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Do Improved Biomass Cookstoves Reduce $PM_{2.5}$ Concentrations? ? If So, for Whom?

Empirical Evidence from Rural Ethiopia

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Abstract

Improved biomass cookstoves have been promoted as important intermediate technologies to reduce fuelwood consumption and possibly cut household air pollution in low-income countries. This study uses a randomized controlled trial to examine household air pollution reductions from an improved biomass cookstove promoted in rural Ethiopia, the Mirt improved cookstove. This stove is used to bake injera, which is very energy intensive and has a very particular cooking profile. In the overall sample, the Mirt improved cookstove leads to only minor reductions in mean household air pollution (10 percent on average). However, for those who bake injera in their main living areas, the Mirt improved cookstove reduces average mean household air pollution by 64 percent and median household air pollution by 78 percent—although the resulting household air pollution levels are still many times greater than the World Health Organization's guideline. These large percentage reductions may reflect decreased emissions due to less use of fuelwood, given Mirt's energy-efficient design, and the likelihood that higher-emissions three-stone cooking is moved outside the main living area once a Mirt improved cookstove is installed. Households in the subsample who experience a greater decline in household air pollution tend to be less wealthy and more remotely located and burn less-preferred biomass fuels, like agricultural waste and animal dung, than households that cook in a separate area.

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1. Introduction

Approximately 40% of the world, or almost 3 billion people, rely on solid fuels, such as coal, wood and charcoal for cooking (WHO, undated; IEA, 2017). This proportion is much higher (68% to over 90% of the population) in Sub-Saharan Africa and is expected to increase through 2030 (IEA 2017, Rehfuess et al., 2006; Smith et al., 2004). In Ethiopia, which is the focus of this paper, the percentage is about 90% (Beyene et al, 2015a), which is typical for low-income countries (WHO, undated). Particularly because of the human respiratory effects of burning solid fuels in homes, but also because of environmental effects (Masera et al., 2015), shifting households from biomass to commercial energy, such as gas and electricity, is a key goal. Such commercial fuels are used for cooking by about three-fifths of the world (Smith et al., 2013, IEA, 2012), but as of 2010, about 1.3 billion people did not have access to electricity, mainly in rural areas of developing countries (MacCarty et al., 2008; Jeuland and Pattanayak, 2012), and many more find commercial fuels too expensive or irregularly supplied to use for cooking and heating.

Reliance on biomass fuels is likely to continue for the foreseeable future in Sub-Saharan Africa and elsewhere in low and lower-middle income countries (IEA 2017). Cookstoves burning gas and electricity produce little or no household air pollution (HAP), but at present such technologies are very rarely used in rural areas of Ethiopia due to their high costs and insufficient access to electricity. Relatively simple improved cookstove (ICS) technologies that use less biomass and may require only minor changes in household cooking habits are therefore potentially important intermediate technologies (Jeuland and Pattanayak, 2012) if they are truly appropriate for users (Mobarak et al., 2012).

In this paper, we analyze the Mirt ("best" in Amharic language) ICS, which is promoted in Ethiopia, and used to make injera, which is a type of pancake or crepe made from teff, which is one of the main staple grains grown in Ethiopia. In areas without refrigeration, injera is generally baked at least twice per week. That cooking does not occur every day makes injera a rather unique product. It is also very energy intensive per cooking event and overall; injera baking is the end-use for approximately 50% of all primary energy consumed in the country (Bizzarri, 2010; Tesfay 2014).

Though not nearly as flexible or portable as the traditional technology, which is the three-stone tripod, the Mirt stove is more efficient than the traditional stove and has been estimated to use

50% less wood in laboratory tests (GIZ, 2011), 40% to 50% based on surveys (Megen Power, 2008; Dresen et al., 2014), and 20% to 30% less in field-based controlled cooking tests (Gebreegziabher et al., 2018). The Climate Resilient Green Economy strategy of the Federal Government of Ethiopia (FDRE, 2011) proposes to distribute ICS that will be used by about 20 million households by 2030. Reducing the demand for biomass by increasing fuel efficiency is indeed currently one of the strategic priorities in the Ethiopian energy sector (FDRE, 2014).

Our paper builds on previous work based on a randomized controlled trial rolled out in 2013 and examines the effects of the Mirt ICS promoted in Ethiopia on HAP in cooking areas, measured as 72-hour mean, median and maximum $PM_{2.5}$ concentrations. We also investigate the types of households that receive HAP benefits. In previous papers we have reported on satisfaction and per-meal fuelwood savings (Gebreegziabher et al., 2018), actual in-field usage (Beyene et al., 2015b), and learning (Bluffstone et al., 2017). This paper extends the analysis to HAP, using a cross-sectional randomized controlled trial (RCT) implemented in 2016.

We find average, maximum and median $PM_{2.5}$ concentrations that are very much in line with the literature (e.g. MacCracken and Smith, 1998; Chen et al., 2016), and several orders of magnitude greater than the WHO guideline concentration values. Our analysis suggests that the Mirt ICS on average has limited effects on HAP, with average of mean concentrations only 10% lower in households randomly assigned to receive a Mirt stove. Digging deeper, we echo findings of Langbein et al. (2017) that cooking location matters for ICS results. We find large reductions in HAP, including average mean reductions of 64% and median reductions of 78%, compared with those who did not receive Mirt stoves, for households that have their cooking/baking areas in their main houses;[1] for these households, adoption of the Mirt ICS may offer significant health benefits.

We analyze the characteristics of these households and find they tend to be poorer by several measures, live farther away from all-weather roads, and are more likely to cook with less preferred, smoky fuels like animal dung and agricultural wastes than households who have a separate cooking and baking area. Though our study design does not allow us to identify the reasons for the large percentage reductions in HAP due to Mirt use by households who cook/bake in their main living areas, they may reflect the decreased emissions made possible by greater stove energy-efficiency and

[1] Though many kitchen areas are distinct rooms for the purpose of cooking and baking, many households combine cooking/baking with living space in small houses. To avoid giving the impression that cooking/baking areas are always "kitchens" in the sense of separate rooms, we generally use the term "cooking/baking areas" rather than "kitchen."

reduced use of fuelwood, combined with the possibility that traditional three-stone cooking is moved out of the main living area once a Mirt stove is installed.

The paper is organized as follows. In the next section we present key literature. Section 3 discusses methods, including data collection, sampling and empirical methods. Section 4 presents results and section 5 discussion and conclusions.

2. Key Literature

Particulate matter (PM) is a general term for small solids and liquid droplets suspended in the atmosphere. In Africa, biomass fuel burning constitutes the major source of ambient PM (Karagulian et al. 2015). Particles with a diameter size between 2.5 and 10 μm ($PM_{2.5}$–PM_{10}) are considered coarse, and those with diameter 0.1 μm - 2.5 μm are fine and those with diameter less than 0.1 μm are considered ultra-fine particles (Anderson et al 2012). $PM_{2.5}$ constitutes 50–70% of PM_{10} in most locations in Europe (WHO-ROE, 2013). PM with a diameter greater than 10 μm have relatively short suspension half-lives and are largely filtered out by the nose and upper airway. As the largest health damages come from particles less that PM_{10}, much of the focus has been on fine and ultra-fine particles (Jeuland et al., 2015).

There is little question that HAP from solid fuel burning in homes around the world is a critical health hazard, especially for women and children (Smith et al., 2004). The important global burden of disease effort, focusing primarily on particulates for which the best evidence exists, argued that about 3.5 million premature deaths are caused each year by HAP due to the indoor combustion of solid fuels (Lim et al., 2013).[1] An additional 0.5 million deaths are attributable to the particle emissions emitted by homes into the outdoor environment, where they represent 16% of total outdoor concentrations (Smith et al., 2013). The WHO estimates that 4.3 million people annually die prematurely due to HAP-related respiratory illnesses, which is more than the 3.7 million total premature deaths attributable to ambient air pollution. All but 20,000 of these HAP-related deaths are in low and middle-income countries, with 580,000 in Africa (Jeuland et al., 2015; Martin et al., 2011; WHO, 2014).

