The Effects of Fuel-Efficient Cookstoves on Fuel Use, Particulate Matter, and Cooking Practices: Results from a Randomized Trial in Rural Uganda

By THERESA BELTRAMO, GARRICK BLALOCK, STEPHEN HARRELL, DAVID I. LEVINE, AND ANDREW M. SIMONS*

Smoke from inefficient combustion of solid fuels contributes to global climate change and kills approximately four million people annually. Manufactured fuel-efficient cookstoves have the potential to reduce this burden. We experimentally examine the effects of introducing fuel-efficient cookstoves on fuelwood use, indoor air pollution, and cooking patterns. Fuelwood usage and indoor air particulates both decline by 12% after introducing a fuel-efficient stove. These reductions are smaller than predicted in laboratory and well short of World Health Organization pollution targets. Even when introducing a second fuel-efficient stove, most households continued to use their traditional smoky stoves a majority of the time.

* Beltramo: United Nations High Commissioner for Refugees, Rue de Montbrilliant 92, Geneva 1201, Switzerland (e-mail: beltramo@unhcr.org); Blalock: Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY 14853 (e-mail: garrick.blalock@cornell.edu); Harrell: Department of Agriculture and Resource Economics, University of California, Berkeley, CA 94720 (email: stephenharrell@gmail.com); Levine: Walter A. Haas School of Business, University of California, Berkeley, 2220 Piedmont Ave., Berkeley, CA 94720 (e-mail: levine@haas.berkeley.edu); Simons: Department of Economics, Fordham University, 441 E. Fordham Rd., Bronx, NY 10458 (e-mail: asimons5@fordham.edu). The study was funded by the United States Agency for International Development under Translating Research into Action, Cooperative Agreement No. GHS-A-00-09-00015-00. The grant recipient was Impact Carbon, which co-funded and managed the project. We would also like to thank the Atkinson Center for a Sustainable Future at Cornell University, the Institute for the Social Sciences at Cornell University, and the Cornell Population Center for

additional funding of related expenses. Data collection was carried out by the Center for Integrated Research and Community Development (CIRCODU), and the project's success depended greatly on its managers—Joseph Arinieitwe Ndemere, Juliet Kyaesimira, Vastinah Kemigisha—and field supervisors—Innocent Byaruhanga, Fred Isabirye, Michael Mukembo, Moreen Akankunda, and Noah Kirabo. We thank Impact Carbon partners Matt Evans, Evan Haigler, Jimmy Tran, Caitlyn Toombs, and Johanna Young; U.C. Berkeley Household Energy, Climate, and Health Research Group partners including Kirk Smith, Ilse Ruiz-Mercado, and Ajay Pillarisetti; Berkeley Air partners including Dana Charron, David Pennise, Michael Johnson, and Erin Milner; and the USAID TRAction Technical Advisory Group. The views expressed in this paper solely reflect those of the authors, and these opinions are not necessarily those of the institutions with which the authors are affiliated. All errors are our own.

I. Introduction

Cooking with wood, charcoal, and dung using traditional cookstoves causes substantial environmental degradation (Bailis et al. 2015), contributes to global climate change (Ramanathan and Carmichael 2008), and causes an estimated four million deaths a year (Lim et al. 2012). The magnitude of this problem is vast, as 2.8 billion people across the globe cook with solid fuels each day (Bonjour et al. 2013). Due to the challenges with affordable and consistent supply of gas or electricity for cooking (Lewis and Pattanayak 2012; Rehfuess et al. 2010), a second-best solution is promoting fuel-efficient cookstoves that use less solid fuel than traditional stoves.

In this paper, we experimentally examine the effects of the introduction of manufactured fuel-efficient cookstoves on the quantity of household fuel use, indoor air pollution, and cooking behaviors in rural Uganda. Companion papers analyzed the household purchase decision, and found that relieving liquidity constraints by allowing additional time for payments (Beltramo et al. 2015b) and providing a free trial with time payments allows users to learn about the stoves' fuel savings properties (Levine et al. 2018) and greatly increases purchase rates (for example, from 5% to 57% in our setting in rural Uganda). To measure how households use their cooking technologies we follow Ruiz-Mercado, Canuz, and

Smith (2012) and affix small, unobtrusive temperature sensors to both the three stone fires and manufactured fuel-efficient stoves.

Our work builds on important antecedents. The first studies to document the link between stove usage, indoor air pollution and human health in developing countries were a series of studies in Kenya in the late 1990s (Ezzati, Saleh, and Kammen 2000; Ezzati and Kammen 2001, 2002) and Guatemala in the early 2000s (Smith et al. 2006; Smith-Sivertsen et al. 2009; Smith et al. 2011). Numerous studies have built on this foundation to learn more about fuel-efficient cookstoves and household cooking behaviors. Hanna, Duflo, and Greenstone (2016) examined the link between stove usage and indoor air pollution in India and found reductions in smoke inhalation in the first year, but no changes over longer time horizons. They suggest the fade-out is due to a lack of stove maintenance by users. Bensch and Peters (2015) examined a stove designed to reduce fuelwood consumption in rural Senegal and found reductions in fuelwood use, smoke emissions, and smoke-related disease symptoms. Pillarisetti et al. (2014) examined stove usage in a sample of pregnant women in India and found that users experimented with the fuel-efficient stove at first, but that over time rates of use of the introduced stove declined. In steady state (about a year after introduction) they found that total cooking (minutes per day) on the combined stoves was the same as before the intervention with about 75% of cooking on the traditional stove, and about 25% on the introduced fuel-efficient stove.

Our work extends these prior studies. First, we examine cooking behaviors among households that were willing to purchase the new stove at market prices (and perhaps therefore value the stove more highly). Among these previous studies, Hanna, Duflo, and Greenstone (2016) distributed highly subsidized stoves (users paid USD 0.75 for a USD 12.50 stove); while Bensch and Peters (2015) and Pillarisetti et al. (2014) distributed stoves for free. Because our results come from users that paid the market price for the fuel-efficient stove, our sample mimics those that would be most likely to purchase.

Like Hanna, Duflo, and Greenstone (2016) and Bensch and Peters (2015) we focus our stove use evaluation metrics on the near term (a year or less), but also returned in the longer term (in our case 3.5 years later) to examine whether the introduced stoves are still being used. A difference between our study and these two studies is that Hanna, Duflo, and Greenstone (2016) used participant health recall surveys along with medical personnel to examine symptoms (i.e., respiratory function, breathing, coughing) while Bensch and Peters (2015) tracked self-reported health symptoms (i.e., cough, asthma, difficulty breathing, eye irritations). We measured household level particulate matter (PM2.5) concentrations. Particulate matter concentrations have been directly linked to human health in numerous studies (Chay and Greenstone 2003; Currie and Walker 2009; Smith-Sivertsen et al. 2009). Due to their small size (2.5 μg or less) these particles can reach deep into the lungs and are the single best indicator of risk for many respiratory related diseases (Chowdhury et al. 2007).[1]

Similar to Pillarisetti et al. (2014) we use unobtrusive temperature sensors to measure detailed household stove use over time and can also report on substitution rates between usage of the introduced stove and the traditional stove. However, unlike Pillarisetti et al. (2014) we introduce random variation in the assignment of when stoves are delivered to causally examine the usage changes due to the manufactured fuel-efficient stove.

Common cooking practice in the study area involved cooking with two pots simultaneously (*e.g.*, rice and beans, or steamed cooking bananas and gravy). Another innovation in our study is that after measuring stove usage when

[1] According to Pope III et al. (2002) each 10 $\mu g/m^3$ increase in long-term exposure to fine particulate matter is associated with approximately 4%, 6%, and 8% increase in the risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively.

households had one fuel-efficient stove, we provided households with a second fuel-efficient stove. The second stove made it easier for them to shift completely to the fuel-efficient cooking technology (if they desired). Thus, this non-experimental intervention lets us measure if the lack of a second cooking surface is the reason for continued stove stacking.

We find that the randomized early introduction of the first fuel-efficient stove reduces wood use by about 12%, reduces particulate matter by 12%, and reduces usage of three stone fires by 3.7 hours per day (30%). Once both fuel-efficient stoves are introduced wood usage falls 27% from the pre-intervention period, particulate matter is reduced by 10%, and hours cooked on three stone fires falls by 5.2 hours per day (41%). While any pollution reduction benefits users, the pre-intervention rates of PM are so high (414 $\mu g/m^3$ 24-hour mean in the control group) that a 10-12% reduction only covers a small part of the reductions that would be required to meet WHO air pollution targets of 25 $\mu g/m^3$ (World Health Organization 2006).

Households use the new stoves more hours per day than the usage of three stone fires declines. The increase in total hours of stove usage blunts reductions in fuel use and household air pollution. At the same time, cooking on multiple surfaces simultaneously increases the utility of the cooks. Anecdotally it appears that cooks are choosing to cook foods on the technology most appropriate for that food (*i.e.*, low-heat simmering of rice, beans, cooking bananas on three stone fires, and making sauces and boiling water for tea on the fuel-efficient stove).

In the longer term (3.5 years) we find low rates of use of the fuel-efficient stove, but lower rates of disrepair than were reported in Hanna, Duflo, and Greenstone (2016). This pattern makes sense as Hanna, Duflo, and Greenstone (2016) examined local artisan-built mud stoves while the stoves used in our study are arguably more sturdy as they are commercially manufactured with the manufacturer stating an expected life of up to ten years.[2]

II. Experimental Setting and Data

A. Background and Site Selection

We selected the Mbarara region of Uganda because it is rural, almost all families cooked on a traditional three stone fire, it was less than a day's travel from Kampala, and the local government was supportive of our work. In pre-experimental discussion groups, we confirmed that there was no active fuel-efficient cookstove intervention in the region, and that families spent a lot of time gathering wood (approximately 10–20 hours per week). The study area is characterized by agrarian livelihoods including farming of *matooke* (starchy cooking banana), potatoes, and millet as well as raising livestock. Prior to our experiment, almost all families cook on a traditional three-stone fire (97%), usually located within a separate cooking hut (62% of households had totally enclosed kitchens with no windows, while 38% had semi-enclosed kitchens with at least one window). Common practice in our study area was to cook almost exclusively in the detached cooking hut.

We implemented a series of companion studies in rural areas of the Mbarara District in southwestern Uganda from February to September 2012 focusing on the adoption and use of fuel-efficient stoves. These studies included an examination of barriers to purchase (Beltramo et al. 2015b; Levine et al. 2018) and of how social networks affect purchase (Beltramo et al. 2015a).

