cell phone and 85% have a flashlight or other form of electric light. (See **Error! Reference source not found.** for more summary statistics.)

76% of households have two or more wood-burning stoves. The mean among controls is 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.

Table 1 | Summary statistics from the household survey

Includes mean-comparison test statistics and proportion test statistics

	Treatment (stdev)	Control (stdev)	Difference (z-stat / t-stat)	
Number of members in household	6.3	6.5	0.2	
	(2)	(2.6)	(0.71)	
Number of wives husband has	1.7	1.7	0	
	(0.9)	(0.9)	(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	4.5	0.1	
	(1.6)	(1.9)	(0.11)	
Number of overall stoves	2.3	1.9	0.4	***
	(0.7)	(0.6)	(7.28)	
Number of traditional stoves	1.4	1.9	0.5	***
	(0.7)	(0.6)	(7.77)	
Share of traditional stoves outdoors	0.64	0.59	0.05	
	(0.43)	(0.36)	(1.44)	
Pct that buy wood	0.03	0.03	0	
	(0.17)	(0.17)	(0.03)	
Pct that sell wood	0.05	0.05	0	
	(0.22)	(0.21)	(0.36)	
Pct that sell charcoal	0.06	0.04	0.02	
	(0.23)	(0.19)	(1.01)	
n	225	263		

* = p<0.1 ** = p<0.05 *** = p<0.01

During the controlled cooking test, treatments and controls cooked indoors in equal proportions and cooked the same weight of food on average (see Table 2). Treatment group participants brought less fuel wood to the controlled cooking test than controls. Treatments also had slightly longer duration CO tube exposure than controls.

Table 2 | Summary statistics from the controlled cooking test

Includes mean-comparison test statistics and proportion test statistics

	Treatment (stdev)	Control (stdev)	Difference (z-stat or t-stat)
Fuel wood use (grams)	1434	1621	187**
	(519)	(705)	(3.53)
Proportion of participants cooking outdoors	0.43	0.48	0.05
			(1.04)
Initial fuel wood presented at cooking test (grams)	2366	2758	392**
	(671)	(954)	(5.46)
Weight of pot & cooked tisert (grams)	6679	6576	103
	(1542)	(1713)	(0.72)
Carbon monoxide tube exposure band (1 to 8, coding described in the text)	5.2	5.2	0
	(2.7)	(2.6)	(0.17)

Minutes wearing carbon monoxide tubes	89	80	9*
	(27)	(65)	(1.91)
n	278	239	

* = p<0.1 ** = p<0.05 *** = p<0.01

3.3 Findings

We first present findings on the usage of traditional and improved cookstoves observed from stove usage monitors and eight-month follow-up. We then present outcome data from the controlled cooking test and household survey.

3.3.1 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 (see 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).

Households reporting more stoves had higher attrition 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 this time, these improved stoves show an average of 185 minutes (and median of 136 minutes) 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 (see **Error! Reference source not found.** for calculation details). Control homes average almost 11 stove-hours per day over 50°C across all traditional stoves (see Table 3); 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 2½ 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 hours total for controls, 9.59 hours for treatments, difference not statistically significant).

The subset of fully-covered households (i.e., those with no SUM attrition) tell 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.

Table 3 | Usage of improved and traditional stoves (minutes over 50˚C)

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

All surviving SUMs	**Treatment**			**Control**
	Traditional	**Improved**	**All**	**Traditional**
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	**Treatment**			**Control**
	Traditional	**Improved**	**All**	**Traditional**
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

Participants commonly employ multiple stoves. Of the 23 completely monitored control group participants reporting two stoves, the median first-ranked stove accounts for 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.

3.3.2 Eight month follow-up observations of stove usage

Approximately half of improved stoves appear to remain in regular use eight months after implementation (Table 4).

Table 4 | Field observations of improved stoves in three villages after 8 months

		Broken (not in use)		Appear in use		Unclear if in use	
	Observed	**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%

3.4 Fuel use during the controlled cooking test

Given the familiarity of participants with the commonly cooked meal of *tisert*, most participants selected an appropriate amount of wood for the task. Thus, we dropped observations (25 treatment, 28 control) where we recorded that the cooks used less than one third of the wood they had presented, as such data were likely due to measurement error.