In their 2017 meta-analysis, Achilleos et al. (2017) find a mean 0.89% increase in overall mortality, a 0.80% increase in cardiovascular deaths, and a 1.10% mean increase in respiratory

[1]Six percent of the global burden of disease is due to lower respiratory infections, which may be linked to HAP, which is second only to ischemic heart disease. In 2000 and 2011, lower respiratory infections were the primary cause of reduced health-related life satisfaction measured as disability adjusted life years (WHO, 2014, WHO, 2013).

mortality per 10 μg/m^3 increase in $PM_{2.5}$. They particularly implicate elemental carbon and potassium as critical elements of $PM_{2.5}$ leading to increased mortality. Salvi (2015) documents that chronic obstructive pulmonary disorder (COPD) is the third most important cause of mortality worldwide, that COPD incidence is very high in Sub-Saharan Africa, and women often spend 3 to 5 hours per day in smoky environments due to indoor cooking with biomass fuels. The author argues for additional attention to reducing the incidence of COPD in Sub-Saharan Africa.

The literature suggests that ICS, even if households continue to use biomass fuels, can reduce HAP. Quansah et al. (2017) conduct a systematic review of the literature and meta-analysis across a variety of interventions. Based on standardized mean difference measures, they find ICS has the largest effects for total particulate matter, with average reductions of 18% in daily average personal PM exposures, and larger effects for children. In their review of the literature, Pope et al. (2017) find large (39%) average effects of ICS on $PM_{2.5}$ even for improved biomass stoves without chimneys. In their extensive lab-in-field study conducted in rural Nepal, Ojo et al. (2015) also find large average reductions in $PM_{2.5}$ concentrations when biomass ICS are introduced. They identify very high baseline mean concentrations, typically exceeding 3,000 μg/m^{3}and reductions in HAP concentrations of 50% - 60% due to the two improved biomass cookstoves they evaluated.

We contribute to this literature on the effects of ICS on HAP using an RCT involving the Mirt stove, which started in Ethiopia in 2013 and continued until 2016. In this paper we focus on the effects on $PM_{2.5}$ concentrations of the intent to treat with the Mirt ICS. Health effects are investigated in related research (LaFave et al, 2018).

3. Methods

3.1 Experimental Design

In this section we present the experimental method we use to identify the effect of the Mirt ICS on HAP. The treatment is provision of the Mirt ICS to randomly-selected households in 36 villages across three regional states in Ethiopia. The control is not receiving the Mirt stove and using only the traditional stove, which is the three-stone tripod. We emphasize that in virtually all households who received the Mirt stove, households continue to actively use their traditional cookstove for non-injera cooking. This is because Mirt is highly specialized for cooking injera and the main burner is approximately 50 cm in diameter, which is much larger than for cooking other foods. It is therefore necessary to have a second stove to cook foods other than injera, such as stews

and coffee.[2] We also note that cooking injera, though occurring every 2-3 days, uses a majority of the fuelwood consumed by households, suggesting that improving the cooking of injera could lead to HAP improvements. The design of the stove is shown in Figures 1 and 2.

Figures

Figure 1

Mirt Stove with Injera Cooking

Source: ethiopiaethos.files.wordpress.com/2010/06/comp5.jpg

Figure 2

Cook pouring Injera batter on Mirt Stove

Source: energypedia.info/wiki/Baking_with_Improved_Ovens

In June-July 2013, 360 Mirt stoves were distributed to 360 rural households in Ethiopia. Households were randomly selected to receive the stove using stratified random sampling at the regional state level to be representative of the state population and forest cover. The three regional states are Amhara, Oromia and Southern Nations, Nationalities and Peoples Regional State, which contain approximately 70 percent of the Ethiopian land area and 80 percent of the population. Households in these regional states generally cook injera and the traditional technology is the three-stone tripod; the cuisines and baseline cooking technology are therefore similar across households.

A total of 10 stoves were distributed to 10 randomly selected households in each of 36 randomly selected villages.[3] As of November-December 2016, when data collection for this paper was conducted, 121 stoves were no longer in use. Approximately ¼ of these were in storage and all except one of the others were discarded, with virtually all abandoned due to breakage. This finding is not surprising, because the stove has an estimated five-year lifespan.

[2]The Mirt stove also has a second burner to cook stews and coffee, which can be used in conjunction with when injera is being cooked.

[3]Stoves were distributed under 3 different monetary treatments – given for free, pay a subsidized cost and paid if used regularly during first 6 weeks. We observed no differences in initial uptake across the monetary treatment arms (Beyene et al., 2015b), so we group all households distributed a Mirt stove in a single treatment for this paper.

At the same time as the initial stove disbursement in 2013, 4 control households were randomly selected in each village, for a total sample size of 504 households. Baseline demographic, socioeconomic and other data were collected from both treatment and control households in June-July 2013 and confirmed balance across the treatment and control groups. No baseline HAP measurements were collected and therefore we utilize a cross-sectional randomized study design to compare air pollution levels across households who randomly received a Mirt and those that did not.

In November-December 2016, 6 of the 14 households under study in each village were randomly selected for HAP monitoring. Three of the households in each village were treatment and three control, for a total sample size of 216. In the field research design, if a randomly selected household was given a Mirt stove that was subsequently abandoned, another household from the same village was randomly selected; only households currently with Mirt stoves in place (though perhaps not actively used) were compared to households that never received a Mirt stove.[4]

This sample size was chosen based on standard conventional power calculations in the HAP measurement literature (see Edwards et al., 2007). These standard conventions include achieving a statistical power of 0.80, a p value of 5% in two-tailed tests and detecting a 30% HAP reduction. A reliable, Ethiopia-based, estimate of the coefficient of variation in HAP reduction was not available prior to our study to compute the minimum sample size. We therefore used a conservative COV estimate of 0.7 (Edwards et al., 2007), which, given our cross-sectional study design, gave a minimum sample size of 86 households in each arm (total 172). Allowing for possible monitoring equipment failure, we utilized a sample size of 216 (108 in each arm). We collected valid data from over 95 percent of the target households, with missing data due to HAP monitoring equipment failures and a small number of households where all members were in the field for coffee harvest on the day of data collection. We note, though, that these failures were random across the treatment and control households and such issues were not unexpected. The sample size remains sufficient to achieve the standard level of power with a modest HAP reduction detection level.

Maximum, mean and median $PM_{2.5}$ levels were measured in the 204 households using Particle and Temperature Sensor Plus (PATS+) light-scattering particle sensors developed by Berkeley Air Monitoring Group of Berkeley, California. The PATS+ devices were in place in

[4]In the appendix we show that based on 23 observables the sample is balanced across those who were subject to HAP monitoring and those who were not monitored. The subsample of households who experienced HAP monitoring is therefore quite representative of our overall sample.

households' cooking/baking areas for 72 hours. Because households typically cook injera at least twice per week, all households should have baked injera during the 72-hour monitoring period.[5]

PATS+ results were calibrated using gravimetric filters co-located for exactly 24 hours in 50 of the sample households. Half of these households received Mirt stoves and half did not. Such calibration is necessary when using light scattering particle sensors (Berkeley Air Monitoring Group, 2017; Chow et al., 2002). Based on these findings, OLS regression was used to estimate an adjustment factor of 0.8065, which was applied to all PATS+ measurements. In gathering HAP information, field enumerators were instructed to follow strict protocols developed by Berkeley Air Monitoring Group. These protocols, which focus on placement of the equipment in cooking areas, maintenance of the equipment and timing of the samples, are included in the Appendix to this paper.