[2] Envirofit Inc. offers a 1-year warranty and claims stoves have been tested for up to 10,000 hours of cooking in durability testing (what they suggest is the equivalent of ten years of use). See https://envirofit.org/ for details. Despite offering a warranty, we acknowledge that it would be unlikely for an Envirofit user in rural Uganda to be able to claim this warranty.

We marketed the Envirofit G3300 wood-burning stove, made by Envirofit International Inc. (see Figure 1 for images of a traditional three-stone fire and the Envirofit G3300). This stove achieves relatively efficient fuel combustion by channeling airflow into the fire and directing heat upward through an insulated cylinder to the cooking surface. These design innovations allow fuel to burn at a controlled rate and enable more complete combustion than a three-stone fire. Emissions testing of the Envirofit G3300 in a controlled laboratory setting found average reductions in CO by 65%, particulate matter reductions of 51%, and a reduction in fuel wood use by 50% compared to a three-stone fire (see Figure 2 for a copy of the emissions and performance report).

B. Selection of Study Participants

In the first stage of the experiment, we randomly selected 12 parishes to receive a traditional cash-and-carry sales offer and 14 parishes to receive a sales offer of a one week free trial followed by four equal weekly time payments (see Levine et al. 2018). Within each parish (a unit of government administration covering about 4,000-6,000 people), we recruited a local point person with the help of local government officials. We asked each focal point person to gather roughly 60 people together for a public sales meeting on a specified day. We did not tell the point person which sales offer his or her parish would receive.

At the sales meeting participants completed a questionnaire focused on household cooking and basic socioeconomic indicators, then the study team presented the Envirofit G3300, discussed the stove's features such as fuel savings and reduced pollution relative to traditional three-stone fires, did a cooking demonstration, and presented the terms of the randomly selected sales offer. While the Envirofit was not commercially available in this region before our experiment, we sold it for the same retail price (40,000 Ugandan Shillings (~USD $16)) that it was selling for in other parts of the country where it had already been introduced. We used the randomized assignment of sales offer by parish as the identifying assumption in Levine et al. (2018) to examine barriers to purchase. For this stove usage study our identification strategy is based on randomly assigning the timing of when purchasers received their Envirofit (we call them early buyers and late buyers). For the usage study, we selected 12 participants from each of the 14 parishes that purchased the Envirofit with a free trial plus time payments sales offer. Therefore, all participants in the usage study received the same sales offer at the extensive margin and all participants fully paid for the stove according to the terms of the sales offer.

Households were eligible to participate in the usage study if they mainly used wood as a fuel source, regularly cooked for eight or fewer persons, someone was generally home every day, and cooking was largely in an enclosed kitchen. In each parish, more than twelve households met these criteria and agreed to join the study; therefore, among those that agreed, we randomly selected twelve households per parish for the usage study with the stove use monitors (SUMs). We asked both early buyers and late buyers if they would agree to have SUMs placed on their traditional three stone fires immediately. We use the randomly assigned time of Envirofit delivery (early buyers vs. late buyers) as the identifying assumption for the causal claims made in this paper.

After participants consented to participate in the usage study, all existing three stone fires were affixed with SUMs. Then approximately four weeks after the SUMs data collection began, the early buyers group received their first Envirofit stove. Approximately four weeks after that the late buyers received their first Envirofit stove.

Based on earlier studies (*e.g.*, Ruiz-Mercado et al. 2011, 2013; Pillarisetti et al. 2014), we anticipated that many households would use both their three stone fire and their Envirofit. One motivation is that common cooking practices in the area require two simultaneous cooking pots (for example rice and beans, or *matooke* and some type of sauce), and the Envirofit heats only one pot. We were interested in whether having a second fuel-efficient stove would substantially end stove stacking. Thus, approximately four weeks after late buyers received their first Envirofit, we surprised both groups with the gift of a second Envirofit stove.

In short, at the first study wave both early buyers and late buyers had only three stone fires; in the second study wave, early buyers had one Envirofit, along with their three stone fires, but late buyers only had three stone fires; in the third study wave both types of buyers have one Envirofit; and in the fourth wave both early buyers and late buyers had two Envirofits. See Table 1 for the steps of the experimental rollout. We tracked stove temperatures for approximately 18 weeks (May-September 2012). Each household had as many as two three stone fires and two Envirofit stoves monitored with SUMs. By the end of the study, numerous SUMs had been lost or burned up; therefore, after we delivered the second Envirofit stove we had a shortage of SUMs, so we focused measurement on both Envirofits and the primary three stone fire.

C. Stove Use Monitor Temperature Data

To track usage, we used small, inexpensive and unobtrusive sensors called stove use monitors (SUMs) to record stove temperatures without the need for an observer to be present.[3] Using SUMs to log stove temperatures was initially suggested by Ruiz-Mercado et al. (2008) and has been used successfully in various settings

[3] The SUMs used for our project, iButtons™ manufactured by Maxim Integrated Products, Inc., are small stainless-steel temperature sensors about the size of a small coin and the thickness of a watch battery which can be affixed to any stove type. Our SUMs record temperatures with an accuracy of +/- 1.3 degrees C up to 85°C. For additional details see the product description website at: http://berkeleyair.com/services/stove-use-monitoring-system-sums/ The SUMs cost approximately USD$16 each. They recorded temperature data every 30 minutes for six weeks in a household before needing minimal servicing from a technician to download the data and reset the device.

(Mukhopadhyay et al. 2012; Ruiz-Mercado et al. 2013; Pillarisetti et al. 2014). We installed SUMs on two Envirofits and two three-stone fires in each household when possible (recall that by the end of the study, numerous SUMs had been lost or burned up; therefore, only a few secondary three stone fires were measured when all users had two Envirofits).

Throughout the study, field staff recorded about 2,400 visual observations of whether a stove was in use (on/off) when they visited homes. Then we used a logistic regression model to examine the temperature data immediately before and after the 2,400 visual observations of stove use. The algorithm analyzed the data to understand how temperature patterns change at times of observed stove use and then predicted cooking behaviors to the wider dataset of 1.7 million temperature readings. This process, developed in Simons et al. (2014a), allowed us to unobtrusively and inexpensively track daily stove usage on a large sample of households for six continuous months. See Appendix A, Harrell et al. (2016), and Simons et al. (2018) for additional details on placing SUMs, and the process of converting temperature readings to measures of predicted cooking.

D. Kitchen Performance Test Data

We also performed standard kitchen performance tests (KPT) (Bailis, Smith, and Edwards 2007) in each household to measure the quantity of fuel wood used, record detailed food diaries of what households cooked, and measure household air pollution[4] before any Envirofits were distributed, when early buyers had one Envirofit, and when both types of buyers had two Envirofits. The KPT lasts approximately 72 hours and involves daily visits by a small team of researchers

[4] We used UCB Particle and Temperature Sensors (UCB-PATS) to measure air pollution particles that were 2.5 micrometers in diameter or smaller (PM2.5).

weighing wood, monitoring household air particulate monitors, and collecting food diaries which recall cooking and stove usage over the last 24 hours.

E. Long Term Stove Usage Data

We revisited households approximately 3.5 years after they initially received their Envirofit stoves. The survey team made quick, unannounced, observation visits in November 2015 to see whether Envirofit stoves were still in use. Because these visits were unannounced, we were only able to observe 137 of the original 168 households (~82%) due to people not being home and/or having moved in the intervening time. The purpose of the visits was for the survey team to observe which stoves were in use at the time of visit, examine Envirofits and three stone fire locations for obvious signs of use (smoke stains, black soot, etc.) and ask a series of quick qualitative consumer satisfaction questions about the different stove types.

III. Specification

We analyze several outcomes: wood usage (kg/day), daily household air pollution (PM2.5) concentrations, and stove usage. Recall that there are four study waves with different levels of stove ownership: (1) households with two three stone fires; (2) early buyers receive an Envirofit, late buyers have only their three stone fires; (3) both types of buyers have one Envirofit; (4) both types of buyers receive a second Envirofit. Due to budgetary constraints, we could only run kitchen performance tests at phases (1), (2), and (4). So, for outcomes measured in kitchen performance tests (wood usage, PM2.5) the regression specification which only uses data from study waves (1), (2), and (4) is:

(1) $$Y_{ipt} = \alpha_{ip} + b_1 * Early\_have\_Envirofit_t + b_2 * Both\_have\_two\_Envirofits_t + \beta_1 (T_i * Early\_have\_Envirofit_t) + \beta_2 (T_i * Both\_have\_two\_Envirofits_t) + \epsilon_{ipt} ,$$

where Y_{ipt} is daily wood use or daily PM2.5 concentrations for household i for parish p in study wave t, α_{ip} are fixed effects for each household, $Early\_have\_Envirofit_t$ and $Both\_have\_two\_Envirofits_t$ are dummies for study wave, and T_i is a dummy equal to one if in the early treatment group. ϵ_{ip} is a residual that may be clustered by parish * study-wave but is assumed to be i.i.d. within a parish and study-wave. The coefficients of interest are β_1 (the effect of being in the early buyer group during study wave (2), or the effect of owning an Envirofit while the comparison group has only three stone fires) and β_2 (the effect of being in the early buyer group during study wave (4), or the effect of owning your first Envirofit for approximately 4 weeks longer than the comparison group when both groups own two Envirofits).

We also run this equation without households fixed effects, but our preferred specification includes them. The household fixed effect controls for unobserved characteristics of the household like the talent and cooking style of the household chef and structural features of the kitchen such as windows or ventilation. Because PM has extreme positive outliers, we analyze the natural log of PM 2.5 (as is typical in studies that examine PM2.5). We also top and bottom code PM2.5 at the 2^{nd} and 98^{th} percentiles, and top-code wood usage at the 98th percentile.

For stove usage, we have data both during and between the three weekly periods when we measured wood usage and PM2.5. So, the regression specification for the SUMs usage data is:

$$(2)\ Y_{ipt} = \alpha_{ip} + b_1 * Early\_have\_Envirofit_t + b_2 * Both\_have\_Envirofit_t + b_3 * Both\_have\_two\_Envirofits_t + \beta_1 (T_i * Early\_have\_Envirofit_t) + \beta_2 (T_i * Both\_have\_Envirofit_t) + \beta_3 (T_i * Both\_have\_two\_Envirofits_t) + \epsilon_{ipt} ,$$

where Y_{ipt} are daily three stone fire or Envirofit usage derived from SUMs readings for household i for parish p in study wave t, α_{ip} are fixed effects for each household, *Early_have_Envirofit*$_t$, *Both_have_Envirofit*$_t$, and *Both_have_two_Envirofits*$_t$ are dummies for study wave, and T_i is a dummy equal to one if in the early treatment group. ϵ_{ip} is a residual that may be clustered by parish * study-wave but is assumed to be i.i.d. within a parish and study-wave. The coefficients of interest are β_1 (the effect of being in the early buyer group during study wave (2), or the effect of owning an Envirofit while the comparison group has only three stone fires) and β_2 (the effect of being in the early buyer group during study wave (3), or the effect of owning your first Envirofit for approximately 4 weeks longer than the comparison group which also owns one Envirofit), and β_3 (the effect of being in the early buyer group during study wave (4), or the effect of owning your first Envirofit for approximately 4 weeks longer than the comparison group when both groups own two Envirofits).

