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Patterns of Stove Usage after Introduction of an Advanced Cookstove: The Long-Term Application of Household Sensors

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Supporting Information

ABSTRACT: Household air pollution generated from solid fuel use for cooking is one of the leading risk factors for ill-health globally. Deployment of advanced cookstoves to reduce emissions has been a major focus of intervention efforts. However, household usage of these stoves and resulting changes in usage of traditional polluting stoves is not well characterized. In Palwal District, Haryana, India, we carried out an intervention utilizing the Philips HD4012 fan-assisted stove, one of the cleanest biomass stoves available. We placed small, unobtrusive data-logging iButton thermometers on both the traditional and Philips stoves to collect continuous data on use patterns in 200 homes over 60 weeks. Intervention stove usage declined steadily over time and stabilized after approximately 200 days; use of the traditional stove remained relatively constant. We additionally evaluated how well short-duration usage measures predicted long-term use. Measuring usage over time of both traditional and intervention stoves provides better understanding of cooking behaviors and can lead to more precise quantification of potential exposure reductions and consequent health benefits attributable to interventions.

INTRODUCTION

Globally, approximately 40% of households rely on solid fuels—including wood, dung, grass, coal, and crop residues—for cooking.[1] The 2010 Comparative Risk Assessment of the Global Burden of Disease attributed 3.6 million deaths yearly to the harmful byproducts of solid fuel combustion for cooking and an additional 0.3 million deaths from contributions of household air pollution to ambient air quality.[2,3] While the proportion of households using solid fuels appears to be declining, the absolute number using these fuels has remained fairly constant.[1]

Most efforts to mitigate this health burden have focused on providing biomass-burning stoves that vent pollution outdoors and/or improve combustion efficiency to reduce emission rates. Increasingly, some are focused on providing access to clean energy for cooking—including electricity or liquefied petroleum gas. Several conditions must be met if household energy interventions are to improve health: continuous access to a low-emissions energy source for cooking,[3] sustained usage of this energy source, and discarding of the more polluting traditional stoves. Mixed use of clean and traditional stoves—dubbed stove "stacking"—can mask or negate any potential benefit of an intervention. Stacking is well-documented through surveys,[4−7] though little objective continuous monitoring of usage of multiple cooking appliances during intervention studies has occurred to date.

In Palwal District, Haryana, we provided a fan-assisted, advanced cookstove, with modifications to improve combustion efficiency (not just improve fuel efficiency or vent pollutants outdoors), to pregnant women via local antenatal healthcare system workers. Preliminary research evaluating potential interventions and describing this community has been published.[8] During this initial work, we identified the stove selected for this study—the Philips HD4012—as suitable, despite requiring access to power for battery charging and the need to chop the biomass fuel into small pieces. Among other goals, this study evaluated the use of the intervention and

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primary traditional stoves over time and investigated predictors of usage.

Monitoring usage and adoption of intervention stoves traditionally relied on simple metrics obtained through interviews or by a trained observer. Such practices introduce the potential for bias—due either to recall bias or to the influence of an outsider in the home (the "Hawthorne effect"). Recent work in Rwanda, for example, highlighted that usage estimates obtained from surveys were biased upward relative to objective measures from electronic sensors.[9,10] These biases have been well described in water and sanitation studies, including recent evidence showing significant effects of structured observation on behavior[11] and attempts to address these issues using simple data-logging sensors.[12] Previous studies[6,8,13−15] of household energy identified Maxim IC's iButton technology as an objective, field-validated Stove Use Monitor (SUM). iButtons are small, coin-shaped thermometers that log time-resolved instantaneous temperatures at the surface upon which they are mounted. Properly placed, iButtons offer both an objective measure of stove usage and a relatively unobtrusive way to monitor interventions over time. Specific sensor characteristics are described elsewhere.[8,15]

This paper describes time-trends in usage of the intervention and primary traditional stoves in rural Indian homes. We examine how well short-term measures (1, 2, and 7 day mean measurements) of stove use predict study means, with the goal of optimizing sampling times and strategies for monitoring household energy interventions. We believe the data set described in this paper is the longest and deepest data set of measured stove usage generated to date, spanning over 15 months of monitoring at 10 min intervals on both intervention and primary traditional stoves in 200 homes (~21 million data points). Measuring multiple stoves required creation of new metrics to characterize shifts in usage patterns over time. Our secondary focus—on reducing total monitoring duration for assessing use, without compromising data quality—informs strategies to optimize the conflicting goals of precise measurements and efficient fieldwork.

■ MATERIALS AND METHODS

Study Site. This study took place approximately 80 km south of New Delhi at the International Clinical Epidemiology Network (INCLEN) SOMAARTH demographic, development, and environmental surveillance site[8] in Palwal District, Haryana, India beginning in November of 2011 and ending in March of 2013. At the time of the study, INCLEN was carrying out demographic and environmental surveillance in 51 villages, covering a population of approximately 200 000.

