Environmental Science & Technology

Article

pubs.acs.org/est

Use of Temperature Sensors to Determine Exclusivity of Improved Stove Use and Associated Household Air Pollution Reductions in Kenya

Matthew J. Lozier,*[,†,‡] Kanta Sircar,[‡] Bryan Christensen,[‡] Ajay Pillarisetti,[§] David Pennise,[§] Nigel Bruce,[∥] Debbi Stanistreet,[∥] Luke Naeher,[⊥] Tamara Pilishvili,[#] Jennifer Loo Farrar,[#] Michael Sage,[▽] Ronald Nyagol,[○] Justus Muoki,[§] Todd Wofchuck,[§] and Fuyuen Yip[‡]

[†]Epidemic Intelligence Service, Centers for Disease Control and Prevention, Atlanta, Georgia 30329-4027, United States

[‡]Air Pollution and Respiratory Health Branch, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Georgia 30329-4027, United States

[§]Berkeley Air Monitoring Group, Berkeley, California 94704, United States

[∥]Department of Public Health and Policy, Institute of Psychology, Health and Society, University of Liverpool, Liverpool L3 5DA, United Kingdom

[⊥]Department of Environmental Health Science, College of Public Health, University of Georgia, Athens, Georgia 30602, United States

[#]Respiratory Diseases Branch, National Center for Immunization and Respiratory Diseases, Centers for Disease Control and Prevention, Atlanta, Georgia 30329-4027, United States

[▽]National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Georgia, United States

[○]Nyando Integrated Child Health and Education Project, Safe Water and AIDS Project, Nairobi, Kenya

Supporting Information

ABSTRACT: Household air pollution (HAP) contributes to 3.5−4 million annual deaths globally. Recent interventions using improved cookstoves (ICS) to reduce HAP have incorporated temperature sensors as stove use monitors (SUMs) to assess stove use. We deployed SUMs in an effectiveness study of 6 ICSs in 45 Kenyan rural homes. Stove were installed sequentially for 2 weeks and kitchen air monitoring was conducted for 48 h during each 2-week period. We placed SUMs on the ICSs and traditional cookstoves (TCS), and the continuous temperature data were analyzed using an algorithm to examine the number of cooking events, days of exclusive use of ICS, and how stove use patterns affect HAP. Stacking, defined as using both a TCS and an ICS in the same day, occurred on 40% of the study days, and exclusive use of the ICS occurred on 25% of study days. When researchers were not present, ICS use declined, which can have implications for long-term stove adoption in these communities. Continued use of TCSs was also associated with higher HAP levels. SUMs are a valuable tool for characterizing stove use and provide additional information to interpret HAP levels measured during ICS intervention studies.

■ INTRODUCTION

Nearly 3 billion people worldwide use biomass (wood, crop residues, charcoal, or dung) or coal as fuel for cooking and heating,[1−3] primary contributors to household air pollution (HAP), which leads to between 3.5−4 million deaths annually.[4,5] The risk of poor health outcomes associated with HAP disproportionately affects women and young children because they spend more time in the home and near the stoves.[2]

The Global Alliance for Clean Cookstoves (GACC) has called for 100 million homes to adopt clean and efficient stoves and fuels by 2020.[6] To date, GACC estimates that more than 20 million clean cookstoves are in use worldwide.[6] Two key factors in the long term success of this goal are initial stove acceptance and sustained use.[7] While various improved stove technologies exist, not all are accepted in all cultural settings

Received: December 23, 2015
Revised: February 29, 2016
Accepted: March 8, 2016
Published: March 8, 2016

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571

worldwide, making HAP reduction and improved health outcomes difficult.

Since 2008, low-cost temperature loggers have been used as objective stove use monitors (SUMs) in a few field studies examining stove acceptance and sustained use. SUMs are placed on stoves and record temperatures at predetermined intervals between 1 and 255 min. Then, an algorithm is applied to the data to count the number of stove use events and their duration. In these studies, SUMs have been used to objectively evaluate one improved cookstove (ICS) in place of, or in conjunction with, traditional stoves. In Guatemala, SUMs were used to evaluate uptake of newly installed ICSs as well as long-term studies of ICS use.[8−10] However, these studies were carried out in a setting where one ICS design is widely accepted. A study in India used questionnaire data to assess stove uptake among multiple ICSs, demonstrating the importance of evaluating multiple ICSs before long-term health outcome studies are carried out.[11] To date, SUMs have not been used in short-term uptake studies to evaluate multiple ICSs.

It is important to measure stove use patterns after ICS installation so that reductions in carbon monoxide (CO) and particulate matter smaller than 2.5 μm ($PM_{2.5}$) (primary components of HAP) can be compared in homes with similar stove use patterns (i.e., exclusive ICS use or stove stacking—ICS and traditional cookstove [TCS] use).[12] In 2007, researchers called for ICS intervention studies to assess: (1) the degree to which the ICSs are actually used, and (2) the extent to which TCSs remain in use.[11,13,14]

In this study, we deployed SUMs to analyze stove use of six different ICSs in Kenya. SUMs were used concurrently with exposure assessment equipment, which allowed us to relate exclusive and multiple stove use patterns to changes in CO and $PM_{2.5}$ concentrations. The objectives of these analyses are to use SUMs data to assess ICS use, observe how frequent stove stacking with the TCS occurred, and assess how stove stacking affects $PM_{2.5}$ and CO concentrations.