A. Adjustments to Account for Hawthorne Effects

The analysis of wood usage and PM uses data only on the days when we had field technicians visiting homes each day. The specification in equation (1) does not account for participants who act differently due to the presence of observers. In a companion paper (Simons et al. 2017), we document that participants increase usage of Envirofits by about 3.0 hours per day and decrease usage of the primary three stone fires by about 1.8 hours per day during the kitchen performance tests, but then revert back to previous usage patterns once observers have left the home.[5]

To adjust for this bias, we borrow from the field of epidemiology which has "efficacy trails" that examine the effects of an intervention under controlled conditions and "effectiveness trials" which examine the effects of an intervention under realistic conditions (Flay 1986). In our setting, the "efficacy trials" are

[5] See Garland, Gould, and Pennise (2018) for an additional example of observer induced behavioral differences in stove use during kitchen monitoring periods.

described by equation (1) and present a valid measure of what happened when observers were present during the measurement week. However, we need to adjust for the gap in usage between measurement weeks and weeks without observers to generalize behaviors more broadly. The adjusted result is more relevant for policy makers as it describes the rates of wood use and pollution during more typical days when no external observers are present.

Let the subscript *type* = *early* or *late* buyer, let the superscript *wave* = *experimental wave* (i.e., (1) households with two three stone fires; (2) early buyers with an Envirofit, late buyers only with three stone fires; (3) both types of buyers with one Envirofit; (4) both types of buyers with two Envirofits). An approximation of the Hawthorne adjusted wood usage is:

$$(3) \qquad Adj\_Wood_{type} = TSF\_Hours\_Used_{type}^{wave} * \left(\frac{TSF\_Wood\_Used}{hour}\right) + ENV\_Hours\_Used_{type}^{wave} * \left(\frac{ENV\_Wood\_Used}{hour}\right)$$

where *Adj_Wood* is the adjusted amount of wood used for each type of buyer, *TSF_Hours_Used* are the hours cooked on the three-stone fire in each wave and by each type of buyer, *ENV_Hours_Used* are the hours cooked on the Envirofit in each wave and by each type of buyer. *TSF_Wood_Used* per hour is calculated by dividing wood consumption by three stone fire use from the first kitchen performance test (when no one had an Envirofit). The *ENV_Wood_Used* per hour is calculated using the laboratory results shown in the "Emission and Performance Report" (Figure 2) (because we do not have any periods in our experimental setting when households only had Envirofits).

We must also make a similar adjustment for particulate matter concentrations. An approximation of the Hawthorne adjusted PM2.5 concentration is:

$$(4)\quad Adj\_PM2.5_{type} = TSF\_Hours\_Used_{type}^{wave} * \left(\frac{TSF\_PM2.5\_Generated}{hour}\right) + ENV\_Hours\_Used_{type}^{wave} * \left(\frac{ENV\_PM2.5\_Generated}{hour}\right)$$

where *Adj_PM2.5* is the adjusted amount of PM2.5 generated for each type of buyer, *TSF_Hours_Used* are the hours cooked on the three-stone fire in each wave and by each type of buyer, *ENV_Hours_Used* are the hours cooked on the Envirofit in each wave and by each type of buyer. *TSF_PM2.5_Generated* per hour is calculated by dividing PM2.5 concentrations by three stone fire use from the first kitchen performance test (when no one had an Envirofit). The *ENV_PM2.5_Generated* per hour is calculated using the laboratory results shown in the "Emission and Performance Report" (Figure 2) (because we do not have any periods in our experimental setting when households only had Envirofits).

Because we have sensor based usage metrics that covers all weeks of the experiment, the estimates for changes in cooking behaviors (hours cooked per day on three stone fires and Envirofits) from equation (2) are not likely affected by the observer induced behavioral response.[6] However, because we only measured wood usage and PM2.5 during the weeks observers (technicians) had to be present to run the machinery to take the PM2.5 readings, we must adjust for Hawthorne effects by using equation (3) and (4) to calculate wood usage and PM2.5 rates.

[6] Observers (technicians) were only present in households in three, 72 hour periods over the 18 weeks that we took sensor readings of stove usage.

IV. Results

A. Summary Statistics and Randomization Tests

Table 2 provides basic summary statistics on stove usage derived from the temperature sensors, particulate monitors and food diaries for the periods of time that line up with kitchen performance tests. Across the three measurement weeks participants used their primary three stone fire an average of 6.70 hours/day and their secondary three stone fires 5.86 hours/day. Once Envirofits were introduced the average usage was 4.23 hours/day on the first Envirofit and 2.52 hours/day on the second Envirofit. The average wood usage in a 24-hour period was 7.95 kg. The average 24-hour particulate matter (PM2.5) concentration was 393.39 $\mu g/m^3$. On average households cooked 3.34 meals each day and the largest daily meal was eaten by 6.38 people.

Table 3 shows that randomization between the early buyers and late buyers was successful. Only one difference among the twenty balance covariates was (weakly) statistically significantly different than zero, participants that randomly received their Envirofits early had a higher value of assets (1,158 USD vs. 905 USD) (p=0.08). The treatment group included slightly more women (73% vs. 68%), were younger (40.4 vs. 44.1 years old), had about the same marriage rates (77% vs. 78%), had about the same rate of wife as primary cook (92% vs. 94%), and slightly fewer (52% vs. 57%) reported that spouses make decisions jointly. The socioeconomic status variables were very similar between groups: share that earns income (88% vs. 92%), share self-employed (73% vs. 73%), share with year-round employment (49% vs. 52%), and share that identify as subsistence farmer (85% vs. 85%). Stove use and fuel use variables were also similar between groups: number at largest daily meal (6.51 vs. 6.16), share that always boils drinking water (72% vs. 74%), share that uses firewood as primary fuel (95% vs. 94%), share that purchased firewood last month (43% vs. 34%), and share that gathered firewood last month (81% vs. 82%).

Households used their first Envirofit about 4.3 hours per day and their second Envirofit about 2.9 hours per day (Table 4).

B. Effects of Envirofits on Fuel Use and Pollution

We begin by analyzing the causal impact of the introduced Envirofit stove on wood usage (Table 5) during our experiment ("efficacy trial"). In the pre-intervention period the control group uses about 9.3 kg of wood/day (Table 3, column 1), these usage rates fall when the early group has one Envirofit (-1.9 kg/day, $p<0.01$, Table 5, column 1) and when both groups have two Envirofits (-2.5 kg/day, $p<0.01$, Table 5, column 1), but there are no statistically significantly different rates of reduction for those that received their Envirofit in the early group. In our preferred specification, with household fixed effects (column 2), the early receipt of an Envirofit is causally associated with a change of about -1.1 kg/day, ($p<0.1$). This reduction in wood consumption is a modest reduction of about 12 percent from the pre-intervention control group wood usage level. When all own two Envirofits, both groups have reduced their wood usage by about 2.5 kg/day ($p<.01$) or 27%, relative to the pre-intervention control group, with no statistically significant difference between groups.

In Table 6 we examine the causal effects of the introduction of Envirofit stoves on household air pollution concentrations. Pre-intervention the control group has a daily concentration of PM of about 414 $\mu g/m^3$ (Table 3, column 1). In our preferred specification with household fixed effects (Table 6, column 2) the introduction of the first Envirofit is causally associated with a reduction of PM concentrations of 12% ($p<.01$) (note that actual PM2.5 levels are flat, as they increased by 12% in the control group). When both groups have two Envirofits, we find that both groups have reduced PM by about 10% ($p<0.01$) with no difference between groups (meaning having had the first Envirofit longer does not result in changed pollution levels once both groups have received both Envirofits). While we find overall reductions in wood usage by about 27% when all own two Envirofits, the PM data only shows a reduction in pollution levels of about 10%. It is unclear why these measures do not mimic each other.

C. Effects of Envirofits on Cooking Behaviors

Next, we examine the effects of the introduction of Envirofits on daily time spent cooking[7] on the existing three stone fires. Columns (1-2) in Table 7 show the effect of the introduction of the Envirofits on total daily combined hours cooked on both three stone fires. Prior to the intervention, control households cooked for a combined total of about 12.4 hours per day on their three stone fires[8] (Table 3, column 1). In our preferred specification with household fixed effects (Table 7, column 2) there is a point estimate of an increase in time cooked on combined three stone fires by about 2.8 hours per day (not statistically significant) in the control group when early buyers have one Envirofit, while the interaction effect shows a reduction in combined three stone fire cooking of 6.4 hours per day ($p<0.01$) due to the early introduction of the Envirofit (this is a reduction of 52% compared to pre-intervention control levels). The point estimates suggest that the control group is cooking about 15.2 hours per day on their combined three stone fires, while the treatment group is cooking only 8.8 hours per day on their combined three stone fires. When both groups have two Envirofit stoves (in addition to two three stone

[7] By cooking, we mean that the algorithm is predicting stove use, not necessarily that a cook is standing above the fire and actively working on a meal. Our algorithm would likely detect "cooking" in cases of banking hot coals for the next meal, while this is not a formal act of cooking, it does contribute to the consumption of fuelwood and the increase of particulate matter in the kitchen.

[8] This is a summation of the hours cooked on the primary three stone fire and the secondary three stone fire conditional on having readings for both three stone fires.

fires), we see a reduction of 10.2 hours per day ($p<0.01$) cooked on the combined three stone fires (a reduction of 82% compared to pre-intervention control levels), and no statistically significant effect for the treatment group (meaning once households have two Envirofits, usage of the combined three stone fires is not different depending on whether the household had their first Envirofit for a longer period of time). It is worth noting that these reductions are larger in magnitude in the three measurement weeks than in the full multi-month period we recorded temperature data. This is detailed in Tables 8 and 9 and discussed in more detail below.