In addition to measuring mean, median and maximum $PM_{2.5}$ concentrations, the PATS+ monitors also measured humidity and temperature. Key data on cooking/baking area characteristics, including size, shape, presence of windows and location (in the main living area or separate), were collected as well as information on the status of Mirt stoves, including if they were broken or unused, and whether traditional stoves were still in place. We also collected updated information on fuels used.[6]

3.2 Empirical Methods

With sufficient sample size and a randomized intervention, if the randomization is successful across the treatment and control groups, we can simply compare sufficient statistics of those in the treatment and control groups to identify the treatment effect. To evaluate the quality of the randomization we compare households receiving Mirt stoves with those who did not receive stoves along 39 dimensions, with a special emphasis on cooking/baking area and environmental characteristics that are very likely to affect HAP concentrations. We also test for balance on smoking behaviors, socioeconomic characteristics, and cooking/eating frequency. We find that only one of the 39 variables is statistically different across the groups, a rate that is just as likely to be due to chance given a 5 percent significance threshold.

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[5]Only 2 households (<1%) report on average cooking injera less than twice per week.

[6]The research design allowed for the possibility that households cooked in two places in their homes (e.g. in main house and a separate kitchen), but no households had two kitchens. Two HAP-monitored households reported they did not use their Mirt stove and one had purchased a replacement.

In the following section we describe the sample, randomization balance checks and treatment effect estimates. We find only minor reductions in mean HAP due to Mirt in the overall sample, but significant differences in HAP depending on the location of baking injera, where the choices are in the main house or inside, but in a separate cooking/baking area.[7] We conduct a number of robustness checks, including running regressions, and conclude that for those who cook/bake in their main living areas, the Mirt stove reduces the average of mean HAP by 64% and median HAP by 78%. Finally, we examine the decision to cook/bake in main living areas using probit models. We find that variables consistent with poverty, isolation and less preferred fuels are most correlated with cooking/baking in households' primary residences.

4. Data and Estimation Results

4.1 Descriptive Statistics

The households in our sample mainly cook in separate, indoor cooking/baking areas, about half of which are round shaped and half that are rectangular. Very few cooking/baking areas have windows and whether or not a Mirt stove was provided in 2013, households continue to use three-stone tripods for cooking foods other than injera. About ¾ of all households cook and bake injera in cooking/baking areas that are separate from their main houses. Average kitchen size is larger for the ¼ of households who cook in their main houses, but those cooking/baking areas are multi-purpose. The average house only has 2.6 rooms and the average household has 9.3 adult equivalent members, so rooms in main houses are very unlikely to be completely dedicated to cooking.

Virtually all households use fuelwood, but substantial minorities also use smaller branches, dung and agricultural wastes; commercial fuels are rarely used and never for injera baking. About 55% of respondents are Ethiopian Orthodox and 25% are Muslim. The remainder are other Christian denominations. A total of 6.86% of households self-identify as female-headed. Means for treatment and control households are provided in the Appendix.

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[7] Only one household cooks/bakes outside in an uncovered location.

4.2 Randomization Balance Tests

As shown via balance tests in Appendix Table A2, the subsample of households who were subjected to HAP monitoring (n=204) are representative of the overall sample (n=504[8]). We test balance across treatment and control households using 39 variables for the subsample that had HAP monitoring. A total of 23 variables are from the baseline survey and 16 are from the endline survey. Though randomization occurred prior to the baseline, we add endline variables related to temperature, humidity, cooking/baking area floor area, other cooking area characteristics and cooking characteristics from 2016 that were not collected in 2013, because these variables may affect 2016 HAP measurements and are invariant to whether a household is in the treatment group.

We find that all 2016 variables are balanced across treatment and control subsamples, suggesting that HAP monitoring will yield an unbiased estimate of the effect of Mirt on HAP. From the 2013 baseline survey, only one variable – existence of metal roofs on main houses - is not balanced at the 5% significance level, which is a rate that is just as likely to be due to chance given the 5% significance threshold; though a majority of both treated and control households have metal rather than thatched roofs, treated houses are more likely to have metal roofs. All balance test results are presented in the Appendix.

4.3 Treatment Effects of the Mirt ICS on Household Air Pollution

Table 1 presents the basic findings from the HAP monitoring. As shown in Table 1, consistent with the literature (Ojo et al., 2015; Chen et al., 2016; MacKracken and Smith, 1998), the mean and maximum values are extremely high. The average of the mean concentrations across the sample is 1,231 $\mu g/m^3$. This figure is about 50 times the WHO (2015; 2006) 24-hour guideline of 25$\mu g/m^3$.[9] The average of the mean concentrations for households with Mirt stoves is slightly lower than for those who did not receive a Mirt stove and use only the traditional technology (1,162 $\mu g/m^3$versus 1,297 $\mu g/m^3$). The average of measured median $PM_{2.5}$ concentrations is 149.39$\mu g/m^3$, with Mirt stove households again a bit lower at 145.12$\mu g/m^3$.

[8]In the endline, when HAP monitoring was conducted, enumerators could not contact 23 households. Attrition was balanced across treatment and control arms of the study, and uncorrelated with household characteristics likely to determine HAP. In balance tests, samples sizes are therefore less than 504.

[9] We omit three observations that could be outliers, because the mean is over 19,000 $\mu g/m^3$ during the three-day monitoring period.

Table 1 Mean, Median and Maximum $PM_{2.5}$ Concentrations in Cooking/baking areas of Households who did and did not Receive Mirt Stoves in 2013

	Mean	Median	Maximum
Mirt, Generally with Traditional Too	1162.11 (1883.21) [98]	145.12 (789.81) [99]	45,465.21 (36,595.46) [98]
Traditional Only	1297.03 (1990.24) [103]	149.39 (710.42) [105]	49,649.25 (45,976.89) [105]

Standard deviations in parentheses and sample size in brackets. Though the stoves may not be used, all treated households have Mirt Stoves in place.

Consistent with other studies in similar environments, maximum concentrations are extremely high in areas where biomass is burned. The average of the maximum concentrations is 47,629 $\mu g/m^3$.[10] Households that received a Mirt stove have lower average maximum concentrations (45,465 $\mu g/m^3$ versus 49,649 $\mu g/m^3$).

In the overall sample statistics reported in Table 1, we do not find statistically significant evidence that the Mirt ICS reduces $PM_{2.5}$ concentrations (average mean, maximum and median). Using two-tailed t-tests that assume normality and allow for unequal variances and Kruskal-Wallis rank-sum χ^2 tests with ties that allow for non-normality, we do not find evidence of statistically significant differences.[11]

We next consider differences in the impact of the Mirt stove based on the location of the cooking environment, focusing on those who cook in their primary living areas. Approximately ¾ of households (n=151) in the sample have located their cooking/baking areas outside the main house where people generally live. All but one of these cooking/baking areas are indoors, though in a separate building. The remaining 53 households have cooking/baking areas located in the house where people live, so these areas serve many purposes besides cooking. There is no difference in treatment assignment depending on whether injera baking occurs in the main house or a separate cooking/baking area (i.e. Mirt stoves did not tend to be differentially installed in main houses or separate cooking/baking areas). We therefore do not conflate cooking location with our treatment effect. Results are available from the first author.

We test randomization across treatment and control subsamples, but now restrict our analysis to the subsample of households who cook in their main living areas, again using the 23

[10] We omit one observation that may be an outlier, because the measured maximum concentration was over 400,000 $\mu g/m^3$.

[11] Based on Shapiro-Wilk W tests for normality, we are able to reject normality at < 0.01 level.

variables collected in 2013 and the 16 variables from 2016 used to test overall balance. Out of 39 variables, no variables from 2016 were unbalanced and only three from 2013 were not balanced at the 5% level based on Kruskal-Wallis tests. Respondents with Mirt stoves were more likely in 2013 to have metal roofs (p-value = 0.0019), which is the same as the overall sample, are less likely to report being food secure over the previous year (p-value = 0.049), and are more likely to drink alcohol (p-value = 0.052).

We find significant effects of the Mirt stove on average $PM_{2.5}$ concentrations if households have their primary baking area in their main house, but not for households with separate cooking/baking areas. When cooking/baking is done in the main living areas, average mean concentrations of $PM_{2.5}$ are estimated to be 64% lower for those who have the Mirt ICS than households without Mirt stoves (592 $\mu g/m^3$ versus 1622$\mu g/m^3$, two-tailed t-test p value=0.03, Kruskal-Wallis rank sum test with ties prob $>\chi^2$=0.10).