■ METHODS

Study Design. We conducted a single-arm pre/post-intervention study between July 2012 and February 2013 to assess acceptability and performance of six ICSs in a setting of normal daily stove use. We used a crossover design to evaluate up to six ICSs in 45 households across 2 villages in Nyando District, Nyanza Province, rural Western Kenya. Inclusion criteria and household selection are described in detail elsewhere.[15] We installed the six ICSs sequentially in each home for 2 weeks and left the TCS in the home while encouraging participants to use only the ICS. In Kenya, the TCS is an open fire that uses three stones to hold the pot in place over the fire. We randomized the order in which the stoves were installed in each household. Each two-week intervention period ("round") was followed by a 1-week "washout" period during which only the TCS remained in the home. The six ICSs included: two electric fan-assisted gasifiers (Ecochula and Philips), two improved rockets (EcoZoom and Envirofit), a double pot rocket with chimney (Prakti), and a built-in mud rocket with thermal-powered fan (RTI TECA). More details about stove types and stove manufacturers are published elsewhere.[16] This study was reviewed and approved by the institutional review boards at the Centers for Disease Control and Prevention (CDC) and the Kenya Medical Research Institute (KEMRI).

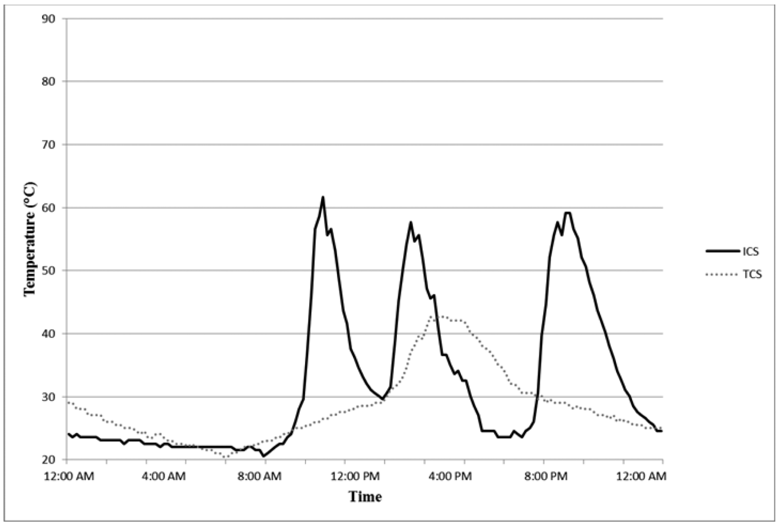
The Kenya Field Team conducted household air pollution monitoring of fine particulate matter, particles smaller than 2.5 μm ($PM_{2.5}$), and CO in the kitchen of each participating home. Detailed air pollution monitoring methods are published elsewhere.[16] Briefly, field research teams installed gravimetric (Casella Tuff Pro pump and BGI Triplex Cyclone with Pall 37 MM Teflo air sampling filters) and real-time devices (UCB-PATS) to measure $PM_{2.5}$, and direct-reading, sensor-based (GasBadge Pro) devices to measure CO. Devices were installed on day 12 of the two-week period and set to run for 48 h (air quality monitoring [AQM] period) and removed along with the ICS on day 14. During days 12 and 14, homes were visited by the field team and study participants were encouraged to only use the ICS. The field team conducted baseline 48-h HAP monitoring prior to the installation of the first ICS to establish baseline TCS use and air pollution concentrations.

Stove Use Monitoring System (SUMs). The field team deployed temperature-logging sensors (iButton model DS1922T, Maxim Integrated, U.S.A.) as SUMs to collect data on how often the stoves were "turned on" (i.e., lit).[10] The field team used heat-resistant tape to affix the sensors directly to the ICS, charcoal, kerosene, and sawdust stoves, while the sensors were affixed to the back of one of the stones for the TCS. A SUM was also placed onto the kitchen wall to measure ambient indoor temperature. The SUMs recorded the stove and kitchen temperature every 10 min for the duration of the study period. At the end of each 2-week period, field workers downloaded data from the SUMs using a "Touch and Hold Probe" connected to a USB to 1-Wire RJ11 adaptor (Maxim Integrated, San Jose, CA, U.S.A.). Stove usage files were saved onto a laptop and transferred to the field office. SUMs were reprogrammed after each download. We analyzed the resulting temperature profiles to determine the frequency of "cooking events" (i.e., number of times the stoves were lit) per day. SUMs data were not recorded during the one-week "washout" periods after one ICS was removed and before another ICS was installed.

Stove Usage Metrics and Algorithms. We sought to assess several key metrics using the SUMs data. We defined stacking as any day, from midnight to midnight, during which both the ICS and any other stove (e.g., TCS, charcoal, kerosene, or sawdust) were used at least once. In order to assess stacking, cooking events for each stove were counted using an algorithm and aggregated by household and day. The Kirk Smith research group and Berkeley Air Monitoring Group created multiple algorithms depending on stove type and the availability of ambient temperature data. The decision to pursue multiple algorithms based on stove type was mostly due to the difference in thermal inertia between ICSs and TCSs (Figure 1). High thermal inertia stoves such as the TCS tend to heat up and cool down slowly, creating less distinct temperature peaks (Figure 1). Conversely, many of the ICSs are smaller and made of metal, which caused them to heat up and cool down more quickly, creating sharper temperature peaks (Figure 1). The location and method for SUMs placement also introduced variability into the temperature data. Algorithms were based on published work but altered to suit local conditions and the various types of stoves evaluated in this study.[8,17]

When indoor ambient temperatures were available, a TCS cooking event was counted when the temperature recorded by the SUMs attached to the TCS, (1) exceeded the mean plus three times the standard deviation of the hourly indoor ambient temperature, and, (2) had a difference from the temperature recorded two points earlier of at least +1 °C. For ICSs, events were counted when the temperature recorded by the SUMs attached to the ICS, (1) exceeded the mean plus six times the standard deviation of the hourly indoor ambient temperature,