Recall that we tracked very few secondary three stone fires at the end of the experiment due to limited number of stove use monitors (this reduces our sample size in columns (1-2) because it only includes households where we had readings for both three stone fires). Therefore, we also analyze this question in terms of only the primary three stone fire (columns 3-4) and only the secondary three stone fire (columns 5-6). Control households increase use of the primary three stone fire by 3.8 hours per day ($p<0.01$) when the early group has one Envirofit (column 4) while treatment households are causally associated with a reduction of 7.8 hours per day ($p<0.01$) of primary three stone fire cooking (compared to controls. There are no statistically significant changes in cooking patterns (column 6) on the secondary three stone fires for either the control or treatment groups. This suggests that the changes that are happening (substituting three stone fire cooking for Envirofit cooking) are happening on the primary three stone fire only, with no changes in secondary three stone fire usage.

D. Stove Usage

We have stove usage data for much longer periods than the three measurement periods. We estimated how the daily hours cooked on each stove varied over the entire six months of the study period (Table 8, based on equation 2). Figure 3 summarizes stove usage by study phase. A more detailed (weekly) time series of stove usage is in Figures 4 and 5.[9]

Total usage on both three stone fires is 12.7 hours per day by the control group in the sample of all weeks prior to Envirofit introduction. In our preferred specification (Table 8, column 2), the causal estimates are that the introduction of the first Envirofit reduces cooking on three-stone fires by about 3.7 hours per day ($p<0.01$). This is a reduction of about 29% from the control group prior to the introduction of the first Envirofit. In contrast, use of three stone fires fell by 52% when only looking at the week when the kitchen performance tests were being performed (Table 7, column 2). This reduction of 29% is more likely the correct magnitude of reduction in three stone fire use caused by the first Envirofit because the measurement weeks had Hawthorne effects induced by the daily visits by our enumerators (Simons et al. 2017).

When late buyers received their first Envirofit (Table 8, column 2), we see a reduction in use of the three stone fires among late buyers by 3.1 hours per day ($p<0.01$) (about 24%); however, at the same time we see an increase in three stone fire use of about 2.9 hours per day ($p<0.01$) (about 23%) in the early buyers (who have owned their Envirofits about 4 weeks longer than the late buyers). It is unclear why these differ in direction, though one possibility is that after initial experimentation with the Envirofit the early group has decided to use their three stone fires more, while the late group continues to experiment with the new Envirofit. This difference appears to resolve itself once both groups receive their second Envirofit (Table 8, column 2), as combined use of the three stone fires reduces by about 5.2 hours per day ($p<0.01$, with no statistically significant

[9] See Appendix Figure A1 and A2 for daily time series of stove use by early and late buyers, respectively.

difference if households received their first Envirofit earlier or later). This is a reduction of about 41% in three stone fire use once both Envirofits are introduced (compared to the reduction of 82% when focusing only on the measurement week, Table 7, column 2). In short, even with two Envirofit stoves most households continued to use their three stone fires regularly.

E. Adjusting for Hawthorne Effects

Because we gathered wood weights and PM2.5 during the weeks with daily observer visits, we adjust the results regarding wood usage and pollution levels so they reflect typical usage.

When we adjust for observer induced differences in behaviors during measurement weeks we estimate an 11% reduction in wood use (Table 9) and a 12% reduction in PM (Table 10) due to the first Envirofit. These estimates are similar to the 12% reduction in wood use and 12% reduction in PM when we did not adjust for the Hawthorne effects (Table 5, col. 2 and Table 6, col. 2).

When both groups have two Envirofits, the results change considerably when adjusting for Hawthorne effects. In Table 9, the change in wood usage for early buyers is -0.18 kg/day and late buyers increased wood use by 0.18 kg/day throughout the experiment. This implies that overall there was no change in total wood consumption during the entire intervention period. This result is markedly different than the estimates from measurement days alone, which showed a reduction of 2.5 kg/day or 27% (Table 5, column 2) during the final kitchen performance test. Results are also different for PM2.5 concentrations. Table 10 shows that early buyers changed PM2.5 concentrations by about -11 $\mu g/m^3$ throughout the experiment, while late buyers increased PM2.5 concentrations by 7 $\mu g/m^3$. Taken together this implies approximately no change in overall PM concentrations (or a slight reduction of 1%, of -4 $\mu g/m^3$ on a base of 419 $\mu g/m^3$).

The estimates from measurement days alone showed a reduction of 10% (Table 6, column 2) in PM2.5 concentrations.

F. Long Term Usage

Similar to other cookstove evaluations (Bensch and Peters 2015; Hanna, Duflo, and Greenstone 2016), we also returned to households to examine longer-term usage behaviors. We made unannounced visits approximately 3.5 years after the initial Envirofit stoves were distributed. Approximately 82% of the original households were home when we visited.

Table 11 describes the key data from the follow-up home visits. In the moment our enumerators arrived, about 48% of households (66 out of 137) were actively cooking. Among those only 9% (6 out of 66) were cooking with an Envirofit stove. Enumerators asked the other 131 households if they could inspect their Envirofit to see obvious signs of use like black soot or fresh ashes in the stove (see example in Figure 6 of a stove with obvious signs of use). Among those households, 65% had an Envirofit with obvious signs of use, 17% had Envirofits stored that were clearly not being used, 2% had Envirofits that were still in perfect condition (essentially never used), 8% said their Envirofit was damaged and disposed of, and a final 8% said they had given the stove away. Next, enumerators asked households to see their second Envirofit to see if it had signs of use. Among this sample, 25% had a second Envirofit with obvious signs of use, 11% had their second Envirofit stored with limited signs of use, 9% had the second Envirofit in perfect condition (never been used), 38% reported they had given the second Envirofit away as a gift, and 16% said the second Envirofit was damaged and they disposed of it.

Among all households visited (N=137), 23% reported that they still used both Envirofits, 50% said they use only one Envirofit, and 27% say they have stopped using Envirofits completely. Enumerators also asked all households if they had to purchase a stove today, would they purchase an Envirofit. Among respondents, 79% said they would purchase an Envirofit, 15% said they would not purchase an Envirofit, with the remaining households unsure. Enumerators then asked open-ended response questions as to the reasons for those hypothetical purchase decisions. The most popular responses among those that would buy another Envirofit were that the stove saves fuel and reduces household time collecting fuel, the stove cooks fast, the stove is easily portable, and the stove produces less smoke than a three-stone fire. Among those that said they would not purchase another Envirofit, the most popular responses were that the preparation of firewood was difficult for Envirofits (needs smaller pieces of wood than a three-stone fire), the stove does not simmer food, the stove was too small for the household's cooking needs, it was hard to prepare some traditional meals on the stove, and the stove was hard to light.

G. Rebound Effects

Figure 3 graphs average daily stove use throughout our experiment. When households first receive an Envirofit they reduce three stone fire usage. However, at the same time, Envirofit usage is larger than the decline in three stone fire use. The aggregate time all stoves are in use increases by about 20% throughout the period we tracked stove temperatures. At the end of our temperature tracking the ratio of stove use was about 2:1 in favor of three stone fires. Late buyers used three stone fires about 12.5 hours a day, at the end of our study period they used three stone fires about 10 hours per day and Envirofits about 5 hours a day, for total stove usage of about 15 hours per day. Early buyers follow a similar pattern over the experimental period with three stone fire use declining about 2.5 hours a day while Envirofit usage increases to 5 hours per day.

V. Discussion and Conclusion

Ours is the first randomized trial collecting usage among a sample that paid the market price for their stoves. We estimate the effect of introducing the first fuel-efficient stove is a reduction of 12% fuelwood use and a reduction of 12% in PM2.5 concentrations (during the measurement week). When we adjust for observer induced Hawthorne effects, the results are essentially the same for the introduction of the first Envirofit. In a non-experimental analysis, when we provided a second fuel-efficient stove, fuelwood use falls 27% from the pre-intervention period, and indoor air pollution concentrations fall 10% (during measurement week). However, those reductions change to no effect when we adjust for observer induced Hawthorne effects.

Almost all households used both three stone fires and fuel-efficient stoves in daily cooking. It appears that households use the fuel-efficient stove to heat things that cook relatively quickly such as boiling water to make tea and sauces, and preferred three stone fires for simmering dishes such as beans and cooking bananas. Through the study period, three stone fire use fell by about 2.5 hours a day, but this is more than offset by about 5 hours a day of new cooking on the introduced stoves. This increase in total cooking time mutes the environmental and indoor air pollution benefits compared to laboratory results.

Particulate matter would need to have declined by more than 90% from pre-intervention levels to reach WHO targets for indoor air pollution. While any reduction in particulate matter is likely beneficial for households,[10] continuing to use solid fuels even with fuel-efficient cookstoves, will not be adequate to reach

[10] There is emerging evidence that small reductions in PM2.5 can have benefits in especially vulnerable subpopulations. For example, even a small reduction in PM2.5 can reduce adverse pregnancy outcomes (Alexander et al. 2018) and improve child growth in children under the age of two (Lafave et al. 2018).

safe levels of indoor air pollution. Thus, policies that assist developing countries to transition up the energy ladder to gas or electricity—particularly when coupled with policies to disable smoky indoor stoves—should take on increased importance.

APPENDIX A

These details summarize previously published methodology work on how to convert temperature readings into stove use metrics (Harrell et al. 2016; Simons et al. 2014, 2018).

A. Placement of SUMs

SUMs must be placed close enough to the heat source to capture changes in temperatures, but not so close that they exceed 85°C, the maximum temperature the SUMs used in this study can record before they overheat and malfunction. We do not need to recover the exact temperature of the hottest part of the fire to learn about cooking behaviors. Even with SUMs that are reading temperatures 20-30 cm from the center of the fire, as long as the temperature readings for times when stoves are in use are largely different than times when stoves are not used the logistic regression will be able to predict a probability of usage.

SUMs for three stone fires were placed in a SUM holder (Figure A3) and then placed under one of the stones in the three-stone fire (left panel, Figure A4). The SUMs for Envirofits were attached using duct tape and wire and placed at the base of the stove behind the intake location for the firewood (right panel, Figure A4).

Figure A5 shows an example of SUMs temperature data for a household across about three weeks. The left panel shows the temperatures registered in a three-stone fire versus the ambient temperature also recorded with SUMs in this household, while the right panel compares the temperature of the Envirofit to the ambient temperature reading.

B. Visual Observations of Use

Each time data collection personnel visited a household he or she visually observed which stoves were in use (whether the stove was "on" or "off" along with the date and timestamp recorded digitally via a handheld device). Enumerators visited each household numerous times during a "measurement week," when we also enumerated a survey and weighed wood for the kitchen performance test. Another enumerator visited once every 4-6 weeks to download data and reset the SUMs device.