We were interested in whether the potentially endogenous covariates of outdoor cooking and the weight of the pot full of cooked *tisert* affected our results. To control for covariates we ran the following linear regression:

(1) Fuel use = β_0 + β_1 treatment group status + β_2 outside location + β_3 cooked tisert weight + β_4 education day attendance + β_5 education day attendance $\times$ treatment + ∂ village + ε

Results (**Table 5**, col. 2) were similar to simple group mean comparisons (col. 1); treatment group members used 12% less fuel wood. Interestingly, the treatment group also brought 15% less wood to be weighted at the start of the cooking test, a statistically significant difference ($P < 0.001$). Inclusion of village fixed effects does not alter this result. Attendance at the cooking training session has no correlation with either fuel wood use or initial wood presented in the cooking test (col. 3). However, the non-random nature of attendance at the training session may obscure its measurable impact.

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. As expected, results show slightly higher fuel savings (14%) when we focus solely on participants who built an improved stove. Inclusion of other covariates does not affect this finding (col. 5).

Table 5 | Fuel wood use during the controlled cooking test

	Fuel wood use (grams)				
	1	**2**	**3**	**4**	**5**
Treatment group	-187 ***	-196 ***	-187 **		
	(54)	(53)	(89)		
Used an improved stove (instrumented with Treatment group)				-218 ***	-215 **
				(63)	(102)
Cooked outdoors during CCT		56	52		41
		(53)	(53)		(53)
Weight of pot & cooked tisert (grams)		0.087 ***	0.088 ***		0.090 ***
		(0.016)	(0.016)		(0.016)
Attended stove use educational session			-41		-40
			(80)		(79)
Education × Treatment			-8		-13
			(110)		(108)
Constant	1621	1021 ***	1042 ***	1634	1049 ***
	(39)	(115)	(122)	(42)	(122)
n	517	517	517	517	517
R^2	0.02	0.08	0.08	0.02	0.08
F	12.07	14.62	8.88	-	-

* = p<0.1 ** = p<0.05 *** = p<0.01

3.4.1 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 (see Table 6). 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 these effects are just sampling error.

Table 6 | 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 ++

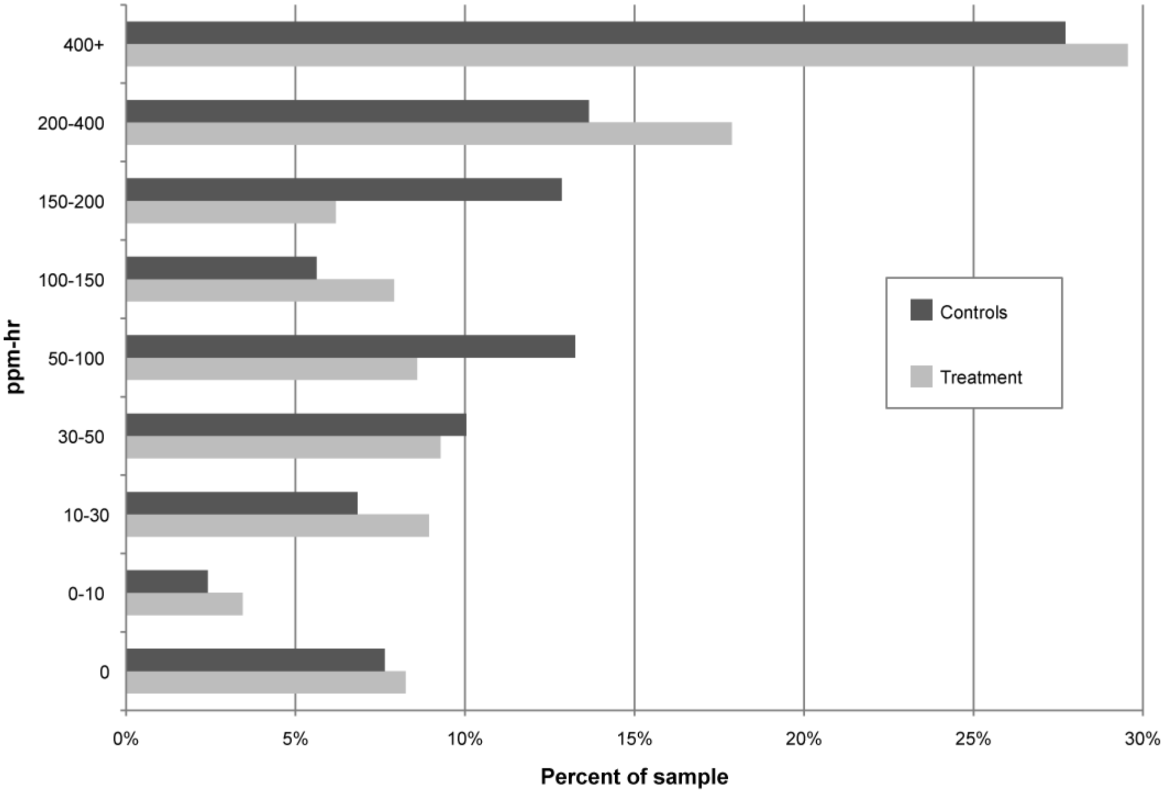
Number of days of wood collection in past week × duration of most recent wood collection (min)				
Mean	349	358	9	
SD	(328)	(386)	(0.24)	
Median	240	240	0	
Number of days since most recent wood collection				
Mean	6.25	5.30	0.95	*
SD	(5.74)	(5.00)	(1.95)	
Median	5	4	1	+++
Number of days wood collected 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
Pearson chi-square for median-compairson test: + = z<0.1 ++ = z<0.05 +++= z<0.01