During the study, ambient temperatures varied widely by season, reaching a maximum of 45 °C in May and a minimum of 4 °C in January (Supporting Information, SI, Figure S1). Temperature data were logged every minute by the project meteorological station (Onset Microstation, Onset Computer Corporation) at the INCLEN field headquarters in Palwal town, between 5 and 12 km from study villages.

Study Sample. The current study focused on 7 rural villages, selected based on their use of biomass for cooking, total population, and their accessibility to the SOMAARTH field headquarters. 205 pregnant women were recruited from these villages. All households recruited into the study used dung, wood, and crop residues in a traditional hearth (Figure 1A) as the primary means of cooking. Nearly all homes (n = 200) cooked outdoors.

Figure 1. Traditional and intervention stoves and placement of stove use monitors. (A) Typical traditional wood and dung-fueled stove. The inset image shows the Stove Use Monitor and its holder. (B) The Philips intervention stove. A metal sheet stamped with a unique identifier and machined with a hole was used to securely hold each stove use monitor.

Intervention. The Philips HD4012 (Figure 1B) is a top-loading, fan-assisted semigasifier stove fueled by small wood pieces 5 cm in length and up to 2.5 cm in diameter. It contains a rechargeable battery that powers a fan used to enhance combustion efficiency. The fan is adjustable via a knob on the front of the stove. The HD4012 requires access to electricity for intermittent charging. Initial selection of the Philips stove was based on its performance in laboratory testing by the U.S. EPA, which found it to be among the cleanest stoves evaluated using standard simulated cooking methods.[16] Field emissions from this stove were evaluated by other research projects in India[17,18] and our research team validated this stove's acceptability in the community prior to this project.[8] At the time of the study, the stove was produced in Ghaziabad, India, and sold for approximately 60 USD.

Participants who received the Philips stove were trained on proper stove use and maintenance by community health workers and INCLEN field staff. Contact information for INCLEN's field office, which was equipped with spare parts and had access to trained technicians and electricians, was provided to participants in case of any stove malfunction, error, or other user complaint. Complaints could be filed during regular household visits by INCLEN field staff, through calls to INCLEN, or by visiting the field headquarters. Upon receipt of a complaint, repair attempts were undertaken first by INCLEN support staff and then, if necessary, by electricians. A supply of replacement stoves was available to avoid prolonged interruption in homes with stove failures. Detailed logs of

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stove reliability, malfunction, and maintenance were maintained by INCLEN field staff (see the SI).

Stove Use Monitoring. Upon enrollment into the study, field staff obtained informed consent, administered a baseline questionnaire, and installed a SUM on the primary traditional stove in each participant's household. The primary cook was informed of the purpose of the sensor. SUMs were placed in a custom-made metal holder and plastered onto the traditional stove side wall with the same slurry of mud and water used to construct and repair stoves. The holder and a SUM can be seen in the inset image in Figure 1A. The selected SUMs placement location did not disturb standard cooking practices, was protected from overflow and spills, and captured variability in temperatures adequately. Stoves varied in shape and size between households; SUMs were placed in approximately the same location on each stove throughout the study.

Within 4 weeks after preintervention monitoring began, the Philips intervention stove, prefitted with a SUM (visible in Figure 1B), was delivered to the home. A custom-made metal bracket, stamped with a unique stove ID, was used to hold the SUMs in an identical location on all intervention stoves.

SUMs logged instantaneous temperature every 10 min continuously throughout the study. Field workers visited homes every 2 weeks to inspect stoves and download data from the SUMs. SUMs were reprogrammed after each download. Raw sensor data were acquired using a "Touch and Hold Probe" connected to a USB to 1-Wire RJ11 adaptor (Maxim Integrated, San Jose, CA, U.S.A.). Data transfer took approximately 2−5 min per stove and involved holding the probe to the surface of the iButton. Stove usage files were transferred to the field office, where they were inspected for errors and minimally processed.[19] Filenames contained metadata, including stove type (Philips or traditional), household ID, and download date. Raw files were archived at the field site and at INCLEN headquarters in New Delhi. Cleaned files were transferred to a secure server in the School of Public Health at the University of California, Berkeley, and analyzed using R 3.0. Approximately 20.6 million SUMs data points were collected during the main study, representing 143 000 stove-days of data from 408 stoves.

Data Processing. The number and duration of usage events, derived from raw SUMs temperature traces, were determined for each stove on each monitored day. Algorithms for processing SUMs data were created using an iterative process, beginning with recommendations from the literature that identify events by setting thresholds for the rate of increase and decrease in temperature.[15] Due to the high variability in ambient temperatures in Palwal, existing algorithms were altered to better suit the local climate and stove types. We took advantage of our continuous ambient temperature measurement to adjust for diurnal variation. To compensate for variability in temperatures between households and the field office, we calculated the mean and standard deviation of ambient temperature by each recorded hour during the study. These values were used to create thresholds for evaluating whether a stove was in use or not.