C. Generating an Algorithm

We matched visual observations of stove use to SUMs temperature data by time and date stamps. The core of our method is a logistic regression using the lags and leads of the SUMs temperature data to predict visual observations of stove usage. We tested ten specifications of differing combinations of current, lagged, and leading temperature readings (Simons et al. 2014).

In order to determine which of the models was most appropriate we tested the ten specifications with the Akaike information criterion (AIC) (Akaike 1981). The AIC trades off goodness of fit of the model with the complexity of the model to guard against over fitting.

The preferred specification included the temperature reading closest to the time of the visual observation, the readings 60 and 30 minutes prior, and 60 and 30 minutes after the visual observation of use, and a control for hour of the day. This regression specification correctly predicted 89.3% of three stone fire observations and 93.8% of Envirofit observations of stove usage. We then compared our algorithm to other previously published algorithms (Ruiz-Mercado, Canuz, and Smith 2012; Mukhopadhyay et al. 2012). Those algorithms focused on defining "discrete" cooking events based on rapid temperature slope increases, elevated stove temperatures, and then followed by a cooling off period. We applied those algorithms to the temperature data we collected and found our logistic regression correctly classified more observations, with a higher pseudo R-squared, than any other algorithm for both three stone fires and the Envirofits.

REFERENCES

Akaike, Hirotugu. 1981. "Likelihood of a Model and Information Criteria." *Journal of Econometrics* 16: 3–14.

Alexander, Donee A., Amanda Northcross, Theodore Karrison, Oludare Morhasson-Bello, Nathaniel Wilson, Omolola M. Atalabi, Anindita Dutta, et al. 2018. "Pregnancy Outcomes and Ethanol Cook Stove Intervention: A Randomized-Controlled Trial in Ibadan, Nigeria." *Environment International* 111: 152–163. https://doi.org/10.1016/j.envint.2017.11.021.

Bailis, Rob, Kirk R. Smith, and Rufus Edwards. 2007. "Kitchen Performance Test (KPT)." Univerisity of California, Berkeley, CA.

Bailis, Robert, Rudi Drigo, Adrian Ghilardi, and Omar Masera. 2015. "The Carbon Footprint of Traditional Woodfuels." *Nature Climate Change* 5 (3): 266–272. https://doi.org/10.1038/nclimate2491.

Beltramo, Theresa, Garrick Blalock, David I. Levine, and Andrew M. Simons. 2015a. "Does Peer Use Influence Adoption of Efficient Cookstoves? Evidence From a Randomized Controlled Trial in Uganda." *Journal of Health Communication* 20 (S1): 55–66. https://doi.org/10.1080/10810730.2014.994244.

———. 2015b. "The Effect of Marketing Messages and Payment over Time on Willingness to Pay for Fuel-Efficient Cookstoves." *Journal of Economic Behavior & Organization* 118: 333–45. https://doi.org/10.1016/j.jebo.2015.04.025.

Bensch, Gunther, and Jörg Peters. 2015. "The Intensive Margin of Technology Adoption – Experimental Evidence on Improved Cooking Stoves in Rural Senegal." *Journal of Health Economics* 42: 44–63. https://doi.org/10.1016/j.jhealeco.2015.03.006.

Bonjour, Sophie, Heather Adair-Rohani, Jennyfer Wolf, Nigel G. Bruce, Sumi Mehta, Annette Prüss-Ustün, Maureen Lahiff, Eva a. Rehfuess, Vinod Mishra, and Kirk R. Smith. 2013. "Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980-2010." *Environmental Health Perspectives* 121 (7): 784–790. https://doi.org/10.1289/ehp.1205987.

Chay, Kenneth Y., and Michael Greenstone. 2003. "The Impact of Air Pollution on Infant Mortality: Evidence From Geographic Variation in Pollution Shocks Induced by a Recession." *Quarterly Journal of Economics* 118 (3): 1121–1167. https://doi.org/10.1162/00335530360698513.

Chowdhury, Zohir, Rufus Edwards, Michael Johnson, Kyra Naumoff Shields, Tracy Allen, Eduardo Canuz, and Kirk R Smith. 2007. "An Inexpensive Light-Scattering Particle Monitor: Field Validation." *Journal of Environmental Monitoring* 9 (10): 1099–1106.

Currie, J, and WR Walker. 2009. "Traffic Congestion and Infant Health: Evidence from E-Zpass." *American Economic Journal: Applied Economics* 3 (1): 65–90.

Ezzati, Majid, and Daniel M Kammen. 2001. "Indoor Air Pollution from Biomass Combustion and Acute Respiratory Infections in Kenya: An Exposure-Response Study." *Lancet* 358 (9282): 619–24.

———. 2002. "Evaluating the Health Benefits of Transitions in Household Energy Technologies in Kenya." *Energy Policy* 30 (10): 815–26. https://doi.org/10.1016/S0301-4215(01)00125-2.

Ezzati, Majid, Homayoun Saleh, and Daniel M Kammen. 2000. "The Contributions of Emissions and Spatial Microenvironments to Exposure to Indoor Air Pollution from Biomass Combustion in Kenya." *Environmental Health Perspectives* 108 (9): 833–39.

Flay, Brian R. 1986. "Efficacy and Effectiveness Trials (and Other Phases of Research) in the Development of Health Promotion Programs." *Preventive Medicine* 15 (5): 451–474.

Garland, C., C. F. Gould, and D. Pennise. 2018. "Usage and Impacts of the Envirofit HM-5000 Cookstove." *Indoor Air* 28 (4): 640–650. https://doi.org/10.1111/ina.12460.

Hanna, Rema, Esther Duflo, and Michael Greenstone. 2016. "Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves." *American Economic Journal: Economic Policy* 8 (1): 80–114.

Harrell, Stephen, Theresa Beltramo, Garrick Blalock, Juliet Kyayesimira, David I. Levine, and Andrew M. Simons. 2016. "What Is a Meal?: Comparing Methods of Auditing Carbon Offset Compliance for Fuel Efficient Cookstoves." *Ecological Economics* 128: 8–16.

Lafave, Daniel, Abebe Damte Beyene, Randall Bluffstone, Sahan T.M. Dissanayake, Zenebe Gebreegziabher, Alemu Mekonnen, and Michael Toman. 2018. "Impacts of Improved Biomass Cookstoves on Child and Adult Health: Experimental Evidence from Rural Ethiopia." Waterville, ME.

Levine, David I, Theresa Beltramo, Garrick Blalock, Carolyn Cotterman, and Andrew M. Simons. 2018. "What Impedes Efficient Adoption of Products? Evidence from Randomized Sales Offers for Fuel-Efficient Cookstoves in Uganda." *Journal of the European Economic Association*.

Lewis, Jessica J, and Subhrendu K Pattanayak. 2012. "Who Adopts Improved Fuels and Cookstoves? A Systematic Review." *Environmental Health Perspectives* 120 (5): 637–45. https://doi.org/10.1289/ehp.1104194.

Lim, Stephen S, Theo Vos, Abraham D Flaxman, Goodarz Danaei, Kenji Shibuya, Heather Adair-Rohani, Markus Amann, et al. 2012. "A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990-2010: A Systematic Analysis

for the Global Burden of Disease Study 2010.” *Lancet* 380 (9859): 2224–60.
Mukhopadhyay, Rupak, Sankar Sambandam, Ajay Pillarisetti, Darby Jack, Krishnendu Mukhopadhyay, Kalpana Balakrishnan, Mayur Vaswani, et al. 2012. “Cooking Practices, Air Quality, and the Acceptability of Advanced Cookstoves in Haryana, India: An Exploratory Study to Inform Large-Scale Interventions.” *Global Health Action* 5: 19016–19016.
Pillarisetti, Ajay, Mayur Vaswani, Darby Jack, Kalpana Balakrishnan, Michael N Bates, Narendra K Arora, and Kirk R Smith. 2014. “Patterns of Stove Usage after Introduction of an Advanced Cookstove: The Long-Term Application of Household Sensors.” *Environmental Science & Technology* 48 (24): 14525–14533.
Pope III, C. Arden, Richard T. Burnett, Michael J. Thun, Eugenia E. Calle, Daniel Krewski, and George D. Thurston. 2002. “Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution.” *Journal of the American Medical Association* 287 (9): 1132–1141. https://doi.org/10.1001/jama.287.9.1132.
Ramanathan, Veerabhadran, and Gregory Carmichael. 2008. “Global and Regional Climate Changes Due to Black Carbon.” *Nature Geoscience* 1 (4): 221–227.
Rehfuess, Eva A., David J. Briggs, Mike Joffe, and Nicky Best. 2010. “Bayesian Modelling of Household Solid Fuel Use: Insights towards Designing Effective Interventions to Promote Fuel Switching in Africa.” *Environmental Research* 110 (7): 725–732. https://doi.org/10.1016/j.envres.2010.07.006.
Ruiz-Mercado, Ilse, Eduardo Canuz, and Kirk R. Smith. 2012. “Temperature Dataloggers as Stove Use Monitors (SUMs): Field Methods and Signal Analysis.” *Biomass and Bioenergy* 47: 459–68. https://doi.org/10.1016/j.biombioe.2012.09.003.
Ruiz-Mercado, Ilse, Eduardo Canuz, Joan L. Walker, and Kirk R. Smith. 2013. “Quantitative Metrics of Stove Adoption Using Stove Use Monitors (SUMs).” *Biomass and Bioenergy* 57 (October): 136–48.
Ruiz-Mercado, Ilse, Nick L Lam, Eduardo Canuz, Gilberto Davila, and Kirk R Smith. 2008. “Low-Cost Temperature Loggers as Stove Use Monitors (SUMs).” *Boiling Point* 55: 16–18.
Ruiz-Mercado, Ilse, Omar Masera, Hilda Zamora, and Kirk R. Smith. 2011. “Adoption and Sustained Use of Improved Cookstoves.” *Energy Policy* 39 (12): 7557–66. https://doi.org/10.1016/j.enpol.2011.03.028.
Simons, Andrew M., Theresa Beltramo, Garrick Blalock, and David I. Levine. 2014. “Comparing Methods for Signal Analysis of Temperature Readings from Stove Use Monitors.” *Biomass and Bioenergy* 70: 476–488.

———. 2017. “Using Unobtrusive Sensors to Measure and Minimize Hawthorne Effects: Evidence from Cookstoves.” *Journal of Environmental Economics and Management* 86: 68–80. https://doi.org/10.1016/j.jeem.2017.05.007.

