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Quantitative metrics of stove adoption using Stove Use Monitors (SUMs)

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ABSTRACT

The sustained use of cookstoves that are introduced to reduce fuel use or air pollution needs to be objectively monitored to verify the sustainability of these benefits. Quantifying stove adoption requires affordable tools, scalable methods and validated metrics of usage. We quantified the longitudinal patterns of chimney-stove use of 80 households in rural Guatemala, monitored with Stove Use Monitors (SUMs) during 32 months. We counted daily meals and days in use at each monitoring period and defined metrics like the percent stove-days in use (the fraction of days in use from all stoves and days monitored). Using robust Poisson regressions we detected small seasonal variations in stove usage, with peaks in the warm-dry season at 92% stove-days (95%CI: 87%, 97%) and 2.56 average daily meals (95%CI: 2.40, 2.74). With respect to these values, the percent stove-days in use decreased by 3% and 4% during the warm-rainy and cold-dry periods respectively, and the daily meals by 5% and 12% respectively. Cookstove age and household size at baseline did not affect usage. Qualitative indicators of use from recall questionnaires were consistent with SUMs measurements, indicating stable sustained use and questionnaire accuracy. These results reflect optimum conditions for cookstove adoption and for monitoring in this project, which may not occur in disseminations undertaken elsewhere. The SUMs measurements suggest that 90% stove-days is a more realistic best-case for sustained use than the 100% often assumed. Half of sample reported continued use of open-cookfires, highlighting the critical need to verify reduction of open-fire practices in stove disseminations.

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1. Introduction

Currently, forty percent of the world's population relies on solid fuels for their cooking and heating needs [1], and this pattern is expected to continue for decades to come. Incomplete combustion of such household fuels releases toxic pollutants into the household environment causing 1.6 million deaths every year [2] and emits about one-third of the global human-caused black carbon emissions [3].

The implementation of stoves that effectively vent smoke to the outside and/or have verified improved combustion efficiencies is potentially among the most cost-effective energy interventions to simultaneously reduce the health burden of household air pollution, achieve significant reductions in climate-altering emissions and meet goals of reduced poverty, social welfare and increased environmental sustainability [4]. This is true, however, only if usage levels and stove performances are maintained through time. Providing access to clean and efficient cooking technologies is a necessary but not sufficient condition to achieve any of the goals of improved stove programs [5]. As with other household interventions, such as clean water and sanitation, the innovation being disseminated is actually a set of practices, in the case of cookstoves cooking practices that go beyond the stove technology and include changes in household behavior. The introduction of a new cookstove into the household often leads to the "stacking"[1] [5–7] or use of multiple fuels and stoves. Rather than fully switching from their traditional fuel–stove combinations to the new ones, households tend to use every combination for the tasks that best fulfill their needs, increasing the portfolio of cooking options for the home [5–9]. Therefore, measuring the levels of use during the initial adoption and sustained use or disadoption of the new and traditional stoves is as important as monitoring other technical specifications of the cooking devices to assure the sustainability of the benefits from cookstove programs.

Over thirty years of experience with cookstove dissemination has demonstrated that a main barrier for success is the lack of systematic ways to maintain usage and determine stove performance in the field. In turn, scientific research, field monitoring and evaluation have been hampered by the lack of tools and frameworks to quantify stove use in ways that are systematic, objective, unobtrusive and that can affordably operate at large scale in widely dispersed populations.

The main methods used for collecting stove usage information had been the same used for assessing exposure to combustion products [10]: questionnaires, diaries, surveys, interviews and observations. Records of stoves sales have also been used to infer stove usage levels, with the major limitation that they only track initial acceptance of the stoves and not their sustained use. Direct observation in kitchens is the current "gold standard" to record behavior-related factors such as stove usage, but it is intrusive, can change people's behavior and becomes impractical and resource intensive over extended periods and numbers of households and changes householder's behavior. Sensor-based measurements of particulate matter, gases, and stove parameters have been used to evaluate stove designs in the laboratory and to assess their performance and impact in the field. Nevertheless, the physical and chemical parameters collected with these instruments had rarely [11] been used to systematically quantify the long-term dynamics of stove usage and to obtain quantitative metrics of stove adoption that do not rely on householder's memory or surveyor assessment.