For each stove, the daily recorded SUMs temperature range (D_{range}) was calculated by subtracting the daily minimum temperature from the daily maximum temperature. SUMs data were then merged with data for mean hourly ambient temperatures ($H_{mean\ amb}$) and their standard deviations ($H_{sd\ amb}$). A stove was considered in use when the SUMs temperature exceeded the mean ambient temperature plus 6 times its standard deviation. Any period detected for which the D_{range} was less than 20 °C was marked as a period of nonuse. To count the total number of daily uses, periods of use that occurred less than 40 min apart were treated as a single use. This clustering threshold was based on manual observation of temperature traces. For each stove, durations of daily use and number of uses per day were saved.

Analyses and Interpretation of Sensor Data. Summarized data were analyzed to understand trends in usage of both the traditional and intervention stoves. All analyses were restricted to households for which we had at least 2 days of preintervention data (n = 177). Analyses were performed separately (1) for the entire data set for these households and (2) for days on which data were successfully collected from both traditional and intervention stoves (see the SI).

The proportion of stove use-time spent using the Philips intervention stove was defined as follows:

$$\mathrm{prop}_{\mathrm{Phillips}} = \frac{\mathrm{dur}_{\mathrm{Phillips}}}{\mathrm{dur}_{\mathrm{Phillips}} + \mathrm{dur}_{\mathrm{traditional}}} \quad (1)$$

where "prop" is proportion and "dur" is duration.

All durations were calculated in minutes. While the proportion of time spent using an intervention is useful to track adoption, it does not take into account gains in efficiency of heat transferred to the pot by the intervention stove, leading to shorter cooking times, and therefore does not allow direct comparison between stoves. Thus, we linked durations of cooking derived from the SUMs with cooking power from laboratory studies[16] to determine the utilized cooking energy (UCE) in megajoules (MJ):

$$\frac{\mathrm{MJ\ cooking\ power}_{\mathrm{st}}}{\mathrm{min}} \times \mathrm{mins\ use}_{\mathrm{st}} = \mathrm{utilized\ cooking\ energy}_{\mathrm{st}} \quad (2)$$

where "st" is the stovetype.

Calculation of UCE allowed estimation of changes in total energy used before and after deployment of the intervention. Laboratory cooking power estimates were derived from controlled burning for water boiling using uniform wood fuel and may not be representative of conditions in the field, where multiple biomass fuels of varying moisture contents may be used.

Statistical Tests and Modeling. The metrics described above were used to create a log of daily household usage, including the number of uses, duration of use, and estimated energy used by each stove. Overall trends in use of the traditional stove before and after introduction of the intervention were compared using t tests.

We evaluated the change in daily mean traditional stove use after introduction of the intervention using linear mixed models to partition the between- and within-household variance components and to calculate the intraclass correlation coefficient (ICC, the proportion of variability explained by between subject differences). Models took the following form:

$$Y_{ij} = \beta_0 + b_i + e_{ij} \quad (3)$$

where Y_{ij} is the i^{th} duration of use in household j, β_0 is the overall intercept, b_i is the random effect for household i, and e_{ij} is the leftover error. This baseline model was run first for the combined data set and then separately by period (preintervention and post intervention) for the traditional stoves. Variability