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571



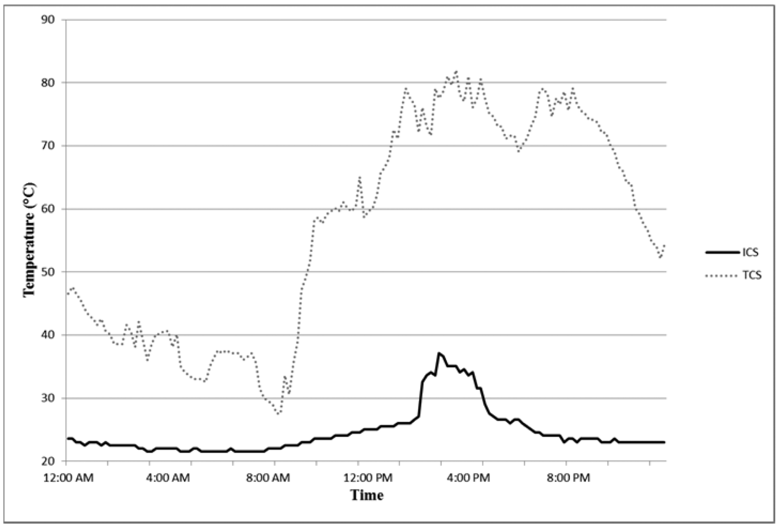


Figure 1. Stove temperatures recorded by stove use monitors (SUMs) with data from one home where cooking events were easier to count (A), and data from another home where cooking events were more difficult to clearly identify (B).

and, (2) had a difference from the temperature recorded two points earlier of at least +1 °C. The mean indoor ambient temperature was 25.4 °C (SD = 3.9; range 13.4–63.7).

When indoor ambient temperatures were not available due to SUMs malfunction or operational constraints, a TCS cooking event was noted as beginning when the temperature recorded by the SUMs differed by +1.5 °C from the recorded temperature two points (20 min) earlier. A similar algorithm was applied for ICSs using a difference threshold of +1.0 °C from the recorded temperature two points earlier. Events detected for any stove at a SUMs temperature of less than 30 °C were discarded because they were too close to indoor ambient temperatures to reliably be true cooking events.

To prevent overcounting, often due to activity in the combustion chamber, such as adding fuel or moving fuel, TCS events clustered within a 60 min time window were grouped and counted as one event. ICS cooking events were not grouped because they were more discrete in nature, making them more recognizable by the algorithm.

While six improved cookstoves were installed in each home, this analysis only covers five of those stoves. The RTI TECA rocket stove was removed from the analysis because it was a large, built in stove that displaced the TCS, making the assessment of stacking nearly impossible.

Time–Activity Logs and Qualitative Data Collection. We collected extensive behavioral data using questionnaires. Each household completed a time activity log (TAL) including self-reported data about each cooking event during the 48-h AQM period. Cooking events reported in the TAL were aggregated into counts by household and round. We used TAL data in this analysis, and other behavioral data regarding stove acceptability are published elsewhere.[18]

Missing Data. Where data were missing for all or one component (TCS or ICS), we were not able to assess stacking. Missing data arose partly from nonplacement of the TCS and wall SUMs during three rounds in one village due to operational constraints, and also (in about one-quarter of cases) due to lost or damaged SUMs, or SUMs malfunction (e.g., temperature not recorded, battery died, or error transferring data from SUMs to hand-held device). Using SUMs data from the six, two-week intervention rounds, we were able to assess stacking for at least 1 day during 96 (47%) household rounds, compared to 109

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564–4571

household rounds that had missing data. There were no significant demographic (income and household size) differences between these two groups.

Analysis of Stove Use: 2-Week Period. We analyzed data from different time periods to evaluate several outcomes (Figure 2). To describe cooking events over the six, two-week periods we calculated frequencies and proportions and stratified them by stove type and study day. We describe stove use in four ways: days only ICS was used (ICS Only), days only non-ICS stoves were used (Other Stove Only), days both an ICS and other stove were used (Stacking), and days when no stoves were used (No Cooking Events). We plotted the temperature profiles on the No Cooking Events day to visually evaluate the SUMs algorithms. We used global and individual χ^2 tests to compare differences in stove use patterns, and ANOVA to compare daily mean cooking events across stove types.

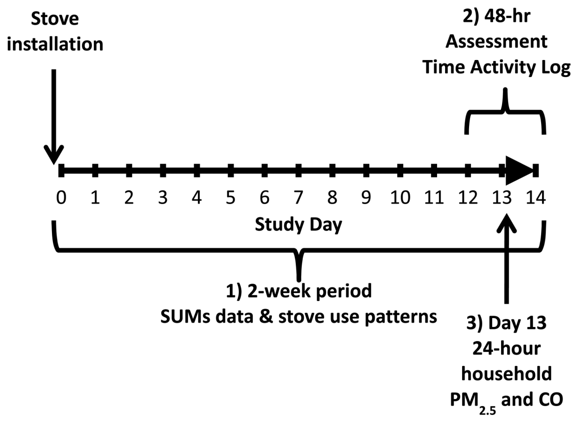


Figure 2. Detail of 2-week stove installation rounds showing data used for statistical analyses: (1) SUMSs data from entire 2-week period, (2) TAL from the 48-h period during the last 2 days of the 2-week period; and (3) $PM_{2.5}$ and CO 24-h average concentrations from day 13.

Comparison of SUMs and TAL: 48-h Period. We calculated Pearson's correlation coefficients to compare aggregate 48-h cooking events detected by SUMs to aggregate 48-h cooking events reported in the TAL during the 48-h AQM periods (Figure 2).