In this paper we analyze the longitudinal patterns of stove use in a group of 80 Guatemalan households participating in a chimney-cookstove epidemiological study. The data were collected over 32 months (16 monitoring periods in alternating months from 2008 to 2010) using temperature dataloggers as Stove Use Monitors (SUMs) as described elsewhere [12] and following the field methodology and signal analysis algorithms detailed previously [13]. The SUMs are a passive, unobtrusive, and objective measuring tool that would seem to offer the highest resolution and the lowest reactivity in stove use now available for biomass-using households, arguably offering a new gold standard. Unlike available methods to measure pollution, fuel use, and other stove performance parameters, SUMs measures offer higher resolution while being less intrusive, more objective, and potentially quite cost-effective as sample size increases.

The main objective of this paper is to formulate metrics and indicators of cookstove adoption[2] for the detailed measures of usage now available with the SUMs.

2. Methods

2.1. Study site

The study area encompasses four municipalities in the State of San Marcos in the western highlands of Guatemala. The region has temperate climate and mostly rural population. Local experience divides the year into three seasons and previous studies have defined them as: dry-cold (Nov 15–Feb 2), dry-warm (Feb 15–Apr 30), and rainy-warm (May 1–Nov 14). Fig. A.1 in the Supplemental material shows the daily mean, maximum and minimum temperature and rainfall trends recorded during the 2008–2010 study period with the weather station (CR800, Campbell Scientific Inc.) located at the study headquarters.

2.2. Study sample

The sample population consisted of a convenience sample of 80 households from ten stove-user communities enrolled in the RESPIRE/CRECER epidemiological study [14–16]. Two cookstove age-groups are present in the sample: one of newer users (65%) who had the chimney cookstove built in their homes from November to December 2007, and a second of older users (35%) whose chimney cookstove was built between

[1] In this paper we apply the term "stacking" to the use of multiple fuel-stove combinations.

[2] For clarity, we use the term "adoption" to denote the adoption process. To indicate that a household has "adopted a stove" we explicitly indicate at what stage in the adoption process (initial acceptance, sustained use or disadoption) usage is taking place.

November 2002 and December 2004. Hundred percent of the SUMs-sampled households consider themselves indigenous (i.e. of Native Mayan heritage) and used indoor open wood-fired cookfires before the study began. Some baseline household characteristics of each group are summarized in Table 1.

2.3. *Chimney cookstoves*

All stoves in both groups of the study were built by the same local manufacturer with standardized materials and dimensions, following the “Plancha” stove design. Although locally known by this name, not being centrally manufactured, design and construction details may vary in other regions. All materials and cookstoves built were checked for quality control by research project staff. After construction, cookstoves require 35 days to dry and cure before use. If this period was observed, the chimney cookstoves built in this study were guaranteed to last a minimum of two years. Their lifetimes can exceed ten years depending on the household’s behavior to operate and maintain the cookstoves. Maintenance tasks include: daily removal of ashes from the combustion chamber, weekly tapping of the chimney pipe to remove buildup soot, bi-monthly removal of the chimney pipe to clean it, and, sealing of roof and chimney openings before the rainy season.

2.4. *Dissemination of cookstoves*

The main differences in the dissemination of stoves between the groups were the timing of initial use and the frequency of the post-monitoring and maintenance provided. Older users with stoves built in RESPIRE [16] (2002–2004) started using them after their individual drying and curing periods ended, while all users with stoves from CRECER [15] built in 2007 were asked to begin use on a specific date, after the last built stove had cured. Monitoring visits by field staff took place weekly for the older users in RESPIRE, all of whom were continuously encouraged to use the cookstoves, and received repairs as needed. From 2008 and until 2010, both groups were monitored quarterly. They were offered repairs at the beginning and end of this period but were not consistently encouraged to use their cookstoves or to abandon their traditional cookfires. The households from both groups received small non-monetary gifts (e.g. a bag of rice or beans, soap or other sundries) to thank their participation in the study and to encourage their participation in the cookstove training workshops. The incentives were not conditioned on levels of cookstove use or participation in the SUMs monitoring.

Table 1 – Baseline characteristics of the households monitored with the SUMs.