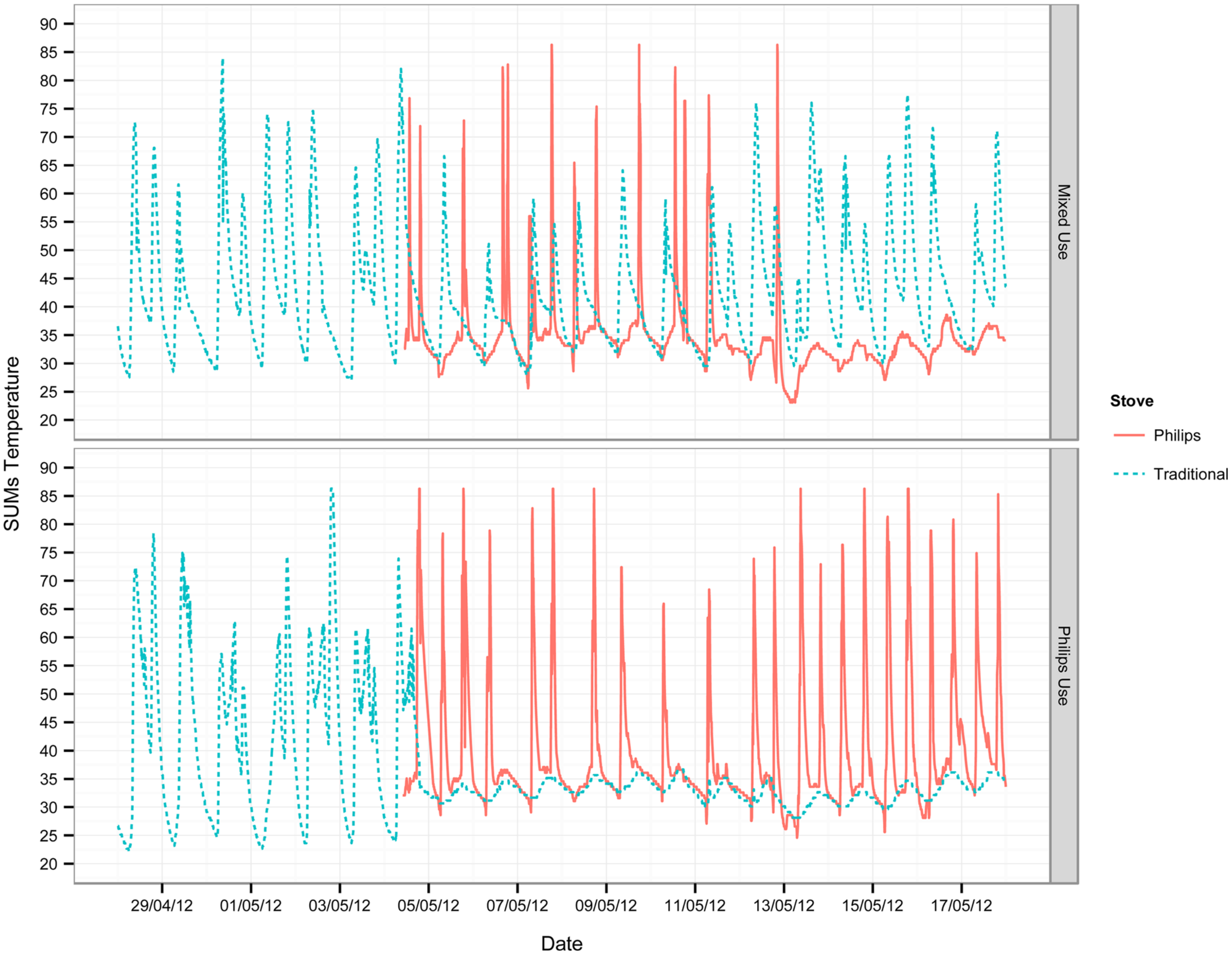

Figure 2. SUMs data from households with different usage patterns. Panels show temperature traces for the traditional stove (blue dashed line) and for the Philips stove (solid red line).

in Philips usage was assessed independently in the same fashion.

Sampling Strategies. We additionally evaluated how well short measures of usage predicted the study average during stable periods of usage. This analysis was restricted to the traditional stove, which exhibited stable use patterns, and was performed independently for the pre- and postintervention periods. We calculated means from varying lengths (1 day, two consecutive days, two random days, 1 week, and 1 day per month) of usage data selected randomly from each household and study period and compared it to the mean duration of use for the entire study period. For these shorter measures, we calculated the probability of a random measurement falling within a precision interval (for instance, within 20% in either direction of the period mean).

RESULTS

Pre- and Postintervention Stove Usage. During the preintervention period, usage of the traditional stove was measured in 177 homes for, on average, 34 days (SD = 35, range = 3−103). In this period, households used their primary traditional stove 1.4 times (SD = 0.8) for an average of 209 min (SD = 105) per day. After introduction of the intervention, the traditional stove was monitored for, on average, 251 days (SD = 97, range = 52−426); the Philips stove was monitored for, on average, 358 days (SD = 54, range = 139−433). During the postintervention period, households exhibited a significant mean decrease in the use of their primary traditional stove to 144 min per day (p < 2.2e-16, SD = 134) once daily. The intervention stove was used, on average, 0.6 times daily (SD = 0.8) for 60 min (SD = 87) after its introduction.

Figure 2 shows patterns of the transition between traditional stoves and the intervention stove, as illustrated by data from two study households. In both panels, the dotted blue line is the SUMs trace from the traditional stove; the solid red line is the trace from the Philips. Pre- and postintervention patterns of use are shown. In the upper panel ("Mixed Use"), the Philips is used upon introduction repeatedly over the course of a week concurrently with traditional stove use. Philips use declines and tapers off in the final week. In the lower panel ("Philips Use"), use of the traditional stove halts after Philips introduction. A third pattern, in which the Philips was rarely or never used, was observed but is not displayed. These types of patterns were typical of the larger population during the first month after introduction of the stove.

Postintervention Cooking Patterns. Use patterns during the first through third months postintervention in homes with SUMs data available on both stoves for at least 15 days per

Table 1. Distribution of Cooking Events Using Philips Stove

		percent of total cooking events using Philips n (%)							
days after intervention	N	no use[a]	0	1–19%	20–39%	40–59%	60–79%	80–99%	100%
0–30	162	0 (0)	1 (0)	11 (7)	34 (21)	55 (34)	33 (20)	19 (12)	9 (6)
31–60	155	5 (3)	8 (5)	25 (16)	25 (16)	34 (22)	23 (15)	13 (8)	22 (14)
61–90	146	4 (3)	8 (6)	30 (20)	29 (20)	19 (13)	13 (9)	16 (11)	27 (18)

[a]No use of either stove recorded.