Analysis of HAP Based on Stacking: Day 13. We used ANOVA to compare geometric means of $PM_{2.5}$ and CO concentrations stratified by stove use patterns on day 13. Day 13 was the only day that had complete, 24-h data for both the exposure variable (SUMs cooking events) and the outcome variables ($PM_{2.5}$ and CO concentrations). All data were analyzed using SAS 9.3 (SAS Institute, Cary NC, U.S.A.) and Microsoft Office Excel 2010 (Microsoft Corp., Redmond, WA, U.S.A.). We considered $p < 0.05$ statistically significant, which is appropriate for the modest number of a priori defined comparisons.

RESULTS

Stove Use: 2-Week Period. Characteristics of the households participating in this study are presented elsewhere.[15] We had SUMs data from ICSs for 2007 household-days over six rounds and SUMs data from the TCSs for 1206 household days over six rounds and baseline. We had concurrent ICS and TCS SUMs data to assess stove stacking for 1098 household days (Table 1) across 44 households. Study days were determined by the algorithm to be categorized as ICS Only 25% (n = 278), Other Stove Only 27% (n = 293), Stacking 40% (n = 435), and, No Cooking Events 8% (n = 92). Stove use patterns varied significantly by stove-type ($p < 0.0001$). The proportion of Stacking days was the highest among Ecozoom (50%), Philips (45%) and Prakti (45%) stoves. Ecochula (38%) and Envirofit (33%) stoves had the highest proportion of ICS Only days compared to all other stove types. The proportion of Other Stove Only days ranged from 21% (Prakti) to 31% (Ecozoom). The stoves with the highest proportion of days during which the ICS was used at least once (ICS only + Stacking) were Prakti (133/190 = 70%) and Philips (149/216 = 69%), significantly higher than the proportion of days that the Ecochula was used (59%; p = 0.03 and p = 0.04, respectively; Table S1 in the Supporting Information).

During the baseline assessment, households averaged 2.4 (SD = 1.4) TCS cooking events per day (Table 2). Additionally, during baseline measurements, SUMs recorded an average of 0.8 cooking events per day on charcoal stoves and 0.3 average daily cooking events on kerosene, Upesi, and sawdust stoves combined. Presence of charcoal, kerosene, Upesi, and sawdust stoves in homes was much less common than TCS. Taking into account all stoves present in the homes, the average number of daily cooking events during the baseline was 2.7 (SD = 1.6), and increased significantly during the six intervention rounds to 3.1 (SD = 1.9) cooking events. The ICS with the highest mean cooking events per day was the Philips stove (mean = 1.9; [SD = 1.7]), followed by the Prakti stove (1.7 [1.5]). The Philips stove was used significantly more than the Envirofit (1.5 [1.4]), Ecochula (1.4 [1.5]), and Ecozoom (1.1 [1.2]) stoves. The Prakti stove was used significantly more than the Ecozoom stove. The TCS averaged 1.5 (SD = 1.4) cooking events when ICSs were present, significantly lower than baseline daily TCS cooking events ($p < 0.0001$). Charcoal stoves were used an average of 0.6 (SD = 1.1) times per day when ICSs where present and kerosene and Upesi stoves were rarely present and used infrequently.

While the average number of daily cooking events varied by stove type, aggregate daily ICS cooking events also changed

Table 1. Distribution of Daily Stove Use by Stove Type on Household-Days for Which Data from the Improved Cookstove and at Least One Other Stove Were Available during the Interventions Rounds (n = 1098 household-days)

	stove type					
daily stove usage	all ICS (n = 1098) n (%)	Ecochula (n = 133) n (%)	Ecozoom (n = 277) n (%)	Envirofit (n = 282) n (%)	Philips (n = 216) n (%)	Prakti (n = 190) n (%)
ICS Only	278 (25)	50 (38)	35 (13)[a]	94 (33)	52 (24)[a]	47 (25)[a]
Other Stove Only	293 (27)	38 (29)	87 (31)	74 (26)	55 (25)	39 (21)
Stacking (ICS + other stove)	435 (40)	28 (21)	139 (50)	85 (30)	97 (45)	86 (45)
No Cooking Events	92 (8)	17 (13)	16 (6)	29 (10)	12 (6)	18 (9)

[a] $p < 0.05$ by χ^2 for comparisons of ICS Only between stove type, with Ecochula as the reference stove because it has the highest proportion of ICS Only days.

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571

Table 2. Number of Cooking Events Per Household-Day by Stove Type[a]

stove type	# of household-days	mean cooking events per household-day (SD)	median	range (min−max)
baseline				
traditional cookstove	147	2.4 (1.4)	3	0−7
charcoal stove	44	0.8 (1.2)	0	0−4
kerosene/Upesi/sawdust combined	12	0.3 (0.7)	0	0−2
total daily cooking events	147	2.7 (1.6)	3	0−8
intervention rounds				
Ecochula[bc]	133	1.4 (1.5)	1	0−6
Ecozoom[c]	277	1.1 (1.2)	1	0−4
Envirofit[bc]	282	1.5 (1.4)	1	0−6
Philips[a]	216	1.9 (1.7)	2	0−7
Prakti[ab]	190	1.7 (1.5)	2	0−7
traditional cookstove	1018	1.5 (1.4)	1	0−8
charcoal stove	394	0.6 (1.1)	0	0−6
Kerosene/Upesi/Sawdust combined	63	0.1 (0.3)	0	0−1
total daily cooking events[b]	1098	3.1 (1.9)	3	0−12

[a]NOTE: Improved cookstoves with different superscript letters have significantly different mean cooking events per household-day based on Scheffe's test with $\alpha = 0.05$. [b]Total daily cooking events during intervention rounds was significantly higher than total daily cooking events during the baseline ($p < 0.05$).

across the two-week intervention period. Average daily ICS cooking events gradually decreased from 1.6 on day 0 (not necessarily the day the ICS was installed) to 1.0 on day 10 (Figure 3). On day 12, the average daily ICS cooking events jumped to 2.1, and remained above 2 average cooking events on days 13 (2.3) and 14 (2.0). When aggregated by AQM period (days 12−14) versus non-AQM period (days 0−11), average daily ICS cooking events was significantly higher during the AQM period (2.1 vs 1.4; $p < 0.0001$). The opposite effect was seen for the TCS, which had significantly higher average daily cooking events during the non-AQM period (1.6) compared to the AQM period (1.3; $p = 0.008$).