There are no statistically significant differences in maximum concentrations, but in percentage terms, effects are very large if central tendency is measured at the median. We find that the average of the median $PM_{2.5}$ concentrations is less than ¼ of what they are in houses that do not have a Mirt stove (19 $\mu g/m^3$ versus 85 $\mu g/m^3$, Kruskal-Wallis rank sum test prob $>X^2$ =0.01). As the distributions of all three $PM_{2.5}$ concentration measures are skewed, medians may be considered better measures of central tendency than means. By this measure, the Mirt stove reduces $PM_{2.5}$ concentration by 78%, which is at the higher end of ICS interventions and may offer health benefits to those in baking areas (Quansah et al., 2017).

Table 2 Mean, Median and Maximum $PM_{2.5}$ Concentrations in Cooking/Baking Areas of Households who did and did not Receive Mirt Stoves in 2013 and who Bake and Cook in their Main House Rather than in a Separate Cooking/Baking Area

	Mean	Median	Maximum
Mirt, Generally with Traditional Too	595.85 (157.23) (21)	19.12 (9.25) (21)	45,579.62 (6828.47) (21)
Traditional Only	1622.93 (421.22) (32)	85.18 (48.77) (32)	43,796.72 (6828.47) (32)

Standard deviations and N in parentheses

It is important to emphasize that there are no statistically significant differences in average $PM_{2.5}$ concentrations when comparing our three concentration measures by cooking location only (main house versus separate cooking/baking area) rather than treatment vs. control assignment

(prob >χ^2 0.33 to 0.62). This suggests that the effect on HAP is not due to cooking location. Instead, the difference appears to be due to Mirt *conditioned on* cooking/baking area location. We also note that the sample size of those households who cook in their main houses (n=53), is not atypical for ICS studies and is sufficiently powered to detect a moderate HAP effect (e.g. see Edwards et al., 2007; Quansah et al., 2017; Balakrishnan et al., 2002; Grabow et al, 2013). To detect the observed 64% reduction in HAP with 80% power and estimated COV=0.7, we would need approximately 20 households in each arm compared to the 21 treatment and 32 control observations we have in this study.[12]

We next estimate a difference-in-difference type specification to test whether cooking location is indeed important for effectiveness of the Mirt stove. The dependent variable is mean $PM_{2.5}$ concentrations, and independent variables include dummies for whether a household received a Mirt stove, whether households cook/bake in the main house and these two variables interacted. The interaction term is our variable of interest and measures the additional change in mean $PM_{2.5}$ for those households who use the Mirt in the main house relative to those who use Mirt elsewhere. In a second model, we add an indicator for roof type, the one variable out of 39 that is unbalanced in the full sample. Robust standard errors are clustered at the Kebele (peasant association) level.

Table 3 reports the difference-in-difference regression results. Based on the coefficient of the interaction term, we find that cooking with Mirt in the main house is estimated to reduce average HAP concentrations by approximately 1,000$\mu g/m^3$, which is similar to the simple mean comparison estimate in Table 2. In both models, the coefficient estimate is significant at the 5% level. We therefore conclude that it is neither the Mirt stove nor baking in main houses alone that reduces HAP, but the two variables together that yield large effects.

[12]Of course, because by definition people live in their main houses, their choice of cooking location affects HAP exposures. This issue is addressed in a related paper by LaFave et al. (2018). We note that injera baking and cooking of other foods, such as stews, coffees and breads, can in principle take place in different locations. As discussed above, at baseline no household had two cooking areas. The 2013 reported locations of baking injera and cooking other foods are virtually perfectly correlated.

Table 3. OLS Regressions. Dependent Variable Mean HAP (μg/m^3)

	Model 1	Model 2
Mirt Stove (0/1)	166.405 (279.95)	259.812 (264.279)
Bakes in Main House (0/1)	472.787 (495.029)	69.300 (463.304)
Mirt Stove * Bakes in Main House (0/1)	**-1193.486**** **(529.668)**	**-1039.694**** **(508.99)**
Metal Roof on Main House (0/1)		**-1104.681*** **(602.294)**
Constant	1150.140	1456.082 (927.024)
N	201	201
R^2	0.019	0.044

Robust standard errors clustered at kebele level. Statistically significant estimates in bold. ***=significant at 1% level, **=significant at 5% level, *=significant at 10% level.

4.4 Characterizing Those Who Cook/Bake in Main Living Areas

We now characterize the approximately ¼ of sample households that bake and cook in their main living areas, where Mirt seems to significantly reduce $PM_{2.5}$ concentrations. We estimate probit regressions to explain the choice to cook and bake in the main house using a combination of variables collected at the time of the initial stove disbursement in 2013 and during the HAP monitoring in 2016. Marginal effects from the probit models are reported in Table 4. Column 1 estimates cooking location as a function of cooking/baking area characteristics. We add basic socioeconomic variables in Column 2. Column 3 then adds additional welfare proxies, such as cooking/baking and eating frequency and distance to an all-weather road, and the full model in Column 4 includes wealth variables, such as agricultural land area, livestock, number of rooms in main houses and roof material. We emphasize that we are not alleging causality, but only correlation to try to characterize the types of households and household circumstances that are closely related to the decision to cook in main houses and therefore potentially identify the types of households who might benefit from the Mirt stove.

Across specifications, we find that cooking/baking areas in main houses tend to have more area (p-value<0.01). This result is not surprising given that main living areas need to fulfill many functions along with cooking, such as sleeping, working and keeping warm, compared to separate areas where only cooking/baking takes place. As already noted, in the full sample, households have a mean of 2.6 rooms for an average of 9.3 adult equivalent household members, making it very unlikely that only cooking occurs in the main house cooking/baking area. Cooking/baking areas in

main houses have more windows and those that are circular in shape are less likely to be in main houses ($p<0.05$). Houses that are made of sticks and mud (>90%) in Model 4 are less likely to have a kitchen in the main house ($p<0.05$). Ethnic (Oromo, Amhara) and religious variables (e.g. Muslim) are correlated with cooking/baking in main houses.

It is also of interest that in several models those who have higher levels of variables representing more assets report cooking/baking in separate areas rather than in their main living quarters. Those who have metal rather than thatched roofs ($p<0.01$), more agricultural land ($p<0.10$) and livestock ($p<0.10$), and who have used a bank in the past year ($p<0.05$) are more likely to cook in separate cooking/baking areas. Households that live in more remote areas – farther away from all-weather roads – are more likely to cook and bake in their main houses ($p<0.01$). Larger households with more members are also less likely to cook in main houses in two of three models ($p<0.01$). Households with more members have more labor and offer a number of other benefits, including old-age insurance, which could suggest they are more resilient than smaller households.

With regard to cooking and eating behaviors, those who bake injera more frequently (a possible sign of well-being, because we also adjust for household size) are more likely to cook in separate cooking/baking areas ($p<0.10$). Finally, households who use less-preferred fuels like dung and agricultural wastes, which also tend to be smokier than fuelwood, are more likely to cook in their main living areas. This result especially seems to hold for agricultural wastes in Model 4 ($p<0.01$).