3.5 Exposure to Carbon Monoxide

We present the histogram of CO exposure for treatments and controls in Figure 5. On average, treatments and controls showed statistically indistinguishable mean exposures to hourly CO. At the same time, the treatments wore the CO tubes 11% longer than controls (89 min vs. 80 min, $P < 0.1$).

Figure 5 | Histogram of exposure to carbon monoxide during controlled cooking test



Given the censored nature of high exposure, we ran a tobit regression to examine exposure to carbon monoxide. We use the following regression specification:

(2) $$\text{band}_i = \beta_0 + \beta_1\,\text{exposure}_i + \beta_2\,\text{treatment}_i + \beta_3\,\text{outside}_i + \beta_4\,\text{treatment}_i \times \text{outside}_i + \varepsilon_i$$

with upper limit censoring at band 8 (i.e., 400+ ppm-hr).

Participants in the treatment group do not register significantly different exposure to carbon monoxide than participants in the control group during the controlled cooking test (see Table 7, col. 1). In column 2 we adjust for whether the cook was outdoors – an endogenous factor – and find that cooking outdoors lowered CO exposure by over one band for controls. Given that the average one-band decrease represents as much as a 50% change in ppm-hours, the decrease experienced by controls cooking outdoors is substantial. The coefficient on the interaction term *treatment × outside* is large but not precisely estimated.

Table 7 | Tobit regression analysis of treatment status effect on CO exposure band

Used a pixel difference threshold between strip recording CO exposure and adjacent portion of CO tube of 10 RGB unit values (where pure black = 0, pure white = 255). Uncertain readings, in which value differences did not decrease steadily, were removed from sample (27% of controls vs. 25% of treatments, difference n.s.)

	1		2
Treatment group	0.016		-0.414
	(0.337)		(0.460)
Minutes of CO tube exposure	0.006	*	0.005

	(0.003)		(0.003)	
Cooked outdoors during CCT			-1.356	***
			(0.499)	
Treatment * Outdoors			0.793	
			(0.676)	
Constant	5.380	***	6.212	***
	(0.364)		(0.471)	
Standard error of regression	3.455		3.433	
n	458		458	
n censored (upper limit)	137		137	

* = p<0.1 ** = p<0.05 *** = p<0.01

These findings are robust when the pixel difference threshold is varied from 2 to 15 RGB units, although the magnitude of the effect of outdoor location decreases as the difference threshold decreases.

3.5.1 Self-reported recent health

Table 8 shows self-reported recent health from the household survey. Control group participants reported experiencing irritated eyes following cooking over twice as many days as treatment group participants reported for the preceding week. Differences were almost as large for symptoms of headache and bad cough or 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). In contrast, there was no difference in the proportion of control and treatment groups reporting children becoming sick in the preceding week.

Self-reported recent use of the improved stove does not show any significant relationship to self-reported recent health. Similarly, self-reported recent health measures do not exhibit a relationship with CO tube readings observed during the controlled cooking test.

Table 8 | Self-reported recent health

	Treatment (stdev)	**Control (stdev)**	**Difference (z-stat / t-stat)**
Number of days in previous week respondent reported problem following cooking			
Irritated eyes	1.0	2.7	1.7***
	(2.1)	(2.6)	(7.63)
Headache	1.0	2.2	1.2***
	(2.0)	(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	0.10	0.19	0.09***
	(0.02)	(0.02)	(2.75)

Bad cough outside of cooking	0.16	0.27	0.11***
	(0.02)	(0.03)	(3.13)
Difficulty breathing	0.12	0.27	0.15***
	(0.02)	(0.03)	(4.32)
Chest pain	0.18	0.31	0.13***
	(0.03)	(0.03)	(3.35)
Excessive mucus	0.13	0.19	0.06
	(0.02)	(0.03)	(1.71)
Number of above symptoms (out of 5)	0.68	1.22	0.54***
	(1.29)	(1.63)	(4.00)
Report sick child in previous week (1 = yes)	0.21	0.24	0.03
	(0.03)	(0.03)	(0.82)
N	225	255	

* = p<0.1 ** = p<0.05 *** = p<0.01

4 Discussion

4.1 Improved Stove Performance

4.1.1 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, many treatment participants 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 traditional stoves among treatments. Also, 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.