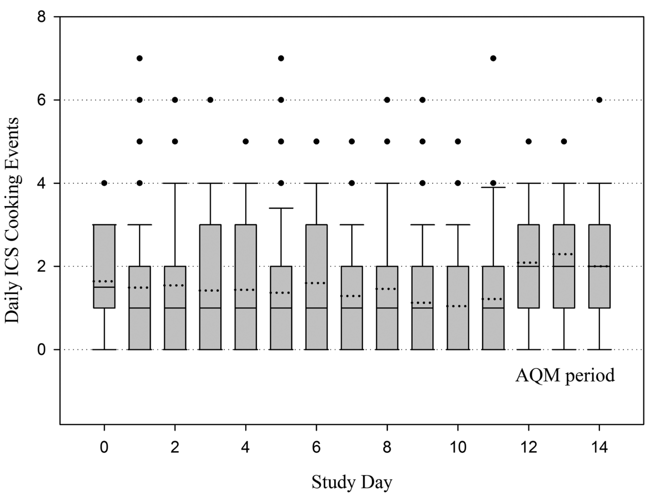


Figure 3. Daily average ICS cooking events by study day. NOTE: Dots above the box plots represent outliers; solid line within boxplot represents median; dotted line within boxplot represents mean. Data includes days for which data were available to assess stacking ($n = 1098$ household-days).

SUMs and TAL: 48-h Period. Total cooking events during the 48-h AQM period from all stoves recorded by the SUMs compared to those reported using the TAL had a correlation coefficient of 0.23 ($p = 0.07$). When dichotomized, 48-h cooking event counts for the TCS and ICS were significantly correlated between SUMs and TAL ($r = 0.42$, $p = 0.0015$; $r = 0.34$, $p = 0.0096$, respectively) (Figure 4).

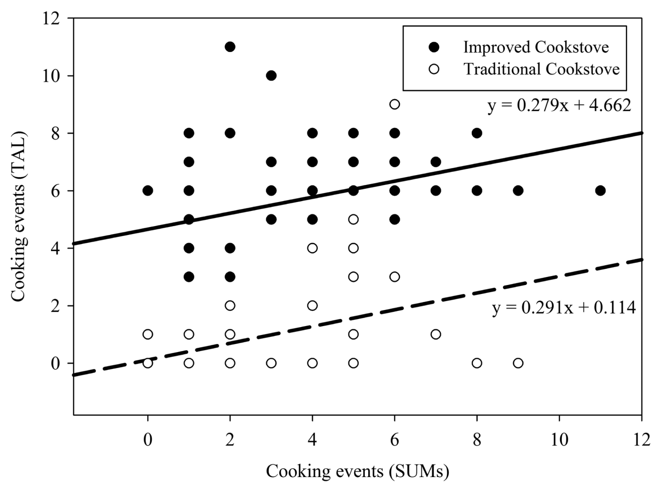


Figure 4. Scatter plots of 48-h cooking events for the TCS ($n = 54$) and ICS ($n = 58$) as recorded by stove use monitors (x-axis) and time activity log (y-axis).

Time Activity Log data indicated that there were 35 48-h periods for which study participants reported zero cooking events with the TCS. Of those, SUMs data showed zero cooking events with the TCS for 15 (43%) periods. For the other 20 periods, SUMs data indicated that the TCS was used an average of 3.2 times (SD = 2.2; range 1−9).

HAP Based on Stacking: Day 13. On the basis of SUMs data, Other Stove Only households on day 13 and during baseline had a significantly higher geometric mean $PM_{2.5}$ concentration (0.99 mg/m^3) than ICS Only households on day 13 (0.53 mg/m^3; $p = 0.004$) and Stacking households on day 13 (0.64 mg/m^3; $p = 0.02$) (Figure 5; see Table S2). Similarly, the geometric mean CO concentration among Other Stove Only households on day 13 (6.5 ppm) was significantly higher than CO concentration among ICS Only households on day 13 (3.1 ppm; $p = 0.005$), but not significantly higher than the mean CO concentration among Stacking households on day 13 (5.3 ppm).