Table 4. Marginal Effects of Probit Regressions of the Decision to Locate Cooking/Baking areas in Main Houses

	Data Year	Model 1	Model 2	Model 3	Model 4
Kitchen floor area any shape (m^2)	2016	**0.014*** (0.009)**	**0.010*** (0.011)**	**0.010*** (0.011)**	**0.002** (0.022)**
Flat Ceiling in Kitchen (0/1)	2016	-0.12 (0.585)	-0.089 (0.562)	-0.108 (0.576)	-0.024 (0.574)
Number of windows in kitchen	2016	0.011 (0.258)	0.117 (0.314)	**0.146* (0.332)**	**0.062*** (0.382)**
Kitchen is a circle rather than rectangular shape	2016	**-0.23** (0.338)**	**-0.188** (0.305)**	**-0.215*** (0.308)**	**-0.029*** (0.675)**
Can see light through the walls of baking area (0/1)	2016	0.082 (0.220)	0.042 (0.268)	0.041 (0.307)	0.007 (0.655)

House is made of sticks and mud	2013	0.061 (0.679)	-0.056 (0.799)	-0.080 (0.870)	**-0.439**** **(0.867)**
Households size (adult equivalent)	2013		**-0.037***** **(0.041)**	**-0.039***** **(0.045)**	-0.003 (0.056)
Respondent is Oromo ethnic group (0/1)	2013		**-0.33***** **(0.588)**	**-0.374***** **(0.605)**	**-0.19***** **(0.663)**
Respondent is Amhara ethnic group (0/1)	2013		**-0.305***** **(0.491)**	**-0.314***** **(0.614)**	**-0.106***** **(0.832)**
Respondent used a bank in the past year (0/1)	2013		-0.057 (0.306)	-0.073 (0.327)	**-0.046**** **(0.701)**
Respondent is member of *equb* savings group (0/1)	2013		0.000009 (0.262)	0.035 (0.331)	0.041 (0.325)
Age of respondent (years)	2013		-0.001 (0.009)	-0.001 (0.009)	0.0002 (0.020)
Respondent is at least literate (0/1)	2013		-0.0.38 (0.200)	-0.058 (0.198)	-0.007 (0.363)
Respondent is a man (0/1)	2013		0.042 (0.445)	0.090 (0.461)	0.003 (0.497)
Ethiopian Orthodox (0/1)	2013		-0.129 (0.310)	**-0.221**** **(0.421)**	-0.006 (0.453)
Muslim (0/1)	2013		0.263 (0.612)	0.237 (0.584)	**0.406***** **(0.631)**
Uses dung for fuel (0/1)[13]	2016		**0.179*** **(0.370)**	**0.152*** **(0.355)**	0.032 (0.361)
Uses agricultural waste for fuel (0/1)	2016		0.014 (0.294)	0.046 (0.316)	**0.066***** **(0.312)**
Two-way walking distance to all-weather road (mins)	2013			**0.0009*** **(0.002)**	**0.0004***** **(0.003)**
Average times per day those over 10 years eat[14]	2016			-0.124 (0.357)	-0.020 (0.371)
Average times per day cooking occurs	2016			0.018 (0.138)	-0.008 (0.195)
Average times per week injera baking occurs	2016			**-0.011*** **(0.024)**	**-0.004*** **(0.038)**

[13]Fuelwood is not included, as virtually 100% of households use fuelwood.

[14]The frequencies at which younger people eat are available, but not reported, because 25% of the observations have no data.

Agricultural land area (ha.)	2013				**-0.018*** **(0.179)**
Livestock (tropical livestock units)	2013				**-0.006*** **(0.070)**
Roof of main house is made of metal (0/1)	2013				**-0.855***** **(0.917)**
Number of rooms in main house	2013				-0.012 (0.199)
Toilet in house (0/1)	2013				0.018 (0.480)
N		199	198	197	192
Prob > Wald X^2		0.000***	0.000***	0.000***	0.000***
Pseudo R^2		0.177	0.343	0.383	0.669
Log pseudo likelihood		-93.25	-74.32	-69.487	-35.718

Marginal effects reported. Robust standard errors (clustered at kebele level) of coefficient rather than marginal effect estimates reported as recommended by Greene (2008, p. 487). Statistically significant estimates in bold. ***=significant at 1% level, **=significant at 5% level, *=significant at 10% level.

5. Discussion and Conclusions

The use of biomass for cooking is expected to increase in Sub-Saharan Africa, at least until 2030. Improved biomass cookstoves have been promoted as an important intermediate technology to reduce fuelwood consumption (Gebreegziabher, 2018) and possibly indoor air pollution, while costing less than stove and fuel combinations involving electricity or LPG. We examine the Mirt improved biomass injera cookstove, because injera cooking is known to be very energy intensive, consuming about 50% of primary energy in Ethiopia.

Looking at mean, median and maximum $PM_{2.5}$ concentrations across households reveals $PM_{2.5}$ concentrations that are at extremely high levels compared to WHO standards, but consistent with the literature. On average across all households, the Mirt stove reduces HAP, but by only a very small amount that is unlikely to affect human health. However, while most of our sample households cook in separate cooking/baking areas, a substantial minority cook inside their primary living areas. We examine this distinction and find that Mirt has significant HAP effects within the subsample that cooks in main houses, with central tendency reductions in $PM_{2.5}$ concentrations in the 63% - 78% range. We emphasize that HAP concentrations are still many times the WHO guideline in these households, but households that cook inside their primary living areas who randomly received a Mirt stove have average mean and median concentrations that are substantially less than those who only have the traditional technology.

We run OLS regressions to explain $PM_{2.5}$ concentrations in terms of the interactions of variables, adjusting for the one variable out of 39 that is unbalanced across treatment and control subsamples. We find that so long as Mirt is located in a household where people cook and bake in their main living areas, mean average HAP is about 1,000 μg/m^3 lower than in houses without a Mirt stove; the Mirt stove therefore appears to have significant effects for those who combine their living and cooking/baking areas. As HAP reductions are well over 60%, Mirt may offer health benefits to those who cook in their main living areas. We also find that these households tend to be less wealthy, more remotely located and more likely to burn less-preferred, smokier biomass fuels like agricultural waste and animal dung than households that cook and bake in separate kitchen areas.

Examining the HAP reducing properties of a technology that substitutes for such an energy-intensive process could yield insights into successes and failures around the world. However, extrapolating to very different contexts should be done with caution, because injera baking has a very different cooking profile than many other foods cooked around the world. While other dishes may be cooked multiple times per day, injera is typically cooked 2-3 times per week. Though we have tried to show that our treatment and control households are balanced based on a variety of observables, we acknowledge that our cross-sectional study design does not allow us to completely rule out that exogenous factors affecting HAP do not confound our estimates.

Our study design does not allow us to identify the reasons for the large percentage reductions in HAP due to Mirt use by households who cook/bake in their main living areas. One explanation is the decreased emissions made possible by greater stove energy efficiency, but it may also be that households cooking in their main living area who adopt Mirt subsequently move their traditional three-stone cooking outside their main living areas. We did not measure footprint of houses (only cooking areas), but poorer households, who we find tend to cook/bake in main living areas, generally have smaller houses.[15] Adopting Mirt may therefore lead to easily-moved three-stone stoves being shifted out of main living areas into new, informal, covered cooking areas that did not exist in 2013. Such shifts would reduce indoor air pollution compared with the control households who still use only less-efficient three-stone stoves inside their main homes. If this explanation is correct, then of course the HAP becomes outdoor ambient air pollution, with all that implies. Even so, because the ambient air pollution is less concentrated and more subject to dispersion outdoors than inside, adopting Mirt may improve respiratory health.

[15] As shown in Table 4, number of rooms does not affect the probability of cooking/baking in the main living area. Adult equivalent household size per room also has no effect.

Mirt is considered a prestige product by many households in rural Ethiopia and we know from related research that it is overwhelmingly positively viewed by users (Gebregziabher, 2018). Faced with a choice whether to have Mirt or the traditional three-stone tripod stove in their main living areas, households with limited means and little space may choose Mirt. It is therefore possible that Mirt reduces HAP and perhaps improves respiratory health by forcing traditional, inefficient, but highly mobile traditional cooking technologies out of main living quarters. This possibility echoes key conclusions of Langbein et al. (2017) that researchers and policy makers must think broadly about what constitutes kitchens in low-income countries and remember that traditional cooking technologies are often extremely mobile.