———. 2018. “Sensor Data to Measure Hawthorne Effects in Cookstove Evaluation.” *Data in Brief* 18: 1334–1339. https://doi.org/10.1016/j.dib.2018.04.021.

Smith, Kirk R, Nigel Bruce, Byron Arana, Alisa Jenny, Asheena Khalakdina, John McCracken, Anaite Diaz, Morten Schei, and Sandy Gove. 2006. “Conducting The First Randomized Control Trial of Acute Lower Respiratory Infections and Indoor Air Pollution: Description of Process and Methods.” *Epidemiology* 17 (6): S44–S44.

Smith, Kirk R, John P McCracken, Martin W Weber, Alan Hubbard, Alisa Jenny, Lisa M Thompson, John Balmes, Anaité Diaz, Byron Arana, and Nigel Bruce. 2011. “Effect of Reduction in Household Air Pollution on Childhood Pneumonia in Guatemala (RESPIRE): A Randomised Controlled Trial.” *Lancet* 378 (9804): 1717–26. https://doi.org/10.1016/S0140-6736(11)60921-5.

Smith-Sivertsen, Tone, Esperanza Díaz, Dan Pope, Rolv T Lie, Anaite Díaz, John McCracken, Per Bakke, Byron Arana, Kirk R Smith, and Nigel Bruce. 2009. “Effect of Reducing Indoor Air Pollution on Women’s Respiratory Symptoms and Lung Function: The RESPIRE Randomized Trial, Guatemala.” *American Journal of Epidemiology* 170 (2): 211–20. https://doi.org/10.1093/aje/kwp100.

World Health Organization. 2006. “WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005: Summary of Risk Assessment,” 1–22. https://doi.org/10.1016/0004-6981(88)90109-6.

Figure 1

Comparison of wood burning stoves: three stone fire versus Envirofit G-3300

(a) Three Stone Fire

(b) Envirofit G-3300

Figure 2

Certified Emissions and Performance Report for Envirofit G3300

April 27, 2011

ENGINES & ENERGY CONVERSION LAB

DEPARTMENT OF
MECHANICAL ENGINEERING
COLORADO STATE UNIVERSITY

1374 CAMPUS DELIVERY
FORT COLLINS, CO
80523-1374
970.491.4796
970.491.4799 (F)
WWW.EECL.COLOSTATE.EDU

Emissions and Performance Report

The stove listed below has been tested in accordance with the "*Emissions and Performance Test Protocol*", with emissions measurements based on the biomass stove testing protocol developed by Colorado State University (available at www.eecl.colostate.edu). Percent improvements are calculated from three-stone fire performance data collected at Colorado State University.

Stove Manufacturer:	Envirofit International
Stove Model:	G-3300
Test Dates:	4/4/2011-4/22/2011
Average CO emissions (grams):	18.7
80% Confidence Interval:	17.7-19.7
Percent Improvement:	65.30%
Average PM emissions (milligrams):	995
80% Confidence Interval:	944-1046
Percent Improvement:	51.20%
Average Fuel use (grams):	596.7
80% Confidence Interval:	591.6-601.7
Percent Improvement:	50.10%
Average Thermal efficiency:	32.6
80% Confidence Interval:	32.3-32.8
Percent Improvement:	105.20%
High Power (kW):	3.3
80% Confidence Interval:	3.3-3.4
Low Power (kW):	1.9
______ 80% Confidence Interval:	1.8-1.9

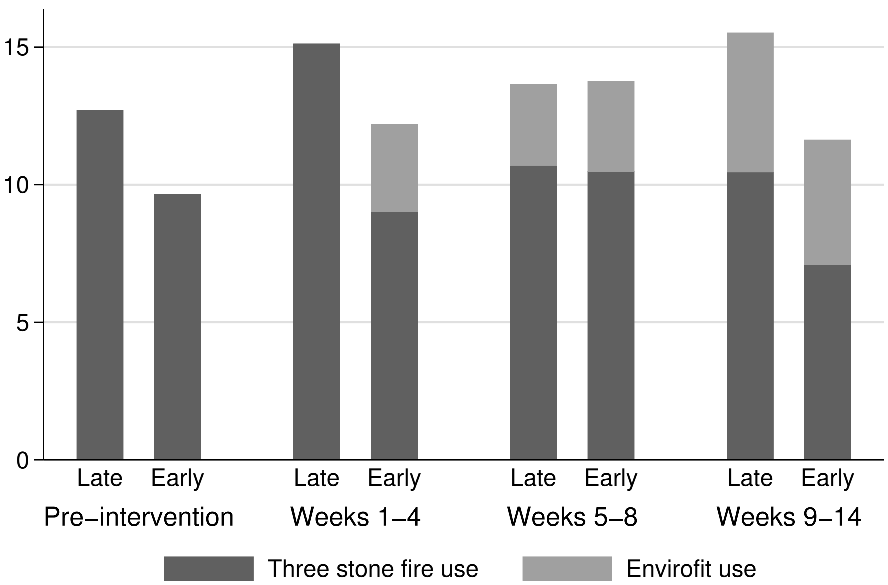
The above results are certified by the Engines and Energy Conversion Laboratory at Colorado State University. All claims beyond the above data are the responsibility of the manufacturer.

Morgan DeFoort
EECL Co-Director
Technical Lead, Biomass Stoves Testing Program

Note: The report can be downloaded at http://www.envirofit.org/images/products/pdf/g3300/G3300Cert.pdf

Figure 3

Average Daily Stove Use



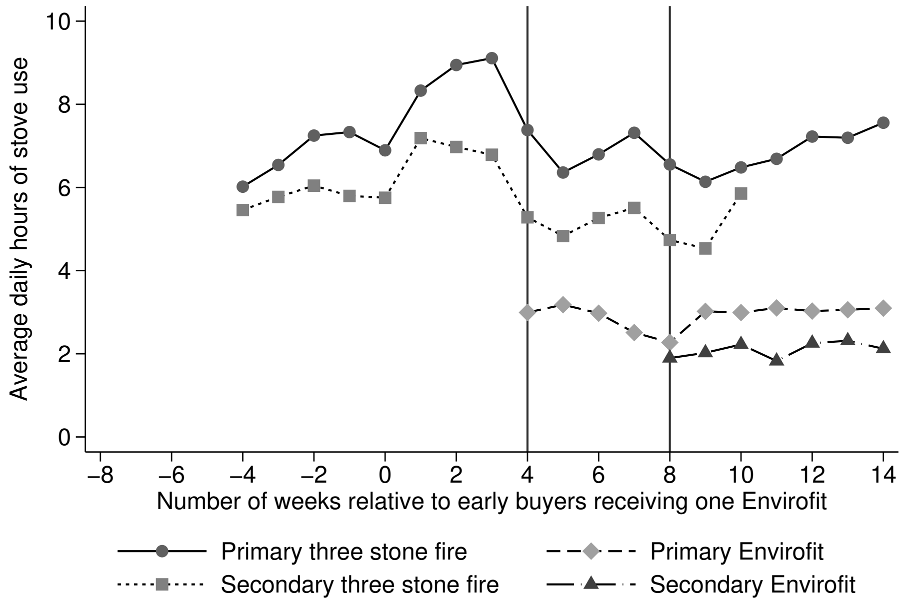
Note: Pre−intervention (4 weeks) no Envirofits; Weeks 1−4 early buyers have one Envirofit; Weeks 5−8 all have one Envirofit; Weeks 9−14 all have two Envirofits.

Figure 4

Weekly Stove Use of Early Buyers

Note: Vertical lines designate when households received their first and second Envirofits.

Figure 5
Weekly Stove Use of Late Buyers



Note: Vertical lines designate when households received their first and second Envirofits.

Figure 6
Envirofit Stove with Obvious Signs of Use (from Long Term Usage Study in Nov. 2015)

Table 1

Timeline of Experimental Rollout

Approximate Timing	Event
Weeks -4 to week 0	Stove use monitoring (SUMs) begins on two three stone fires
Week 0	Baseline kitchen performance tests (wood weighting) and particulate matter (PM2.5) monitoring*
End of week 0	Deliver first Envirofit to early buyers
Weeks 1-4	SUMs monitoring continues
Week 4	Midline kitchen perfomrance test and PM2.5 monitoring*
End of week 4	Deliver first Envirofit to late buyers (now all participants have one Envirofit)
Weeks 4-8	SUMs monitoring continues
Week 8	Deliver second Enviforit to both early and late buyers
Weeks 8-14	SUMS monitoring continues**
Week 14	Endline kitchen performance test and PM2.5 monitoring*

Note: Measurement dates and timing are approximate as roll-out was staggered across the 14 parishes. Stove usage monitors (SUMs) were on all Envirofit stoves and usually on two three stone fires per household.
*****Each measurement week (weeks 0, 4, 8) involved three 24-hour periods with wood weighing and particulate matter (PM2.5) monitors.
******After we delivered the second Envirofit stove in week 8 we had a shortage of SUMs, so some homes only had a SUM on one three stone fire.

Table 2

Daily hours cooked, particulate matter concentrations, and food diary data

Variable	Mean	Std. Dev.	Min.	Max.	N
Daily hours cooked on primary three stone fire	6.70	7.15	0.00	24	941
Daily hours cooked on secondary three stone fire	5.86	6.81	0.04	24	555
Daily hours cooked on all three stone fires	11.52	10.37	0.06	47.44	571
Daily hours cooked on primary Envirofit	4.23	3.89	0.00	16.75	482
Daily hours cooked on secondary Envirofit fire	2.52	3.29	0.00	16.93	256
Daily hours cooked on all Envirofits	5.74	4.60	0.02	24.59	390
Net wood used daily (weight in kg)	7.95	4.58	0.00	22.38	1116
Average PM2.5 reading over measurement day (μg/m^3)	393.39	218.68	21.37	1010.54	1242
Number of meals cooked per day	3.34	0.81	0	4	1251
Number of main meals cooked per day (lunch and/or dinner)	1.88	0.34	0	2	1260
Number of instances of beans or matooke per day	2.58	1.03	0	4	1260
Max number of people cooked for lunch or dinner	6.38	2.34	0	21	1263

Note: Data was collected on daily sequential visits to each household. In a few cases data was not retrieved until two days later, therefore we scale all measures to be proportional to use in a 24 hour period.

Hours cooked is derived from a predictive logistic regression of temperature data on observations of stoves in use. The process is described in detail in Simons *et al.* (2014).