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571

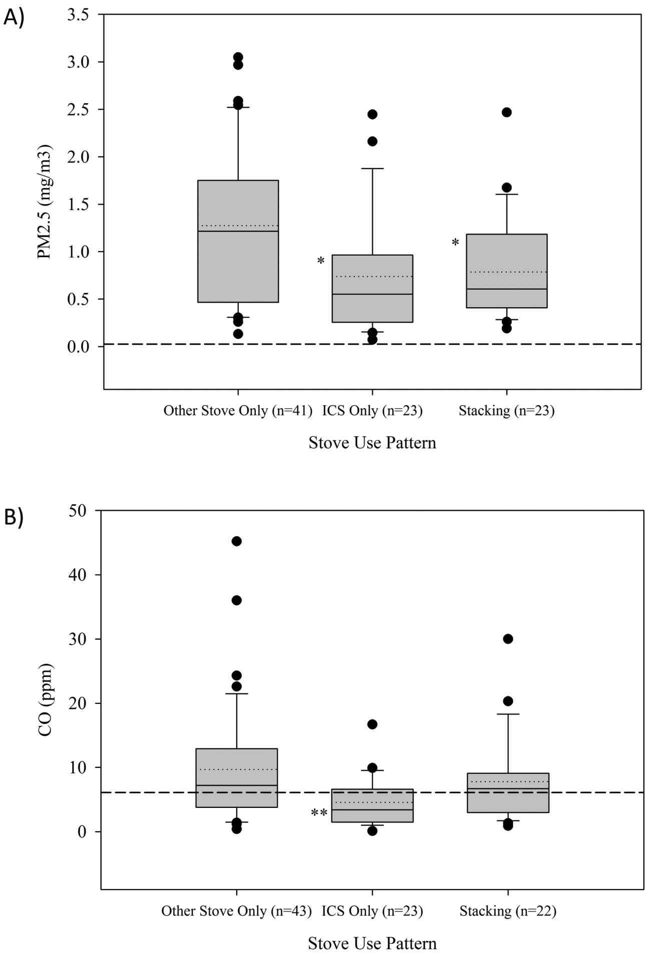


Figure 5. $PM_{2.5}$ (A) and CO (B) concentration distributions on day 13 stratified by stove use patterns. NOTE: Baseline data were included in "Other Stove Only" to increase sample size from $n = 6$ to $n = 44$. "ICS Only" = household-days when only the ICS was used; "Other Stove Only" = household-days when only the TCS, charcoal, or kerosene stoves were used; and "Stacking" = household-days when stacking occurred. The dotted lines represent (A): the 24-h WHO $PM_{2.5}$ air quality guideline value of 25 $\mu g/m^3$; and (B) the WHO 24 h CO Indoor Air Quality Guideline of 7 mg/m^3 (6.1 ppm based on standard conditions at 25 °C and 1 atm). *Geometric mean $PM_{2.5}$ concentration of ICS only and stacking is significantly lower than other stove only geometric mean concentration ($p < 0.05$). **Geometric mean CO concentration of ICS only is significantly lower than other stove only geometric mean concentration ($p < 0.05$).

■ DISCUSSION

This study presents objective stove use data from an ICS intervention study in Kenya. Analysis of SUMs data showed that while ICSs were used, they did not replace TCSs on most days and stove stacking occurred regularly. Stove use patterns varied by type of ICS, and we detected an observation effect when comparing stove use during the AQM period to the non-AQM period. SUMs data showed that $PM_{2.5}$ and CO concentrations were significantly lower on days when only ICSs were used compared to days when only TCSs were used, and slightly lower on days when stacking occurred.

In an ICS intervention pilot study in Guatemala, researchers found that ICS use increased rapidly and then leveled off.[10] The average daily hours of ICS use increased from 2 to 11 hours during the first week and then leveled off during days eight to 19, fluctuating between 10 and 12 h.[10] While the Guatemala study used a different stove use metric (daily hours of ICS use), the trend is different than that observed in our Kenya study where we saw decreasing stove use during days 0 to 11. Factors that may explain these differences could be, (1) six ICSs used in Kenya compared to one in Guatemala, and (2) the newness of ICSs in Kenya, whereas in Guatemala the ICS design is well-known, desirable, and particularly well-suited to the local cuisine and habits.[19]

In an ICS intervention study in India, researchers used SUMs to evaluate ICS use for more than one year.[13] Overall daily stove use was lower among participants in India compared to participants in our study in Kenya. However, both studies saw a decrease in TCS use from preintervention baseline to when the ICS was present.[13]

The implications of our results are important for understanding stove use and performance during ICS interventions. Our effectiveness study was designed to give the best indication of change in household air pollution concentrations in a real world setting.[14] Therefore, household concentrations of $PM_{2.5}$ and CO from our study reflect the real changes in HAP. The significant reduction of HAP on days when only ICSs were used provides some indication of the potential reduction of HAP that full ICS adoption could achieve. While useful in that regard, exclusive ICS use occurred on only 25% of the study days.

Despite the significant reduction in HAP, $PM_{2.5}$ concentrations on ICS only days (0.53 mg/m^3 = 530 $\mu g/m^3$) were about 20 times higher than the 24-h WHO $PM_{2.5}$ air quality guideline value of 25 $\mu g/m^3$.[20] Carbon monoxide concentrations on ICS only days (3.1 ppm) were below the WHO 24 h CO Indoor Air Quality Guideline of 7 mg/m^3 (6.1 ppm based on standard conditions at 25 °C and 1 atm).[21] Detailed results presenting household air pollution and personal monitoring and their correlation are published elsewhere.[16]

Other factors relevant to the use and adoption of ICSs may go beyond simply cooking food efficiently. A mixed methods case study analysis from this Kenya study found the widely held view that traditional foods are better cooked on the TCS.[22] Additionally, many women viewed the ICS as a technology to add to the existing stove, rather than a replacement. Studies in Guatemala and Mexico showed that stove and fuel stacking typically occur where participants perform a cooking practice on the stove best suited for that particular practice.[7,23] Also, the TCS could have been used as a source of heat and light, and as a social gathering point for families, as shown in a Guatemala study.[24]

SUMs data from an ICS intervention study in Bangladesh showed an observation effect similar to this study.[25] Among intervention households, daily ICS use dropped from between 2.1 and 3.3 uses per day (depending on stove-type) to less than one use per day when field teams stopped visiting homes daily.[25] The observation effect has important implications for interpreting results; HAP exposure reductions measured during periods when researchers (observers) visit participant homes frequently may not truly represent HAP exposure reductions over the long-term outside of a research setting. Additionally, we may have seen an observation effect between day 0 and day 12 caused by the presence of SUMs on the stoves. However, it is difficult to tease this out because there was no comparison group that did not have SUMs in place and because each stove was installed for 2 weeks.

It was necessary to modify existing stove-use algorithms to the available data and the local conditions of this study.[8,13] While modifying SUMs algorithms to meet the objectives of a specific study is necessary, it could be beneficial to share validated

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571

algorithms with researchers to expand the integration of SUMs into improved cookstove intervention research.