Our estimated stove usage is only a rough approximation for multiple reasons: different stove models had different placement of the usage monitors; stoves vary in how well they conduct heat to the SUM; many of the SUMs over-heated, leading to non-random attrition; and we are unsure if SUM readings on indoor stoves are comparable to readings on outdoor stoves.

The non-random survival of SUMs may introduce negative bias. Recall that almost a third of stove usage monitors were either destroyed by heat or misplaced. For example, surviving SUMs will under-state average usage if, as is likely, SUMs overheated more often when placed on stoves that were used more intensively. In addition, improved stoves' walls were thin compared to traditional stoves; the decreased thermal mass means improved stoves were likely to heat and cool faster than traditional stoves—and so therefore might record less usage than traditional stoves. Furthermore, because rarely-used stoves presumably are less likely to overheat SUMs, the rate of non-adoption (10%) is likely to be overstated.

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, it is clear adoption of a new stove does not imply 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.

4.1.2 Indoor air pollution

Based on the CO tube measures, improved stoves do not by themselves reduce exposure to smoke. Cooking outdoors produces a significant decrease in exposure to smoke for controls; the same, however, cannot be said for treatments. Treatments had far better self-reported recent health than controls, despite the lack of measured reductions in CO exposure. Self-reported health also does not bear a relationship with CO tube measures. It is unclear what is behind the divergence. We emphasized health concerns as a rationale for the improved stove; it is possible that members of the treatment group responded with “courtesy bias” during the survey by giving encouraging responses on self-reported health.

The indoor stoves were designed with a chimney to remove smoke. Perhaps for this reason, a higher share of the new stoves were placed indoors than was typical. However, moving indoors could offset any emissions reductions improved cookstoves might have. We observed many improved stoves emitted some amount of 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 (blocking the chimney inlet by pushing fuel wood too far into the stove), or unexpected cooking behavior (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). The WHO (2006) also cites 26 ppm as the average limit for 1-hour exposure to carbon monoxide indoors; cooks using both stoves frequently exceeded this level.

We found no detectable decline in exposure to carbon monoxide among treatment group participants during the controlled cooking test. 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). This divergence may indicate that exposure to carbon monoxide is not a direct proxy for exposure to smoke, at least as reflected in the health of cooks. On the other hand, 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.

4.1.3 Fuel use

Treatment group participants achieved economically and statistically significant 12% reduction in fuel wood use during a controlled cooking test. This reduction is modest compared to claims for many improved stoves. However, we have greater reason to believe that our findings are precise. We assume that variance in fuel consumption between individuals is not different that variance within individuals (i.e., over time). The large number of observations in our study captures fuel consumption variance with sufficient power to detect an average reduction of 12%.

If the wood savings on the cook test generalized, we would expect treatment households to spend less time collecting wood. There was no decline in our measures of time spent per week gathering wood.

4.2 Future Directions

4.2.1 Implications for stove programs

An improved cookstove program has to account for the vast 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.

The relative advantages of a stove—what makes it "improved," often according to engineers—are not sufficient to entail adoption and use. Rogers (1962) identified several attributes of innovation that affect consumer decisions to adopt a technology, among them the concept of compatibility—"the degree to which an innovation is perceived as being consistent with existing values, past experiences, and needs of potential adopters." Improved cookstoves need to have some compatibility with local cooking and architectural norms to be more likely to be adopted – or possess such extraordinary relative advantage that cooks and families unfailingly perceive these advantages and change cooking practices. The stove we studied was attractive enough for adoption, but not necessarily for replacement of existing stoves.

4.2.2 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).

5 Conclusion

We have undertaken a rapid assessment randomized-control trial of improved cookstoves using methods less demanding than current longitudinal studies. While our methods do not represent the highest precision, they suffice to approximate stove usage over time, changes in fuel wood use, and changes in exposure to smoke. By identifying simply whether a stove project has significant impacts or not, our approach should prove useful for non-profit organizations and others attempting to discern whether or not a stove project is "working." Follow-up studies can then refine estimates in fuel and exposure reductions if such estimates are critical for scientific or policy purposes.

The modest reductions in wood use we find are probably 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 better health as part of the fight against global climate change.

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