	Both Groups	Group 1 Newer users	Group 2 Older users
Sampled population characteristics			
Households monitored (percent)	82 (100%)	53 (65%)	29 (35%)
Mean cookstove age in years (S.D.)	5.2 (2.1)	3.8 (0.0)	8.0 (0.8)
Mean household size at baseline (S.D.)	7.8 (2.6)	7.6 (2.6)	8.2 (2.7)
Mean household size at exit (S. D.)	8.0 (2.7)	7.5 (2.5)	8.5 (2.3)

2.5. *Measures of stove use*

2.5.1. *Stove Use Monitors (SUMs)*

We deployed temperature dataloggers as Stove Use Monitors (SUMs) to determine stove usage and obtain counts of the daily meals from the temperature signals. We recorded temperature data every 20 min in 16 monitoring periods of 28 days each in alternating months during 32 months from January 2008 to September 2010. The sensor characteristics, placement, data collection, data management, analysis methods and algorithms are described elsewhere [13]. Briefly, we used perforated metal sheets to attach the temperature dataloggers to the back surface of the cookstoves. These locations did not disrupt cooking activities, ensured integrity of the sensors, and, allowed sensing of adequate temperature signal-strength. Temperature signal peaks due to cookstove activity were identified as “fueling events”, the minimum unit of stove use. Events found within a fixed-time window were then clustered to define a “cooking event” or “meal”. Each house had one chimney cookstove only. In this paper we present the results for the chimney-cookstove measurements only, the results for the open-cookfire measurements are presented in a separate publication. Fig. 1 shows a PDA downloading data from a SUM installed in a cookstove.

The first monitoring period (from January to February 2008) followed an initial sample of 50 homes (30 newer users and 20 older users) during the stage of initial adoption, after construction of the chimney cookstoves of the new users. Thirty more homes (20 newer users and 10 older users) were added to the sample in February 2008 and the subsequent 15 monitoring rounds followed sustained use in the 80 households. A total of 30,122 days from all cookstoves were recorded with the SUMs in the 15 periods of sustained use, with an average data loss rate of 10% [13]. Table 2 in the section below describes the number and distribution of measurements collected with the SUMs.

2.5.2. *Recall questionnaires of chimney-cookstove and open-cookfire activity*

Quarterly questionnaires about cookstove and cookfire use were performed in both groups after the construction of their chimney cookstoves as part of the RESPIRE/CRECER research protocols. The recall questions [13] answered by the main cook included: frequency of chimney-stove and open-cookfire use, the amount of time spent preparing each meal, and the number of hours the chimney cookstove was lit at each meal time. Table 2 summarizes the distribution of the SUMs and questionnaire data collected in the 80 homes during the period of SUMs monitoring. The numbers of questionnaire and SUMS data points that could be matched for comparison (Table 2(3)) are smaller than the data points on either dataset, because data collection for the two instruments was not synchronized. All households in the group of new users had at least one matching pair of measurements, while 75% of the older users had one match only (Table 2).

Fig. 1 – Small temperature dataloggers were used as Stove Use Monitors (SUMs). The SUMs, attached to the chimney-cookstove body, were programmed bi-monthly in the field and the data was downloaded using PDAs.

2.5.3. *Indoor kitchen carbon monoxide (CO) concentrations*

Minute-by-minute CO concentrations were recorded with an electrochemical Carbon Monoxide Logger (Hobo, Onset Corp.) in 11 households (four newer users and seven older users) during the period of initial use of the group of newer users. The electrochemical sensors were calibrated against CO span gas before deployment, and were placed in the study kitchen walls following the standardized protocols described elsewhere [14,17]. The CO loggers were co-located with the SUMs to study the reductions in indoor air pollution with increased cookstove use.

2.6. *Definition of metrics of stove use*

In this section we formulate individual and population level metrics to quantify stove usage.

Let δ_{ti} be the binary indicator of daily use for the i-th stove on day t (equal to one if the stove is used that day, zero if not), Let m_{ti} and h_{ti} be, respectively, the number of meals and hours that the stove was in use. T_i the total number of days that the i-th stove was monitored, P_{ti} the number of hours that the i-th stove was monitored in day t, and I_t the number of stoves monitored on day t.