This study has several limitations. Because of the short-term nature of this study and frequent visits by field staff to participating households, results may not be generalizable. A long-term exposure assessment study with SUMs that evaluates the effectiveness of the top one or two performing stoves from this study is necessary to fully understand stove use and HAP reduction. Missing data arose from nonplacement of the TCS and wall SUMs during three rounds in one village due to operational constraints and lost or malfunctioning SUMs. While the algorithm was adapted to account for missing household ambient temperature, it is possible that an increased temperature signal from the ICS could have also been picked up by the TCS SUMs and recorded as a cooking event by both stoves, resulting in overestimation of cooking events and misclassification of stacking. The TCS algorithm may have under-counted cooking events by grouping events that were actually separate. Future studies could include a more in-depth evaluation of cooking behavior before and after ICS installation to understand better the most appropriate way to cluster cooking events for both TCSs and ICSs. While algorithms were modified to improve performance, using different algorithms for different stoves may have introduced misclassification. The substantial amount of time and resources necessary to clean data and modify and create new algorithms makes application of this technology inaccessible for some smaller studies. However, it is expected that a better understanding of SUMs placement and algorithms derived from this research will lead to algorithms that can be more widely applied in the future. Placing SUMs on the three-stone TCS was difficult, and placement may have changed during the two-week periods when the stove was cleaned and stones were moved, occasionally resulting in low quality data. It is necessary to develop a better performing method of SUMs placement on TCSs for future application of SUMs in larger, long-term studies. The algorithm reported 8% of the days had no cooking events. However, manual examination of temperature profiles showed that cooking did take place on those days, indicating that the algorithm missed cooking events. SUMs could have been removed from stoves, resulting in under-reporting of cooking events. However, three visits to each household during each round and detection of relatively few days with no cooking events makes this unlikely. Responses given during the completion of the TAL could have been influenced by social desirability response bias,[26] which may have caused differential misclassification in the number of TCS and ICS events recorded by the TAL. Also, in the qualitative interviews women reported that on some days they cooked outside on the TCS and these events would not have been monitored by SUMs, but could have contributed to HAP and personal exposure. Lastly, kerosene lamps were used in many of the homes and likely contributed to HAP. However, there is no reason to suggest there is a relationship between the type of ICS and kerosene lamp use, so the effect would likely have been random.

While SUMs have limitations, they continue to be a valuable tool for assessing stove use in ICS interventions. SUMs are an inexpensive way to assess stove use and have the potential to reduce the observation effect by monitoring stove-use over longer periods when researchers are not present in homes or communities. In the future, SUMs data can be integrated with qualitative, behavioral data from this study to fully understand stove use patterns and stove acceptability.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b06141.

Additional tables showing the proportion of days the ICSs were used at least once, stratified by ICS; and the distribution of $PM_{2.5}$ and CO concentrations stratified by stove use patterns (PDF)

AUTHOR INFORMATION

Corresponding Author

*Phone: (770) 488-0794; fax: (770) 488-1540; e-mail: mlozier@cdc.gov (M.J.L.).

Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare the following competing financial interest(s): David Pennise is employed by and co-owner and co-founder of Berkeley Air Monitoring Group, a mission-based, for-profit consulting company that provides scientific field testing and monitoring services to the household energy sector, including the sale of SUMs and air pollution monitoring devices. M.S. works as a consultant for M&E Sage, LLC, a consulting company that provides services in global public health programs and evaluation.

ACKNOWLEDGMENTS

The study was funded by the U.S. Centers for Disease Control and Prevention (CDC), World Health Organization (WHO), and Global Alliance for Clean Cookstoves. The authors would like to thank the following groups; Public Health Institute (PHI) for their partnership; the Safe Water Aids Project (SWAP) and Berkeley Air Monitoring Group for their tremendous efforts in data collection, data management, and field study management; and the U.S. Environmental Protection Agency (EPA) for laboratory testing support. Preliminary descriptive data from this manuscript was presented at the 2014 International Society for Exposure Science conference.

REFERENCES

(1) Clark, M. L.; Peel, J. L.; Balakrishnan, K.; Breysse, P. N.; Chillrud, S. N.; Naeher, L. P.; Rodes, C. E.; Vette, A. F.; Balbus, J. M. Health and household air pollution from solid fuel use: the need for improved exposure assessment. *Environ. Health Perspect.* **2013**, *121* (10), 1120−8.

(2) Martin, W. J., 2nd; Glass, R. I.; Balbus, J. M.; Collins, F. S. A major environmental cause of death. *Science* **2011**, *334* (6053), 180−1.

(3) Bonjour, S.; Adair-Rohani, H.; Wolf, J.; Bruce, N. G.; Mehta, S.; Pruss-Ustun, A.; Lahiff, M.; Rehfuess, E. A.; Mishra, V.; Smith, K. R. Solid fuel use for household cooking: country and regional estimates for 1980−2010. *Environ. Health Perspect.* **2013**, *121* (7), 784−90.

(4) Lim, S. S.; Vos, T.; Flaxman, A. D.; Danaei, G.; Shibuya, K.; Adair-Rohani, H.; Amann, M.; Anderson, H. R.; Andrews, K. G.; Aryee, M.; et al. 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* **2012**, *380*, 2224−2260.

(5) Smith, K. R.; Bruce, N.; Balakrishnan, K.; Adair-Rohani, H.; Balmes, J.; Chafe, Z.; Dherani, M.; Hosgood, H. D.; Mehta, S.; Pope, D.; Rehfuess, E.; Group, H. C. R. E. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annu. Rev. Public Health* **2014**, *35*, 185−206.