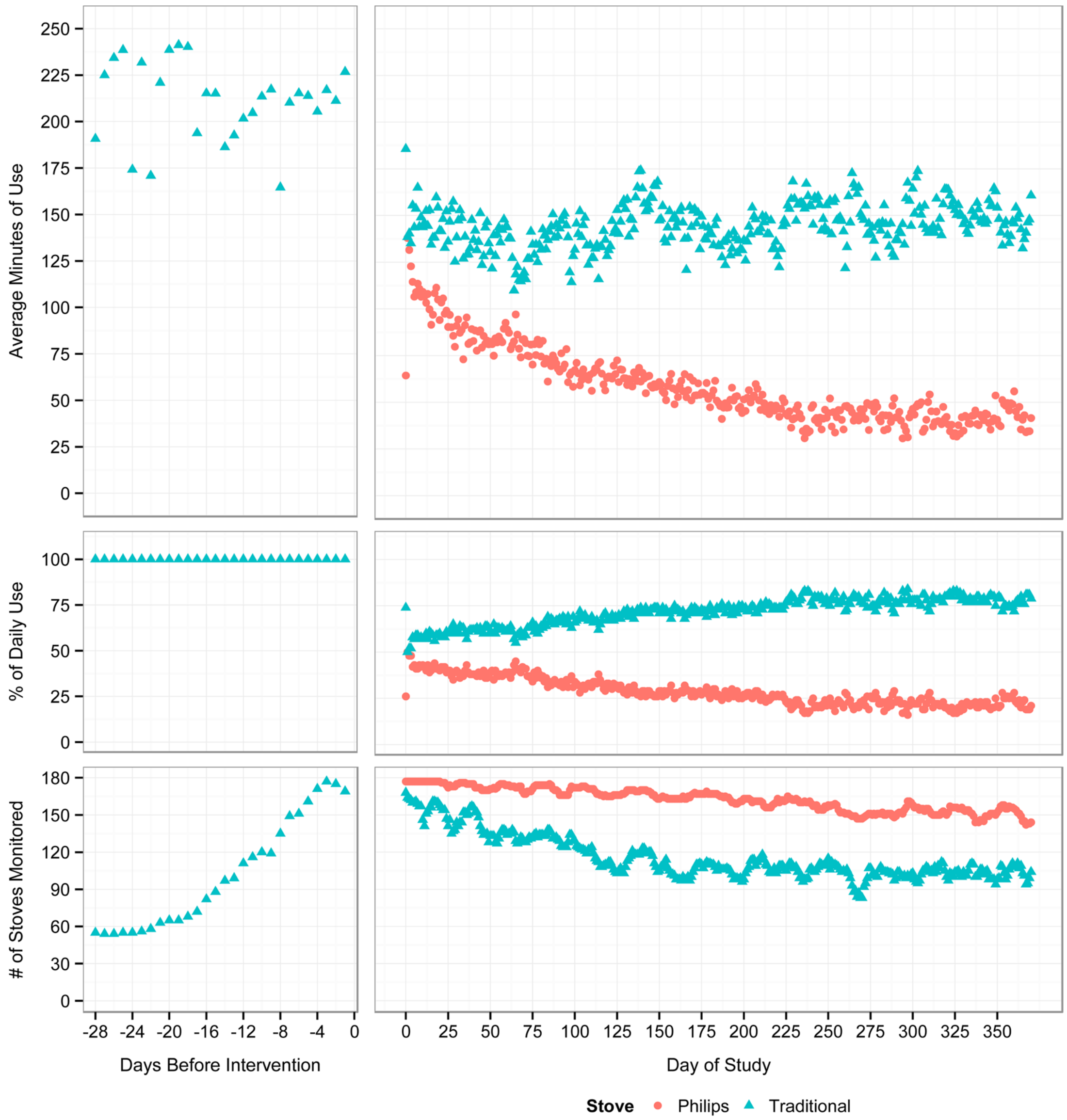

Figure 3. Use and monitoring of traditional and intervention stoves throughout study. The upper panel depicts daily mean usage of monitored stoves by stove type. Day 0 is the day the intervention stove was introduced. The middle panel depicts the percent of time each stove was used. The bottom panel depicts the number of stoves monitored per study day.

month are described in Table 1. During the first month with the Philips, almost all homes used both stoves (n = 152). 6% of homes used the Philips exclusively (n = 9); only one home did not use the Philips. Among the homes using both stoves, the Philips accounted for greater than 80% of cooking events in 17% of homes (n = 28).

Subsequent months exhibited wide variability between and within homes (see the SI). Among the 9 homes that exclusively used the Philips during the first month, average use of the Philips decreased from 111 min daily during the first month postintervention to 78 min daily across the remaining months. Traditional use increased from 0 to 52 min daily across the same period. Additionally, all households exhibited multiple days during later months in which neither stove was in use, suggesting that food was obtained by other means (from relatives or purchased), cooked in alternate locations, or cooked using stoves not fitted with SUMs. Similar trends were noted for homes exclusively using the Philips in months two and three.