For an individual stove i, we assessed usage during a monitoring period of T_i days by:

- Counting the *days in use* or the *percent days in use* in the period:

$$\text{days in use} = \sum_t \delta_t = X \tag{1}$$

$$\text{\%days in use} = \frac{\sum_t \delta_t}{T} = \frac{X}{T} \tag{2}$$

- Counting the *number of meals* or the *average meals* in the period:

$$\text{meals} = \sum_t m_t = Y \tag{3}$$

$$\text{average meals in } T = \frac{\sum_t m_t}{T} = \frac{Y}{T} \tag{4}$$

- And by counting the *number of hours in use* or the *percent hours in use* in the period:

Table 2 – Stove use measurements collected with during initial adoption (1) and sustained use (2) with Stove Use Monitors (SUMs) and during sustained use with recall questionnaires (3).

	Both Groups	Group 1 Newer users	Group 2 Older users
Data collection			
(1) Initial adoption – SUMs measurements			
Number of cookstoves[a] in 1st monitoring period (percent)	50 (100%)	30 (60%)	20 (40%)
(2) Sustained use – SUMs measurements			
Mean cookstoves in periods 1–16 (S.D.)	72.4 (2.7)	45.9 (2.3)	26.5 (2.8)
Mean monitoring periods per cookstove (range)		13.7 (1–15)	12.9 (10–15)
Total cookstoves and days measured	30,122	19,058	11,064
(3) Sustained use – recall questionnaires & SUMs			
Questionnaires with SUMs[b] during 15-day recall	192	131	61
Questionnaires with SUMs during 3-month recall	168	109	59

[a] At each house only one chimney cookstove was monitored.
[b] The responses to the quarterly recall questionnaires of each household were matched with SUMs measures recorded during the 3-month and 15-day periods prior to the questionnaire date.

$$\text{hours in use} = \sum_t h_t = Z \tag{5}$$

$$\%\text{hours in use} = \frac{\sum_t h_t}{T} = \frac{Z}{T} \tag{6}$$

Similarly, on a single day t, the number of stoves used (or the percent of stoves used, out of I_t stoves monitored on day t), the number of meals from all stoves on that day (or the average meals per day across I_t stoves) and the number of hours of use in that day (or the average hours across I_t stoves) can be defined.

In terms of days of use, we define the following group-level metrics:

- *Stove-days in use*, given by the sum of days in use during the monitoring period of each stove:

$$\text{stove-days in use} = \sum_{t,i} \delta_{t,i} = \sum_i X_i = U \tag{7}$$

- *Percent stove-days in use*, given by the fraction of days in use from all stoves and days monitored (the monitoring periods T_i need not be of equal length):

$$\%\text{stove-days in use} = \frac{\sum_{t,i} \delta_{t,i}}{\sum_i T_i} = \frac{\sum_i X_i}{\sum_i T_i} = \frac{U}{T} \tag{8}$$

For example, three out of ten monitored stoves each used every day during a ten day monitoring period yield 30 stove-days in use, the same that result from one out of ten monitored stoves used every day during a 30-day monitoring period. Nevertheless, the first case accounts for 30% stove-days in use and the second one for 10% stove-days in use.

At the meal level, we represented group usage in two ways:

- *Meals in group*, given by the sum of all meals cooked during the monitoring period of each stove:

$$\text{meals in group in } T = \sum_{t,i} m_{t,i} = \sum_i Y_i = M \tag{9}$$

- *Average meals*, the total meals in the group of stoves during their monitoring periods divided by the total monitored days from all periods:

$$\text{average meals in } T = \frac{\sum_{t,i} m_{t,i}}{\sum_i T_i} = \frac{\sum_i Y_i}{\sum_i T_i} = \frac{M}{T} \tag{10}$$

The number of total meals that can be cooked in a day with the stove varies between homes and is different across populations and seasons. Thus, Equation (10) is an average of meals across monitored stoves and days, and not a percent of all possible meals from all households.