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Appendix
Field Protocols for taking HAP Measurements

Berkeley UNIVERSITY OF CALIFORNIA

Placement and Retrieval of Devices – Personal Monitoring Households

Standard Operating Procedure

Placement and Retrieval of Devices – HAP-only Households

NOTES:
- The UCB and PATS+ should stay in a plastic bag until reaching the sampling destination
- Place the UCB-PATS and PATS+ **BEFORE** the setup of ay pumps
- Fill out sampling forms as necessary during placement and retrieval processes

Hanging KITCHEN AREA monitors
1. Ensure UCB and PATS+ are operating, zeroed, and ready to deploy.
2. Find a single spot to hang all monitors that is 1.0 meter from the edge of the main cooking stove and at least 1.0 meter away from windows and doors.
   - ***FOR SECOND SAMPLING ROUND:*** *place monitors in exact same location as first round*
3. At this location, hang the "UCB" 1.5 meters above the floor and 1.0 meter from the main cooking stove. Measure from the center of the UCB
   - ***FOR SECOND SAMPLING ROUND:*** *place UCB directly above the UCB push-pin on the right*
4. At same location, hang the "PATS+" so that the inlet is level with the center of the UCB
   - ***FOR SECOND SAMPLING ROUND:*** *place PATS+ directly above the PATS+ push-pin, to left of UCB*
5. To the left of the UCB, hang the pump bag 30-50cm below the UCB and PATS+
6. Position the cyclone to the left of the PATS+ so that the plastic cassette is level with the PATS+ inlet
   - ***FOR SECOND SAMPLING ROUND:*** *place cyclone directly above the cyclone push-pin, to left of PATS+*
7. Turn pump on. Using cyclone cap and rotameter, set pump flow to 1.5 Liters per minute
8. Place one colored pushpin each at the bottom of the PATS+, the UCB, and the cyclone.

Retrieving KITCHEN AREA Monitors
1. DO NOT REMOVE THE PUSH PINS
2. Place UCB and PATS+ together into a single plastic bag
3. At the office, place the monitors on a flat surface for at least 30 minutes for the post-sample zero calibration. 60 minutes is preferred.
4. Download all data.

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PATS+ Quick Reference

PURPOSE: The PATS+ is a semi-passive, battery-operated, light-scattering device for measuring particulate matter, developed by Berkeley Air Monitoring Group, the University of California-Berkeley, and EME Systems. The PATS+ also measures temperature and humidity.

I. Required Equipment

- PATS+ (includes particle sensor, temperature sensor and humidity sensor)
- PICA (Platform for Integrated Cookstove Assessment) software
- PC Computer (Windows 7 or 8) with latest .net framework installed
- USB micro cable
- Zeroing box
- SD card (included in PATS+)
- Paperclip or other item to press PATS+ button
- Supplies as needed for installing equipment

II. Programming the PATS+

- Check that your computer clock time is accurate (recommend syncing with time.nist.gov).
- Connect PATS+ device to the computer using USB micro cable (make sure the SD card is fully seated).
- Open **PICA** software and select the Launch page.
- Fill the data fields for reference notes. For example, 'the project title' or 'household ID'.
- Select the logging interval by clicking the up and down arrows (standard interval is 60 seconds) above the **'log interval'** option.
- Click the **'Sync Launch'** button.
- Disconnect the device from the computer. The PATS+ indictor LED will start flashing two red flashes to show it is in standby mode.

III. Zeroing the monitor

- Before the PATS+ starts sampling, it must be zero-particle environment for 10 minutes.
- At the sampling location, find a clean, safe area out of direct sunlight.
- Press and hold the PATS+ button until it changes from red to green and then release the button.
- Check that the PATS+ indicator LED is flashing orange (once per second) and place it in the box with the intake hole exposed. The orange indicator means that it is in the zeroing mode, which will last for 10 minutes.
- Repeat as quickly as possible for up to 4 PATS+ units (this is the maximum that will fit in a zero box).
- Close the box and pump 40 squeezes of air into the box using the squeeze pump.
- After 10 minutes (or when you see that the PATS+ lights are flashing green once every other second) open the box and check that the light is flashing green every two seconds. It is now in sampling mode.

IV. Installing and uninstalling the PATS+

- Install the PATS+ as required for the given sample.
    - In the case of the kitchen sample, it should be ~1.5 meters from the ground, 1.0 meter away from the stove's combustion zone, and at least 1.0 meter from open windows and doors (if possible). Make sure that the PATS+ is secure. The PATS+ should also not interfere with the participant's activities.
    - For personal sampling, put the PATS+ in the armband and explain to the participant that he or she can remove it when sleeping, bathing, or doing other activities for which it is not possible to wear the device. Fit the armband to the participant and show him or her how to adjust and remove it.
- Connect the PATS+ to a USB power bank if needed.
- Record placement and start time.

- At the end of the sampling period, remove the USB power bank if attached, then press the button and hold it until the LED changes from red to green, then release the button. The flashing orange LED every 3 seconds indicates that the **end zeroing period** has started, immediately put the device in the plastic bag for the **end zeroing period.**
- After the end zeroing period, the LED will start flashing **double red** and it can be taken out of the box.

V. Downloading Data

- Connect the device to the computer using USB micro cable.
- Open **PICA** software.
- Right click on the filename which you want to download from the **Pats+** page.
- You should see the graph and the **selected file details** updated.
- Then click on the **Data** tab, you should have the file you selected from the Pats+ page.
- To download the file, click the **'Save to Excel'** button.
- Select a location where you want to save the file.
- Then click the **'save'** button and the file will be saved at the selected location.
- Rename the file as needed.
- After each day of data is downloaded, turn the entire file into a zip file and email to the project manager.

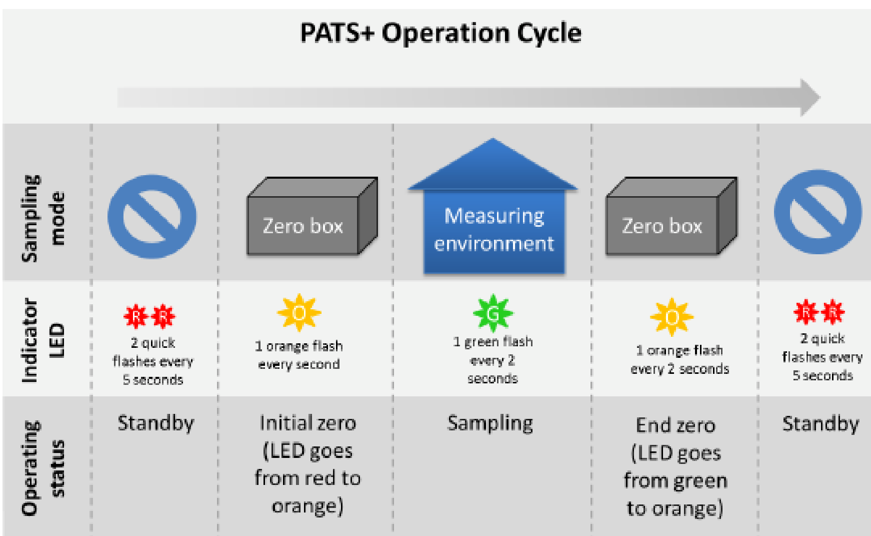
VI. Maintenance

- It takes approximately 2 hours to charge a fully depleted PATS+. When the PATS+ is fully charged, the battery light will go from bright blue to dim blue.
- If the baseline photoelectric signal increases over 100 mV, it is recommended to clean the PE chamber. In a clean environment, remove the enclosure by unscrewing the middle screw. Then unscrew the brace holding the photoelectric chamber and gently turn the chamber so the opening is available. Use the hand squeeze pump to clean the chamber. 40-50 pumps into the chamber at different angles are recommended.
- When not in use, store the PATS+ in plastic bags in a clean, dry location with the SD cards unseated.