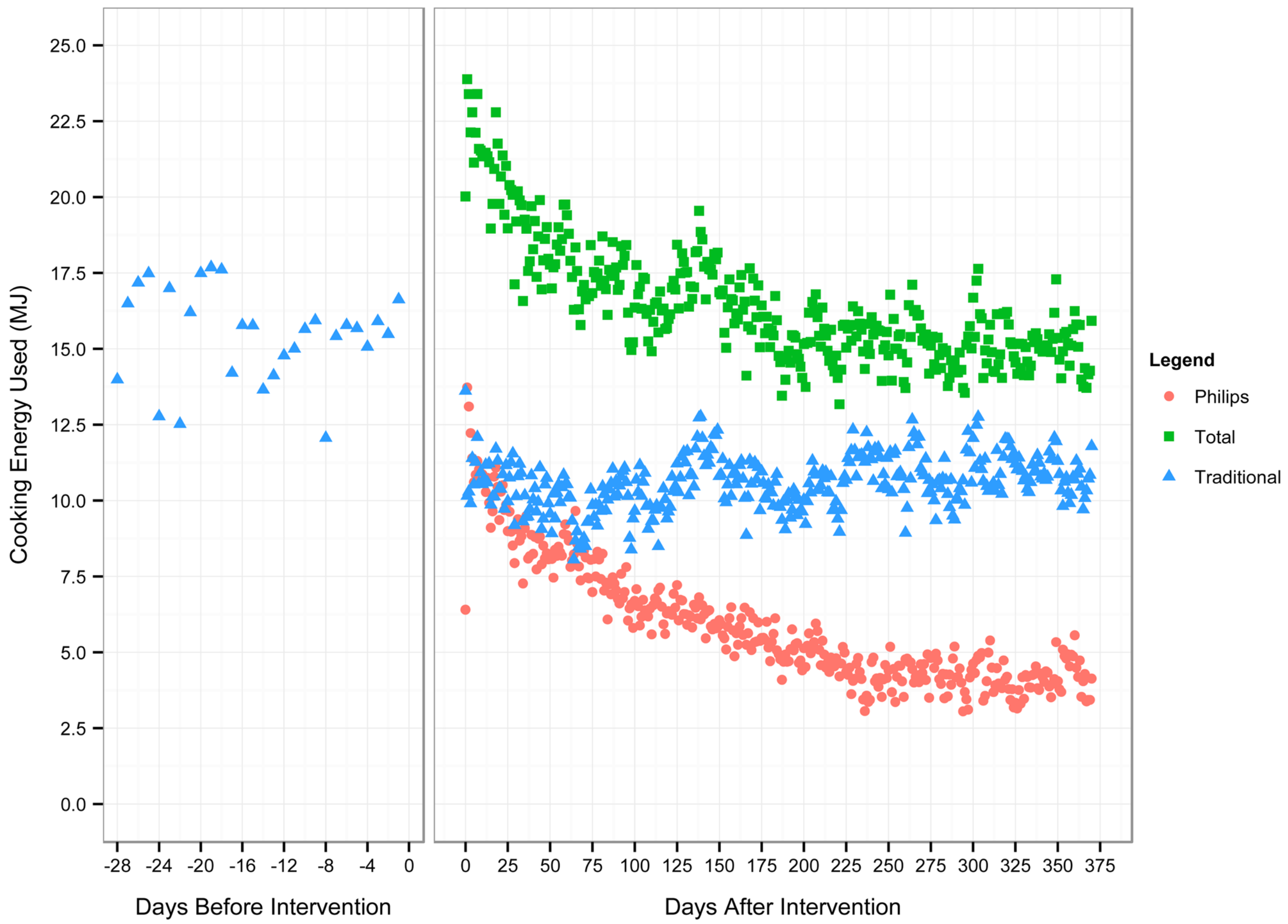

Figure 4. Utilized cooking energy in megajoules throughout intervention. The utilized cooking energy is presented separately for the traditional and intervention stoves (blue and red, respectively) and pre- and postintervention periods. The total energy use is presented in green.

The variability in usage of the intervention and the lack of displacement of cooking tasks from the traditional stove to the intervention is emphasized at the study population scale in Figure 3. Between introduction of the intervention and postintervention day 200, there is a significant and consistent decrease of 0.28 min/day in use of the Philips (p < 2e-16); between day 200 and the end of monitoring, usage stabilizes but continues to decrease by 0.04 min per day. The traditional stove use after Philips introduction was stable. Similar trends were noted for daily use event counts over time (see the SI).

Most of the total variability in usage across stove types was due to variability within homes: 66% across periods for traditional stoves and 78% for intervention stoves. The total variability was highest for traditional stoves in the post-intervention period, perhaps indicative of either a shift first to and then from the Philips or mixed use of both stoves. SI Table S3 shows the means of use duration overall and by stove type and period and presents the calculated ICCs, the proportion of variability explained by differences between subjects.

Utilized Cooking Energy. Prior to the intervention, households utilized 15.5 MJ of energy per day (SD = 1.5) from cooking with their traditional stoves (Figure 4). After introduction of the intervention stove, utilized cooking energy from the monitored traditional stove decreased significantly to 10.6 MJ per day (SD = 0.86, $p < 2.2 \times 10^{-16}$). In the first month after introducing the intervention, however, total average utilized energy increased to 21 MJ daily, due to use of both stoves. Counterintuitively, perhaps, decreasing usage of the more efficient Philips in subsequent weeks led to decreasing total energy use. Assuming the rate of energy consumption of each stove remained constant throughout the study, the average daily utilized energy across the postintervention period increased to 16.3 MJ (p = 0.003).