Average Particulate Matter (PM) concentration is based on protocol for UCB Particle and Temperature Sensors produced by Berkeley Air Monitoring Group, and are top and bottom coded at 98% and 2% of the distribution while wood use is top coded at 98%. The World Health Organization recommends concentrations for $PM_{2.5}$ of 25 μg/m^3 or less.

Number of meals cooked per day is based on four potential meals: breakfast, lunch, tea, and dinner.

Net wood used is calculated after dropping 17 observations of negative wood weights, which likely occurred when households added wood to the designated pile before it was weighed.

Max number of people cooked for lunch or dinner takes the highest value of either lunch or dinner as those meals are the bulk of cooking.

Table 3

Balance of covariates

	Control Mean	Control SD	Treatment Mean	Treatment SD	Difference	p-value	N
Household demographics							
Female respondent (share)	0.68	0.47	0.73	0.45	0.05	0.38	164
Age of respondent	44.06	13.46	40.38	12.29	-3.68	0.14	163
Married (share)	0.78	0.42	0.77	0.43	-0.01	0.85	164
Wife is primary cook (share)	0.94	0.24	0.92	0.28	-0.02	0.6	164
Spouses make decisions jointly (share)	0.57	0.50	0.52	0.50	-0.05	0.52	164
Socioeconomic status							
Earns income (share)	0.92	0.28	0.88	0.33	-0.04	0.56	163
Self employed (share)	0.73	0.45	0.73	0.45	0.00	1.00	164
Year round employment (share)	0.52	0.50	0.49	0.50	-0.04	0.62	164
Identify as subsistence farmers (share)	0.85	0.36	0.85	0.36	0.00	1.00	164
Value of assets (USD)	905.10	1240.82	1158.37	1650.68	253.27	0.08	164
Stove use and fuels							
Number at largest daily meal	6.16	1.95	6.51	2.25	0.35	0.23	163
Always boils drinking water (share)	0.74	0.44	0.72	0.45	-0.02	0.69	164
Firewood primary fuel source (share)	0.94	0.24	0.95	0.22	0.01	0.81	164
Purchased firewood last month (share)	0.34	0.48	0.43	0.50	0.08	0.24	162
Gathered firewood last month (share)	0.82	0.39	0.81	0.39	-0.01	0.97	163
Baseline cooking measurements							
Daily hours cooked on primary three stone fire	7.30	6.75	8.14	7.21	0.84	0.47	118
Daily hours cooked on secondary three stone fire	5.91	6.41	4.51	5.68	-1.41	0.28	99
Daily hours cooked on all three stone fires	12.43	9.71	10.34	8.99	-2.1	0.34	91
Net wood used daily (weight in kg)	9.30	4.10	10.02	4.70	0.73	0.38	153
Average PM2.5 reading, $\mu g/m^3$	414.3	240.84	372.66	228.91	-41.64	0.33	150
Number of households receiving offer	82		82				164

Note: Household data collected at parish wide sales meetings. We adjust standard errors for clustering at the parish level. To minimize the effect of outliers the value of assets and PM2.5 readings are top and bottom coded at 98% and 2% of the distribution while wood use is top coded at 98%. The prices used to calculate asset values are taken from the 2011-12 round of the Uganda Living Standards Measurement Survey (LSMS) published by the World Bank (see appendix table A4). Values presented are rounded to two decimal places, the value in the difference column is calculated prior to rounding.

Table 4
Envirofit stove use

Variable	Mean	Std. Dev.	Min.	Max.	N
Early buyers have one Envirofit					
Daily hours cooked on primary Envirofit	4.35	3.89	0.02	16.75	188
All buyers have two Envirofits					
Daily hours cooked on primary Envirofit	4.25	3.68	0.00	16.23	198
Daily hours cooked on secondary Envirofit	2.86	3.48	0.00	16.93	202
Daily hours cooked on all Envirofits	7.03	4.84	0.23	24.59	202

Table 5
Effect of the Envirofit on daily wood used for cooking

Dependent variable = kg. of wood used daily

VARIABLES	(1) OLS	(2) FE
Treatment	0.72	
	(0.72)	
Early buyers have one Envirofit	-1.86***	-1.73***
	(0.60)	(0.56)
All buyers have two Envirofits	-2.48***	-2.48***
	(0.68)	(0.66)
Treatment x Early buyers have one Envirofit	-0.95	-1.08*
	(0.85)	(0.56)
Treatment x All buyers have two Envirofits	-0.46	-0.55
	(0.88)	(0.59)
Constant	12.40***	
	(0.46)	
Observations	1,116	1,116
R-squared	0.15	0.42
Number of household fixed effects		163

Standard errors clustered at parish-wave level in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: Wood weights are top coded at 98%. OLS regressions include parish fixed effects.

Table 6
Effect of the Envirofit on daily PM concentrations

Dependent variable = natural log daily PM concentrations

VARIABLES	(1) OLS	(2) FE
Treatment	-0.02	
	(0.03)	
Early buyers have one Envirofit	0.12**	0.12**
	(0.05)	(0.05)
All buyers have two Envirofits	-0.10**	-0.10*
	(0.04)	(0.05)
Treatment x Early buyers have one Envirofit	-0.13*	-0.12**
	(0.07)	(0.06)
Treatment x All buyers have two Envirofits	-0.02	-0.02
	(0.06)	(0.06)
Constant	6.57***	
	(0.07)	
Observations	1,242	1,242
R-squared	0.87	0.92
Number of household fixed effects		164

Standard errors clustered at parish-wave level in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$
Note: OLS regression includes parish fixed effects and all regressions include PM monitor fixed effects. PM2.5 readings are top and bottom coded at 98% and 2% of the distribution prior to taking the natural log.

Table 7

Effect of the Envirofit on daily hours cooked on three stone fires - measurement weeks

Dependent variable = daily hours cooked on all (cols. 1 and 2), primary (cols. 3 and 4), or secondary (cols. 5 and 6) three stone fire(s)						
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	OLS	FE	OLS	FE	OLS	FE
Treatment	-1.93		0.78		-0.91	
	(2.00)		(1.01)		(1.14)	
Early buyers have one Envirofit	4.35**	2.75	2.56**	3.77***	2.17**	1.55
	(1.93)	(1.95)	(1.16)	(1.01)	(0.86)	(0.94)
All buyers have two Envirofits	-3.56	-10.20**	-1.49	-0.86	1.06	0.94
	(2.85)	(3.81)	(1.19)	(1.34)	(1.62)	(2.40)
Treatment x Early buyers have one Envirofit	-7.41***	-6.36***	-6.56***	-7.79***	-1.09	-1.07
	(2.52)	(1.63)	(1.57)	(1.17)	(1.49)	(0.99)
Treatment x All buyers have two Envirofits	-3.16	3.38	-2.42	-2.53	1.71	0.30
	(3.71)	(4.71)	(1.83)	(1.74)	(3.38)	(3.75)
Constant	12.36***		5.06***		6.73***	
	(1.62)		(0.94)		(0.79)	
Observations	571	571	941	941	555	555
R-squared	0.24	0.73	0.18	0.60	0.13	0.73
Number of household fixed effects		129		155		133

Standard errors clustered at parish-wave level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: This table only includes data from weeks with a kitchen performance test. OLS regressions include parish fixed effects.

Table 8

Effect of the Envirofit on daily hours cooked on three stone fires - all weeks

Dependent variable = daily hours cooked on all (cols. 1 and 2), primary (cols. 3 and 4), or secondary (cols. 5 and 6) three stone fire(s)						
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	OLS	FE	OLS	FE	OLS	FE
Treatment	-2.58		0.26		-1.86	
	(2.47)		(1.36)		(1.22)	
Weeks 1-4 (Early buyers have one Envirofit)	1.80	1.96**	1.28	1.49*	0.82	1.22***
	(1.79)	(0.83)	(1.00)	(0.84)	(0.82)	(0.32)
Weeks 5-8 (All buyers have one Envirofit)	-2.72	-3.09***	0.34	0.42	-0.73	-1.04**
	(1.82)	(0.95)	(1.19)	(0.88)	(0.90)	(0.42)
Weeks 9-14 (All buyers have two Envirofits)	-3.61*	-5.15***	-0.45	-0.38	-0.13	-0.85
	(2.08)	(1.53)	(1.15)	(0.91)	(0.94)	(0.62)
Treatment x Early buyers have one Envirofit	-3.16	-3.73***	-3.33**	-3.68***	0.15	-0.58
	(2.67)	(0.74)	(1.60)	(1.12)	(1.37)	(0.48)
Treatment x All buyers have one Envirofit	1.83	2.89***	-1.91	-1.77	2.96**	3.07***
	(2.78)	(1.05)	(1.86)	(1.09)	(1.35)	(0.78)
Treatment x All buyers have two Envirofits	-0.29	0.73	-1.47	-1.03	2.66	1.19
	(3.18)	(1.75)	(1.96)	(1.25)	(1.68)	(1.07)
Constant	14.39***		5.63***		6.27***	
	(1.76)		(0.92)		(0.92)	
Observations	8,595	8,595	13,890	13,890	8,056	8,056
R-squared	0.13	0.58	0.10	0.45	0.08	0.52
Number of household fixed effects		144		160		146

Standard errors clustered at parish-wave level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: Data includes all weeks that temperature sensors were on stoves. OLS regressions include parish fixed effects.

Table 9
Wood consumption (kg/day) adjusted for Hawthorne effect

Study wave	Buyer type	Three stone fires (TSF) (hr/day)	TSF wood usage (kg/hr)	Fuelwood by TSFs (kg/day)	Envirofits (ENV) (hr/day)	ENV wood usage (kg/hr)	Fuelwood by ENV (kg/day)	Total fuel-wood (kg/day)	Diff-in-diff	% change	Change (pre-intervention to two ENVs)
Weeks -4 to 0 (Pre-intervention)	Early	9.64	0.64	6.17	0.00	0.32	0.00	6.17			
Weeks -4 to 0 (Pre-intervention)	Late	12.71	0.64	8.13	0.00	0.32	0.00	8.13			
Weeks 1-4 (Early buyers have one Envirofit)	Early	9.03	0.64	5.78	3.17	0.32	1.01	6.79	-0.92	-11.3%	
Weeks 1-4 (Early buyers have one Envirofit)	Late	15.12	0.64	9.68	0.00	0.32	0.00	9.68			
Weeks 5-8 (All buyers have one Envirofit)	Early	10.48	0.64	6.71	3.29	0.32	1.05	7.76			
Weeks 5-8 (All buyers have one Envirofit)	Late	10.7	0.64	6.85	2.94	0.32	0.94	7.79			
Weeks 9-14 (All buyers have two Envirofits)	Early	7.08	0.64	4.53	4.55	0.32	1.46	5.99			-0.18
Weeks 9-14 (All buyers have two Envirofits)	Late	10.46	0.64	6.69	5.06	0.32	1.62	8.31			0.18

Note: Three stone fire wood usage per hour calculated during first kitchen performance test when no one owned an Envirofit. Envirofit wood usage per hour is calculated using the laboratory results shown in the Emission and Performance Report (Figure 2) because we do not have any periods in our experimental setting when households only had Envirofits.