PATS+ operation cycle

The diagram below shows the PATS+ operation cycle. Quick tips:

- To move between modes, the button must be pressed and held until a red light does one long flash followed by a long green flash. Release the button during the green flash.
- Make sure to check that the anticipated change in operating mode is indicated by the LED (red to orange for the initial zero period and green to orange for the final zero period).
- The cycle can be repeated as many times as desired (note that after 26 tests files are recorded, the PATS+ will beginning rolling over the oldest files).
- If the PATS+ is flashing red just once, then the button needs to be pressed and released – then it will be in standby mode.
- Removing the SD card switches the PATS+ to off.
- When the device is logging data, it will flash bright green once every 10 seconds during zeroing periods and then at the frequency for which the logging interval is set during the sampling period.
- If you hold down the button long enough for the red LED to flash three times, it will force the PATS+ to stop. This will end a sample and it will not be possible to get the data from that sample.
- When the PATS+ has a USB cord connecting it to a power pack or computer – it will think it should be communicating with PICA. This is not a problem once the PATS has starting sampling, but it will cause problem if you connect the power supply is connected when the button is pressed to start a zeroing period. Only connect a power supply when it is already in sampling mode.



Filter Shipping

Purpose:
To avoid particle loss by keeping filters a) as cold and b) as gently handled as possible during shipment.

Regarding Cold Temperatures:
Heat can cause particles to volatilize (turn from particle to gas) and be lost. For this reason, filters are ideally kept below 4°C during storage and transport, but can remain around 25°C for up to a total of 24 hours. Filters should thereby be shipped via "cold transport" or with as many cold packs as possible.

Regarding Gentle Handling:
Abrupt movement, dropping, tossing, and other rough handling of filter cassettes can cause particles to fall off of the filters and, possibly, be lost. For this reason, soft foam padding and/or other such measures should be used to ensure that cassettes are as protected from rough handling of transport packages as possible. Filters should also be labeled as "Fragile" and "Handle with Care". Cassettes should also be placed in their bags/boxes/packages with the blue plugs facing up. Then, their packages should be appropriately labeled "this side up" with arrows to indicate this to non-English speaking handlers.

Regarding Packaging
Cassettes should be kept in sealed plastic bags to be kept clean, wrapped in aluminum foil (if available) to avoid static, wrapped again in plastic bags to protect from condensation or water leaking from cold packs, and stored in an insulated container.

Chain of Custody
Keep track of the individual filters included in each package via an Excel list. Name this list "Filter Chain of Custody," and emailed to the Berkeley Air supervisor.

SUMS to track temperature
Launch a few SUMS and place them in the filter packages so that we can track the temperature of the shipments.

Example
1. Put filter cassettes into plastic bags (~ 9 to 12 will fit per small sandwich Ziplock)
2. Wrap one of these bags into one tinfoil "brick"
3. Place each brick in a plastic bag
    - As waterproof as possible… if no large ziplocks available, then wrap in several regular plastic bags and "seal" with duct tape.
4. Place ~ 4 plastic-bag-wrapped bricks into a **gray cooler bag with 2 cold packs,** vertically placed, one on each side. (NOTE: Do not pack too tightly, or the cold air will not circulate appropriately, leaving some filters warmer than others.)
5. Place filters in cooler bags in the Styrofoam cooler box so filters are facing up. Put padding around the cooler bags so they don't bounce around within the cooler box. Label the cooler box as "fragile" and an arrow indicating wich way is "up".
6. When ever in a hotel or long layover, store cooler bags or individual bricks in freezer when possible.

NOTE: if available, ship filters with "dry ice" (solid CO_2) or cold packs (instead of bags of ice) instead of tightly wrapped bags of ice.

1. Using the AirChek5000

Keypad Basics

✱ (star key)	Scrolls through parameters in user setup functions.
[▲▼] (up/down arrow keys)	Increase or decrease flow rate, timed run, and run delay time.

Key Sequences

[▲▼].	Press keys simultaneously. Toggles between Run and Hold and exits user setup functions.
✱ ▲ ▼ ✱	Security code to access user setup functions. With pump in a non-running state (no flashing blue LED), press keys in sequence.

Operation

· **Pump On**	Press and hold ✱
· **Pump Off**	Press and hold ✱ through countdown. Auto-off will shut down pump after 5 minutes without activity.
· **Mode Change**	Press [▲▼] to toggle between Run and Hold.
· **Keypad Lock**	Press ▼ 5 times **quickly** to activate. Press ▼ 5 times **quickly** to deactivate.
· **Run/Hold**	With pump in a non-running state (no flashing blue LED), Press [▲▼] to run pump. Press [▲▼] to Hold pump when completed.

Accessing User Setup Functions

· ***Entering User Setup Functions***

With pump in a non-running state (no flashing blue LED), press ✱ ▲ ▼ ✱

· ***Exiting User Setup Functions***

Press [▲▼]. Pump is ready. Press [▲▼] to run the pump or to start a run delay.

User Setup Functions

To navigate while in user setup functions, press ✱ until the desired function displays.

Function	When LCD Displays	UserAction	Result
Clear Accumulated Run Time *Function only available when accumulated run time exists.*	"CLr" and flashing "Hold"	Press [▲▼].	Clears run and run time and exits func- tions. Press [.AT] to run pump.
Adjust Flow Rate*	"---" and flashing "ADJ Flow"	Press ▲ or ▼ Press [▲▼] to exit functions.	Flow increases/ decreases. Press [.AT] to run pump.
Set Timed Run†	Flashing "Set Timed Run" and "min"	Press ▲ or ▼ Press [▲▼] to exit functions.	Minutes increase/ decrease. Press [.AT] to run pump.
Set Run Delay†	Flashing "Set Run Delay" and "min"	Press ▲ or ▼ Press [▲▼] to exit functions.	Minutes increase/ decrease. Press [.AT] to start run delay. Blue LED flashes. Pump starts after delay elapses.

* *Changing flow rate in user setup functions will not clear accumulated run time.*
† *Changing timed run and/or run delay settings in user setup functions will clear accumulated run time.*

2. Deployment

** Placement of the gravimetric sampler follows the same protocols as described in the UCB and PATS+ protocols. Refer to these protocols for placement heights and directions.*

2.1. Before departing the office, remove the plastic cassette cover and place on the cyclone.

2.2. Check cassette-cyclone seal with hand pump "Mity Vac". Place this inside a clean Ziploc bag for transport to the field. You will also need:
- Tygon tubing
- Charged SKC Airchek Pump
- Small screwdriver for adjusting flow
- Nails, hammer, string/wire for hanging the cyclone
- Insulated bag and foam (to make pump quieter)
- Calibration cap
- Rotameter
- Luer adaptors (to connect tubing to cyclone/cassette)

2.3. The pumps may take 4-6 hours to charge and should be left to charge overnight.

2.4. Set the sample duration for the pump to 3000 minutes. This is a little more than 48-hours (2 days).

2.5. Once in the home, hang the cyclone vertically (cassette on top, grit pot at bottom). Do not hang sideways or upside-down as this may influence the operation of the cyclone.

2.6. Use Tygon tubing to connect the pump to the cyclone, the cyclone to the calibration cap, and the calibration cap to the rotameter.

2.7. Adjust the flow rate to achieve a flow of 1.5 L/min. (Note: you may want to do this at the office with the "Defender" before you leave for the field. *IF YOU DO THIS*, use the same pump, cyclone, and filter that you will be deploying in-field. ***Then, upon arrival at the home, check the flow with the rotameter.*** If necessary, adjust flow to achieve 1.5 L/m).

2.8. Once the flow is set, remove the calibration cap and turn the pump off until you are ready to begin the sample.

2.9. Place a colored pin at the base of the cyclone (if second round of sampling, hang the cyclone with the base of the cyclone touching the pin from the previous sample).

2.10. Note the start time & date , flow rate, filter ID, and Pump ID on the sampling form.

2.11. When you leave the home, turn all pumps on and note this time as the start time of the pumps on the sample forms.

3. Midpoint Pump & Filter Replacement (Pump 1 Retrieval, Pump 2 Deployment)

3.1. After 24 hours from deployment of Pump 1, you will return to the household to replace Filter 1, and deploy Filter 2. (Note: you should bring a new, fully assembled cyclone-filter setup with you.)