Comparing Short-Term Measures of Stove Usage to Study Means. We evaluated the ability of "short measurements" of cooking duration—1 day, 1 day per study month, 2 random or 2 consecutive days, and one consecutive week—to predict mean stove usage of the traditional stove during the pre- and postintervention periods. These periods for the traditional stove were selected because they exhibited relative stability over time, as compared to the Philips.

Short measurements had a low probability of predicting the study-wide mean of stove usage. Precision varied across the pre- and postintervention periods (SI Figure S5 and Table S4). Short-term measures adequately predicted preintervention means with traditional stoves. During this period, a consecutive week of sampling had the highest probability (75%) of being within 20% of the long-term mean. After introduction of the intervention stove, short-term means performed poorly. Just 18% of random single days were within 20% of the long-term mean for the traditional stove. The mean of samples taken for 1 day per month postintervention had a 66% chance of being within 20% of the long-term average.

■ DISCUSSION

We report on the usage of an intervention stove distributed to 177 pregnant woman and related changes in use of the traditional stove over approximately 60 weeks in rural India. The data set consists of one of the largest and longest objective measurement campaigns of stove usage to date. By deploying stove use sensors for over a year, we were able to track and report for the first time the changes in usage of an advanced cookstove intervention and the primary traditional stove over time.

Analysis and Application of Stove Usage Data. Few algorithms for converting temperature traces to event counts and durations of use have been published. We offer a novel analysis method: usage events defined as periods that deviate from ambient temperatures. This method does not rely on any additional assumptions about the distribution of the data and facilitates relatively fast analysis of large volumes of data. It does, however, require local measurement of ambient temperature, which can introduce additional cost. We focus on durations of use, as we believe this to be a more health-relevant metric and a better indicator of potential risk than number of events, which can be easily obtained from duration data if needed (see SI).

Further evaluation of this algorithm is ongoing on both previously collected and new SUMs data sets. We are additionally investigating the feasibility of household or village level "ambient SUMs" to aid with signal processing and to account for microclimatic variability not captured by a single, meteorological station. Finally, we are monitoring usage on many different stove phenotypes globally; these activities will help optimize SUMs placement practices, and evaluate and hone the described algorithm to determine its broader applicability.

We see a need for standard methodologies for interpretation of iButton signals that cater to specific research or programmatic goals. Daily time of use and number of uses are simple metrics obtainable from SUMs data through a number of methods. Interstudy comparisons of usage may be complicated, however, by the algorithm design decisions used to generate these metrics. For instance, time-of-use is impacted by the threshold at which the stove is no longer considered to be on; the number of uses is similarly affected by decisions about clustering of temperature peaks. This implies that there is likely no single algorithm for SUMs data analysis. Clear specification of algorithm parameters—ideally in the form of open-source code—and evaluation of algorithms in multiple studies can help clarify differences between methods.

Stove Usage and Adoption in Haryana. We found continuously decreasing population trends in usage of the intervention stove over time. This trend leveled off between 175 and 200 days postintervention. While usage of the intervention had not completely ceased at the end of data collection, the number of homes using the intervention stove regularly and the related durations of use were lower than immediately after stove distribution. Our findings are supported by other studies that have (1) indicated "stacking" of devices throughout the adoption process[14] and (2) acknowledged a trial period during which the household evaluates the suitability of the intervention.[6,7]

Utilized cooking energy showed similar trends, with an increase in total UCE following introduction of the Philips followed by a leveling off and stabilization. Future studies should focus on similar calculations to understand if there is a "rebound effect" as discussed elsewhere[20] in the household appliance literature. In our setting, addition of the advanced stove seemed to increase overall energy use, perhaps because the users took advantage of an additional stove to provide more cooking services rather than substituting the Philips for the traditional stove. Any future studies seeking to calculate UCE should evaluate cooking power in the field, as laboratory and field stove performance parameters often vary widely.[21−23] Because we relied on these laboratory estimates and applied them uniformly over the study period, we may be mis-estimating the actual utilized cooking energy.

Our findings indicate that the Philips may have temporarily offset a portion of measured traditional cookstove usage, albeit in a way that may have increased total energy use. Despite this continued use of the Philips, however, it failed to become the dominant stove used in the home, as would be necessary to maximize health protection. Changes in pollution exposure during the current study will be reported separately.

Importantly, without measurement of usage of both the primary traditional and intervention stoves, we would have been unable to make any determinations about the role of the Philips—as an added cooking appliance—in household cooking. Finally, we would not have observed the initial uptick and subsequent decrease in UCE after introduction of the intervention.

Stove Usage Variability. The high within-household variability of daily usage of both stoves—especially in the postintervention period—indicates that care must be taken when using short-term measures of usage to predict long-term means. This stands in stark contrast to previous work in Guatemala,[14] where the majority of variability was found to be between households. Most likely, this is due to the difference between the character of the intervention in Guatemala, which was well-known to the community and locally created, and the intervention in India, which while vetted in the community was an engineered object brought in from elsewhere.