Table 10
Particulate matter concentrations (μg/m^3) adjusted for Hawthorne effect

Study wave	Buyer type	Three stone fires (TSF) (hr/day)	TSF PM2.5 (μg/m^3 per hr)	PM2.5 by TSF (μg/m^3 per day)	Envirofits (ENV) (hr/day)	ENV PM2.5 (μg/m^3 per hr)	PM2.5 by ENV (μg/m^3 per day)	Total PM2.5 (μg/m^3 per day)	Diff-in-diff	% change	Change (pre-intervention to two ENVs)
Weeks -4 to 0 (Pre-intervention)	Early	9.64	32.95	317.64	0.00	16.08	0.00	317.64			
Weeks -4 to 0 (Pre-intervention)	Late	12.71	32.95	418.79	0.00	16.08	0.00	418.79			
Weeks 1-4 (Early buyers have one Envirofit)	Early	9.03	32.95	297.54	3.17	16.08	50.97	348.51	-48.54	-11.6%	
Weeks 1-4 (Early buyers have one Envirofit)	Late	15.12	32.95	498.20	0.00	16.08	0.00	498.20			
Weeks 5-8 (All buyers have one Envirofit)	Early	10.48	32.95	345.32	3.29	16.08	52.90	398.22			
Weeks 5-8 (All buyers have one Envirofit)	Late	10.7	32.95	352.57	2.94	16.08	47.28	399.84			
Weeks 9-14 (All buyers have two Envirofits)	Early	7.08	32.95	233.29	4.55	16.08	73.16	306.45			-11.19
Weeks 9-14 (All buyers have two Envirofits)	Late	10.46	32.95	344.66	5.06	16.08	81.36	426.02			7.23

Note: Three stone fire PM2.5 generated per hour calculated during first kitchen performance test when no one owned an Envirofit. Envirofit PM2.5 generated per hour is calculated using the laboratory results shown in the Emission and Performance Report (Figure 2) because we do not have any periods in our experimental setting when households only had Envirofits.

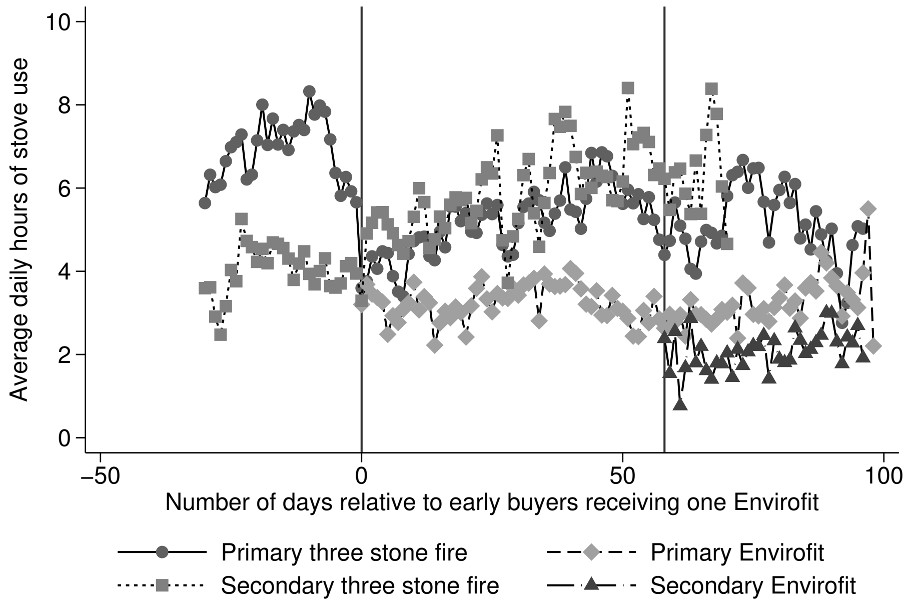
Table 11

Long term usage study: unannounced home visit 3.5 years after initial Envirofits delivered

	N	%
Someone home for unannounced long term usage study	137	
Actively cooking in moment when enumerators arrived	66	
-among those, cooking on three stone fire only	52	78.8%
-among those, cooking on Envirofit only	6	9.1%
-among those, cooking on other (mud/charcoal) stove	8	12.1%
Among all households not using Envirofit when enumerators arrived, enumerators asked to see primary Envirofit stove for signs of use	131	
-primary Envirofit with obvious signs of use	85	64.9%
-primary Envirofit stored and clearly not being used	22	16.8%
-primary Envirofit stored and in perfect condition (basically never used)	3	2.3%
-primary Envirofit damaged and disposed of	11	8.4%
-primary Envirofit given away (condition unknown)	10	7.6%
Among all households that stated they received two Envirofits, enumerators asked to see secondary Envirofit stove for signs of use	129	
-secondary Envirofit with obvious signs of use	32	24.8%
-secondary Envirofit stored and clearly not being used	14	10.9%
-secondary Envirofit stored and in perfect condition (basically never used)	12	9.3%
-secondary Envirofit damaged and disposed of	21	16.3%
-secondary Envirofit given away (condition unknown)	49	38.0%
Asked: "Do you still use the Envirofit stove?"	137	
-"I still use both Envirofits"	31	22.6%
-"I still use only one Envirofit"	69	50.4%
-"I have stopped using Envirofits"	37	27.0%
Asked: "If you bought a new stove today, would you purchase an Envirofit?"	137	
-Yes	108	78.8%
-No	21	15.3%
-Unsure or no response	8	5.8%

Figure A1

Daily stove use of early buyers



Note: Vertical lines designate when households received their first and second Envirofits.

Figure A2

Daily stove use of late buyers

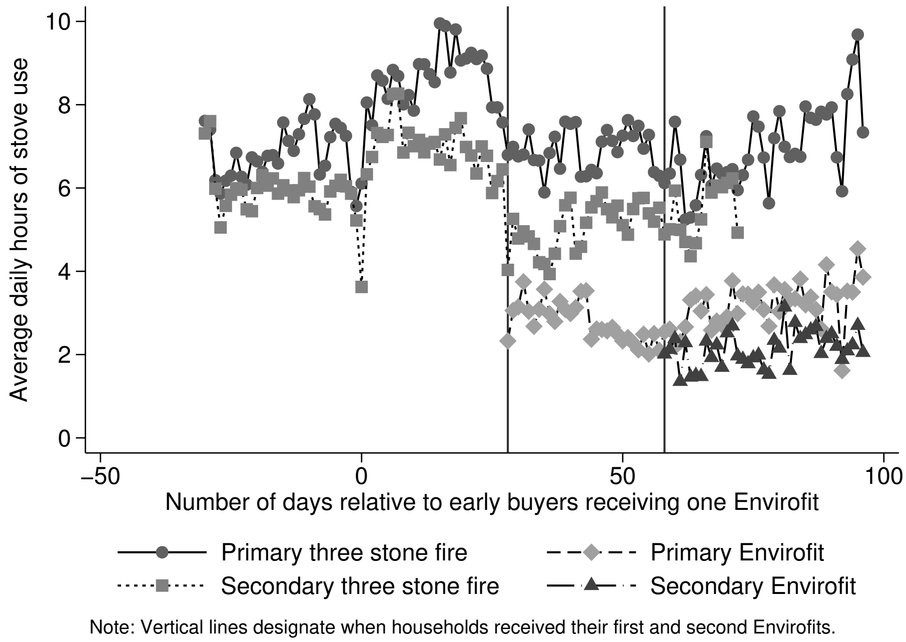


Figure A3

SUM holder designed to encase the stove use monitor to protect it from malfunctions when exceeding temperatures of 85 degrees Celsius

Figure A4

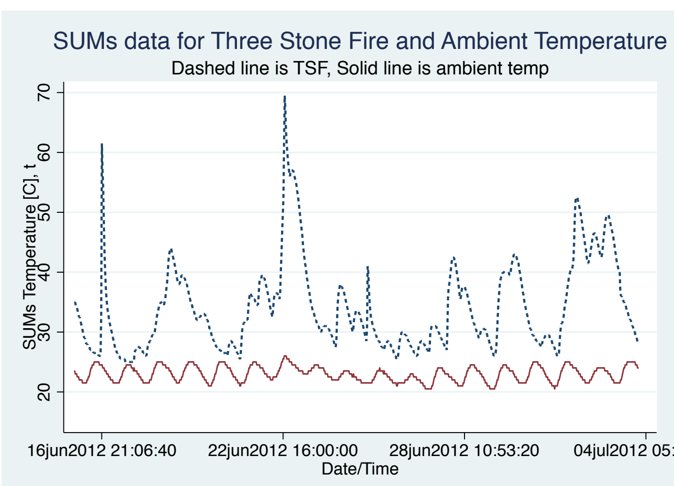
Arrows mark the placement of SUMs on three stone fire and Envirofit

(a) Three Stone Fire

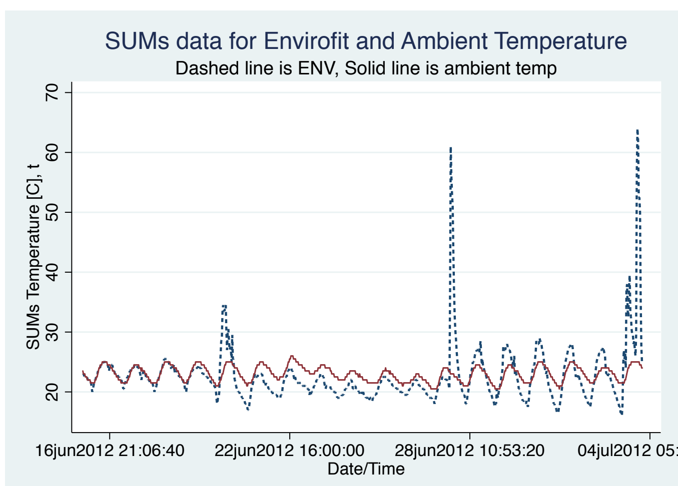
(b) Envirofit

Figure A5

Example of household level SUMs temperature data in same household at same times



(a) Three Stone Fire



(b) Envirofit