3.2. Connect the calibration cap and rotameter to Filter 1 while it is still attached. Note the flow rate, filter ID, and Pump ID on the sampling form.

3.3. Pause the pump flow. Note both the time & date at which you paused the pump ("**end time**" and "**end date**"), and the **sample duration** shown the pump screen. If any errors occurred (e.g. flow fault, battery failure) note this on the form.

3.4. Remove Filter 1 and attach Filter 2 to the sampling train.

3.5. Check cassette-cyclone seal with hand pump "Mity Vac".

3.6. Un-pause the pump. Adjust the flowrate as necessary to achieve a flow of 1.5 L/min. Note the flow rate, filter ID, cyclone ID, and Pump ID on the sampling form.

3.7. Once the flow is set, remove the calibration cap and pause the pump until you are ready to begin the sample.

3.8. When you leave the home, turn all pumps on. Note this as the start time & date, current sample duration.

4. Collection (After 48 hour sample ends)

4.1. Measure the end flow rate and record the value on the form.

4.2. Pause the pump. Note both the time & date at which you stopped the pump and the sample duration on the pump screen. If any errors occurred (e.g. flow fault, battery failure) note this on the form as well as the sample duration that was achieved. Then, turn off the pump.

4.3. Remove the cyclone from the wall, replace the end-cap and stoppers to the cassette, and store in a Ziploc for transport (in a cooler with an icepack, if possible).

4.4. After returning to the office, remove the cassette from the cyclone, place the top onto the cassette (with end-cap) and place the cassette into the freezer bag and freezer for storage until transport back to UC Berkeley for post-weighing.

5. Cleaning

5.1. The cyclones should be cleaned after each use using 70% ethanol, q-tips, and kimpwipes.

5.2. Disassemble the cyclone into its three components and wipe thoroughly with a kimpwipe and ethanol.

5.3. Allow the components to dry before re-assembling

5.4. If tubing becomes dirty or brittle it should be disposed of and replaced.

6. Filter Storage and Transport

6.1. When not in use filters should be stored in Ziploc bags in the office freezer.

6.2. After sampling, filters should be stored and transported <u>facing upwards</u> (sample face pointing up) as to minimize sample loss during transport.

6.3. If possible, transport filters with ice packs VERY CAREFULLY WRAPPED to **not leak**.

Appendix Table A1: Balance Tests across Treated and Control Households

Variable	N	Mean of Treated	Mean of Control	Two-Tailed t-test p value (unequal σ^2)	Kruskal-Wallis Rank-Sum Test with ties p value
2013 Data					
Livestock in TLU	201	5.164	4.689	0.311	0.192
Households size (adult equivalent)	204	9.340	9.310	0.945	0.752
Number of children under 15 years	187	3.054	2.798	0.236	0.222
Respondent smoker in 2013 (0/1)	203	0.061	0.076	0.661	0.661
Ethiopian Orthodox religion (0/1)	204	0.576	0.514	0.361	0.380
Respondent is at least literate (0/1)	204	0.646	0.619	0.687	0.686
Muslim religion (0/1)	204	0.286	0.212	0.226	0.226
Respondent is a man (0/1)	204	0.899	0.943	0.250	0.245
Respondent is married (0/1)	204	0.942	0.039	0.917	0.966
Age of respondent (years)	204	42.94	42.95	0.964	0.930
House has metal roof (0/1)	204	0.828	0.619	0.001^{***}	0.001^{***}
Number of rooms in respondent's house	204	2.72	2.56	0.217	0.178
Respondent has toilet inside house (0/1)	204	0.909	0.923	0.706	0.705
Total household land (ha.)	204	1.87	1.73	0.517	0.614
If farmer, food produced is sufficient for year (0/1)	201	0.531	0.486	0.521	0.577
Respondent used a bank in the past year (0/1)	204	0.242	0.171	0.211	0.214
Respondent is a member of an *equb* mutual savings group (0/1)	203	0.112	0.086	0.530	0.527
Altitude of house above mean sea level (m)	203	2205.14	2220.99	0.772	0.908
Two-way walking distance to all-weather road in minutes	203	46.91	60.89	0.180	0.198
House is made of sticks and mud	203	0.970	0.962	0.761	0.760
Respondent drinks alcohol (0/1)	204	0.545	0.488	0.164	0.164
Respondent is Oromo ethnic group (0/1)	204	0.343	0.381	0.580	0.578
Respondent is Amhara ethnic group (0/1)	204	0.232	0.229	0.950	0.950
2016 Data					
Mean temperature (degrees C)	204	20.847	20.831	0.972	0.978
Mean % humidity	204	48.170	48.696	0.721	0.679
Kitchen is a circle rather than	204	0.556	0.657	0.139	0.138

rectangular shape					
Kitchen floor area any shape (m^2)	198	28.19	20.21	0.386	0.993
Number of windows in kitchen	201	0.203	0.194	0.897	0.623
Kitchen ceiling is flat rather than peaked (0/1)	203	0.051	0.086	0.328	0.331
Can see light through the walls of baking area (0/1)	202	0.778	0.825	0.401	0.399
There is a three-stone tripod in kitchen (0/1)	204	0.96	0.990	0.164	0.155
Bakes injera in main house (0/1)	201	0.212	0.305	0.132	0.133
Other household members smoked in 2016 (0/1)	204	0.071	0.067	0.894	0.894
Number of meals eaten per day by household members >= 10 years	204	2.94	2.91	0.603	0.608
Number of times cooked per day	204	2.404	2.438	0.782	0.785
Number of times injera baked per week	204	5.242	5.514	0.746	0.374
Uses fuelwood for baking injera	204	0.980	0.990	0.533	0.527
Uses animal dung for baking injera	204	0.444	0.438	0.928	0.928
Uses agricultural waste for baking injera	204	0.192	0.257	0.266	0.266

Appendix Table A2: Balance Tests across Households Subject to HAP monitoring and those not Monitored Baseline (2013) Data

Variable	**N**	**Mean of Treated**	**Mean of Control**	**Two-Tailed t-test p value (unequal σ^2)**	**Kruskal-Wallis Rank-Sum Test with ties p value**
Livestock in TLU	475	4.921	5.093	0.606	0.707
Households size (adult equivalent)	481	9.33	9.177	0.628	0.456
Number of children under 15 years	434	2.925	3.085	0.277	0.345
Respondent smoker in 2013 (0/1)	481	0.686	0.578	0.631	0.627
Ethiopian Orthodox religion (0/1)	481	0.544	0.502	0.360	0.359
Muslim religion (0/1)	481	0.250	0.318	0.102*	0.106
Respondent is at least literate (0/1)	481	0.632	0.599	0.462	0.462
Respondent is a man (0/1)	480	0.922	0.880	0.131	0.141
Respondent is married (0/1)	481	0.943	0.892	0.048**	0.058*
Age of respondent (years)	480	42.90	41.78	0.353	0.374

House has metal roof (0/1)	481	0.721	0.664	0.185	0.188
Number of rooms in respondent's house	481	2.64	2.59	0.526	0.543
Respondent has toilet inside house (0/1)	481	0.917	0.845	0.014***	0.019**
Total household land (ha.)	481	1.800	1.820	0.896	0.987
If farmer, food produced is sufficient for year (0/1)	477	0.507	0.442	0.159	0.158
Respondent used a bank in the past year (0/1)	481	0.206	0.238	0.398	0.400
Respondent is a member of an *equb*mutual savings group (0/1)	477	0.099	0.142	0.142	0.151
Altitude of house above mean sea level (m)	480	2213.26	2201.24	0.731	0.585
Two-way walking distance to all-weather road in minutes	480	54.07	69.01	0.084	0.895
House is made of sticks and mud	481	0.966	0.960	0.756	0.759
Respondent drinks alcohol (0/1)	204	0.495	0.512	0.705	0.704
Respondent is Oromo ethnic group (0/1)	204	0.363	0.404	0.354	0.355
Respondent is Amhara ethnic group (0/1)	204	0.230	0.256	0.513	0.514