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571

(6) GACC, G. A. f. C. C. Global Alliance for Clean Cookstoves. http://cleancookstoves.org/about/our-mission/index.html (March 9, 2015),.
(7) Ruiz-Mercado, I.; Masera, O.; Zamora, H.; Smith, K. R. Adoption and sustained use of improved cookstoves. *Energy Policy* **2011**, *39* (12), 7557−7566.
(8) Ruiz-Mercado, I.; Canuz, E.; Smith, K. R. Temperature dataloggers as stove use monitors (SUMs): Field methods and signal analysis. *Biomass Bioenergy* **2012**, *47*, 459−468.
(9) Ruiz-Mercado, I.; Canuz, E.; Walker, J. L.; Smith, K. R. Quantitative metrics of stove adoption using Stove Use Monitors (SUMs). *Biomass Bioenergy* **2013**, *57*, 136−148.
(10) Ruiz-Mercado, I.; Lam, N. L.; Canuz, E.; Davila, G.; Smith, K. R. Low-cost temperature loggers as stove use monitors (SUMs). *Boiling Point* **2008**, *55*, 16−18.
(11) Sambandam, S.; Balakrishnan, K.; Ghosh, S.; Sadasivam, A.; Madhav, S.; Ramasamy, R.; Samanta, M.; Mukhopadhyay, K.; Rehman, H.; Ramanathan, V. Can currently available advanced combustion biomass cook-stoves provide health relevant exposure reductions? Results from initial assessment of select commercial models in India. *Ecohealth* **2015**, *12* (1), 25−41.
(12) Edwards, R.; Hubbard, A.; Khalakdina, A.; Pennise, D.; Smith, K. Design considerations for field studies of changes in indoor air pollution due to improved stoves. *Energy Sustainable Dev.* **2007**, *11* (2), 71−81.
(13) Pillarisetti, A.; Vaswani, M.; Jack, D.; Balakrishnan, K.; Bates, M. N.; Arora, N. K.; Smith, K. R. Patterns of Stove Usage after Introduction of an Advanced Cookstove: The Long-Term Application of Household Sensors. *Environ. Sci. Technol.* **2014**, *48* (24), 14525−14533.
(14) Smith, K. R.; Dutta, K.; Chengappa, C.; Gusain, P. P. S.; Masera, O.; Berrueta, V.; Edwards, R.; Bailis, B.; Shields, K. N. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project. *Energy Sustainable Dev.* **2007**, *11* (2), 5−18.
(15) Pilishvili, T.; Loo, J. D.; Schrag, S.; Stanistreet, D.; Christensen, B. C.; Yip, F.; Sadumah, I.; Nyagol, R.; Sage, M.; Bruce, N.Effectiveness of six improved cookstoves in reducing household air pollution and their acceptability in rural Western Kenya. *PLoS One***2016**, Under review
(16) Yip, F.; Christensen, B. C.; Sircar, K.; Naeher, L.; Bruce, N.; Pennise, D.; Lozier, M.; Pilishvili, T.; Loo, J.; Stanistreet, D.; Nyagol, R.; Muoki, J.; de Beer, L.; Sage, M.; Kapil, V. Characterization of Indoor and Personal Exposures to Traditional and Improved Stoves in Rural Western Kenya, 2012−2013. Submitted to *Environ. Int.* **2016**.
(17) Mukhopadhyay, R.; Sambandam, S.; Pillarisetti, A.; Jack, D.; Mukhopadhyay, K.; Balakrishnan, K.; Vaswani, M.; Bates, M. N.; Kinney, P. L.; Arora, N.; Smith, K. R. Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: an exploratory study to inform large-scale interventions. *Global health action* **2012**, *5*, 1−13.
(18) Loo, J. D.; Hyseni, L.; Ouda, R.; Koske, S.; Nyagol, R.; Sadumah, I.; Bashin, M.; Sage, M.; Bruce, N.; Pilishvili, T.; Stanistreet, D., User Perspectives of Characteristics of Improved Cookstoves from a Field Evaluation in Western Kenya. *Int. J. Environ. Res. Public Health* **2016**, *13*, (2).16710.3390/ijerph13020167
(19) Clough, L. The Improved Cookstove Sector in East Africa: Experience from the Developing Energy Enterprise Programme (DEEP); GVEP International: September 2012, 2012; p 108.
(20) WHO. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global Update 2005, Summary of risk assessment; WHO/SDE/PHE/OEH/06.02; World Health Organization: 2006.
(21) WHO. WHO Guidelines for indoor air quality: Selected pollutants. WHO Regional Office for Europes: 2010.
(22) Stanistreet, D.; Hyseni, L.; Bashin, M.; Sadumah, I.; Pope, D.; Sage, M.; Bruce, N. The role of mixed methods in improved cookstove research. *Journal of health communication* **2015**, *20* (S1), 84−93.
(23) Zamora, H. Impactos socio-ecológicos del uso sostenido de estufas eficientes de leña en comunidades de Michoacán, México. Masters, Universidad Nacional Autónoma de México: Morelia, Michoacán, 2011.
(24) Bielecki, C.; Wingenbach, G. Rethinking improved cookstove diffusion programs: A case study of social perceptions and cooking choices in rural Guatemala. *Energy Policy* **2014**, *66*, 350−358.
(25) Rosenbaum, J., Derby, E., Dutta, K., Jagoe, K., Pennise, D. Understanding Consumer Preference and Willingness to Pay for Improved Cookstoves in Bangladesh; USAID: August 2013, 2013; p 55.
(26) Sudman, S., Bradburn, N. M. *Asking Questions: A Practical Guide to Questionnaire Design (Social & Behavioral Science Series)*, 1st ed.; Jossey-Bass: San Francisco, CA, 1982; p 416.

DOI: 10.1021/acs.est.5b06141
Environ. Sci. Technol. 2016, 50, 4564−4571