Continuous measurements allowed us to evaluate the ability of short-term measurements to predict the long-term mean. Short-term measurements of one or two consecutive days did a poor job of predicting the long-term mean, with the majority of measurements deviating from the mean by over 20%. Measurements that were spread through time−for instance, one 24 h measurement per month of the study−were much closer to the long-term mean. These findings suggest that future intervention studies should measure stove usage regularly to capture inherent variability in household behavioral patterns and to best capture changes in usage over time. Given that short-term measures fail to accurately predict long-term means in relatively stable situations, their value in dynamic situations, such as the days and weeks following intervention introduction, is limited. Attempts to assess adoption and use must track behaviors consistently for longer periods of time.

Limitations and Challenges. This study has a number of limitations. Although promoted by village health workers, the stoves were given to participants free-of-charge, which has been shown to impact perceptions of value.[24] Participants were enrolled based on pregnancy during the initial phases of the study and may not represent the broader population. Cultural cooking practices related to pregnancy may impact adoption of an intervention stove; initial and long-term usage in households without a pregnant woman may be more consistent or significantly different from the patterns we observed. However, as our study population represents a particularly vulnerable group, indications on how they use this free intervention can inform future studies targeted toward similar communities. Second, we were unprepared to instrument the other traditional stove types found in many households. While we placed two sensors, one on the intervention stove and one on the participant-reported primary traditional cookstove, it is possible that other traditional stoves were also used during the study period. Further, there is possibility of the Hawthorne effect: instrumentation of the primary traditional cookstove may have shifted usage to other, unmonitored traditional stoves. Among users who exclusively used the Philips during month 1 or 2 of the study, we noted multiday periods of inactivity with both monitored stoves in subsequent months, indicative of cooking elsewhere or use of another stove. We believe either of these reasons may account for the higher levels, on average, of traditional stove usage in the preintervention period. As a result of these caveats, our study paints only a partial picture of the true usage patterns in the home. As these secondary and tertiary stoves were reported to be used only for simmering milk or cooking during inclement weather, we do not believe there were wide changes in their use as a result of introduction of the Philips. We cannot, however, discount the possibility of use of unobserved and unmonitored stoves.

A number of challenges arose during the study. The fieldworker burden for this study was high, with a small team of fieldworkers visiting each household every 2 weeks. Households were spread over a relatively wide area, leading to significant transit time and costs and fieldworker turnover. Similarly, the volume of data proved to be a logistical challenge to manage, clean, and transfer. Strict protocols and fieldworker assurances facilitated analyses but could not, inherently, decrease data transfer and processing times. SUMs on traditional stoves were especially difficult to maintain over long periods of time due to challenges with placement related to overheating and exposure to water (see SI). We are exploring alternate measurement techniques—including infrared thermometers, thermocouple-based data-loggers, and wireless transmission of data—to improve data completeness and fidelity for traditional stoves. Comparisons of data measured with SUMs to participant-reported stove use and perceptions of the Philips as a replacement for the traditional stove are in preparation. Such comparisons have, in some cases,[14] revealed that reported stove use is similar to measured use, while in other cases reported use exceeds measured use.[9] Future intervention studies should focus on long-term objective measurement of stove use and seek a deeper understanding of the individual and community behaviors motivating use or nonuse of an intervention through qualitative methods from behavioral science.

Stove usage is a critical link between the potential and delivered benefits of intervention programs.[6,23] Monitoring of usage over time is necessary to fully understand the potential for delivery of those benefits; in this study, short-term measurements of benefits immediately after intervention distribution would have been misleading and potentially led to mistaken claims of benefits.

The low long-term usage of the intervention stove, while disappointing, is informative. It indicates (1) that preliminary work, while valuable to assess initial feasibility of an intervention, will most likely not predict long-term viability; (2) that measurement of usage of both traditional and intervention stoves is required—over time—to fully understand and accurately characterize adoption of an intervention and changes in traditional habits; and (3) that a combination of more transformative, aspirational interventions—that can fully displace the traditional stove—and education and training, to sway participants away from the old stove, will be required to fully realize benefits.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional figures, tables, and methodology detailing ambient temperature at International Clinical Epidemiology Network's headquarters in Palwal, Haryana, India; counts of stove usage and related analyses; analysis restricted to days with valid Philips and traditional stove usage data; intraclass correlation coefficients from linear mixed models; optimizing measurement strategies for SUMs sampling; maintenance and repairs of the Philips stoves; percent of cooking with the Philips by study month; and SUMs field performance and failures. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Author Contributions

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Notes

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■ ABBREVIATIONS

SUM	stove use monitor
D_{range}	daily temperature range
$H_{mean\ amb}$	hourly mean ambient temperature
$H_{sd\ amb}$	hourly ambient temperature standard deviation
UCE	utilized cooking energy
MJ	megajoules
ICC	interclass correlation coefficient
SD	standard deviation

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