In terms of time of use, group usage can be similarly represented by the *hours in use* and by the *percent hours in use* during all hours that each stove was monitored:

$$\text{hours in group} \sum_{t,i} h_{t,i} = \sum_i Z_i = H \tag{11}$$

$$\%\text{hours in group} = \sum_{t,i} h_{t,i} = \frac{\sum_{t,i} h_{t,i}}{\sum_{t,i} P_{t,i}} = \frac{\sum_i Y_i}{\sum_i P_i} = \frac{H}{P} \tag{12}$$

Similar formulations can be made to quantify the level of use among users only. For example, the *average meals in T* in Equation (10) can be redefined as the:

- *Meals per stove-days in use*, the total meals in the group during their monitoring periods divided by the stove-days in use only:

$$\text{meals per stove-day in use} = \frac{\sum_{t,i} m_{t,i}}{\sum_{t,i} \delta_{t,i}} = \frac{\sum_i Y_i}{\sum_i X_i} = \frac{M}{U} \tag{13}$$

2.7. Statistical models

We applied the quantitative metrics described above to the SUMs measures of sustained use (monitoring periods 2–16), to aggregate the data into one observation per monitoring round for each stove. Each observation in the final dataset contained the number of days in use, the number of meals cooked with the stove, the days in the monitoring period, the household baseline covariates and the time-varying covariates for the monitoring period.

We used Poisson linear regression models [18] implemented in STATA (STATA Corp) to estimate the population-averaged percent stove-days in use and daily meals and to assess the effects of stove age differences, household size at baseline and season. Robust standard errors were estimated to account for the correlation between repeated measures on each stove. In the final models only the effect of season was significant. The full models had the form:

$$\ln(\mu_{use}) = \ln(E(X_{ij}|W_{ij})) = \beta_1 + \beta_2(\text{cold})_j + \beta_3(\text{rainy})_j + \beta_4(\text{stoveage})_i + \beta_5(\text{hhsize})_i \tag{14}$$

$$\ln(\mu_{meal}) = \ln(E(Y_{ij}|W_{ij})) = \gamma_1 + \gamma_2(\text{cold})_j + \gamma_3(\text{rainy})_j + \gamma_4(\text{stoveage})_i + \gamma_5(\text{hhsize})_i \tag{15}$$

where μ_{use} and μ_{meal} are the expected means of the observed percent stove-days X_{ij} and daily meals Y_{ij} respectively, for the i-th household in the j-th monitoring round given the W_{ij} covariates. β_1 and γ_1 are the intercepts of each model, β_2, γ_2, β_3, and γ_3 are the incidence rate ratios of the seasonal effects, β_4 and γ_4 are the effects of the difference in stove age between new and old users and β_5 and γ_5 are the effects of household size at baseline.

To assess the stability of daily usage within households and the level of homogeneity in stove activity between homes we apportioned the between and within household variances (σ_b^2 and σ_w^2) using linear mixed models [18] in the data without covariates. We used the square root transformation of the outcome to stabilize the variance of the actual count distribution and we used an exchangeable correlation structure. The models, implemented in STATA, had the form:

$$E((X_{ij})) = \beta_0 + (\alpha\_use)_i + (\varepsilon\_use)_{ij} \quad (16)$$

$$E((Y_{ij})) = \beta_0 + (\alpha\_meal)_i + (\varepsilon\_meal)_{ij} \quad (17)$$

where α_use_i and α_meal_i are the random effects for the n-th household and ε_use_{ij} and ε_meal_{ij} are the random error (the random deviation of the observed Y_{ij} and Z_{ij} from μ_{use} and μ_{meal} respectively, on the j-th monitoring round for the i-th household).

We used the intraclass correlations from the models $\rho = \sigma_b^2/(\sigma_b^2 + \sigma_w^2)$ and the standard deviation of the observed means to obtain in STATA sample size estimations from one-sample comparisons of means to hypothesized values for set levels of significance and power.

3. Results

3.1. Cookstove adoption process in the CRECER study

3.1.1. Initial adoption

The gradual transition from the traditional open cookfire to the new chimney cookstove after the scheduled start date had different timing across households. Fig. 2 depicts the learning or adjustment period for two different houses in the group of new users, as seen by the SUMs signals (black, left axis) and by the drastic reductions in the kitchen levels of carbon monoxide (red, right axis). For household #1 it only took four days after the start date until they cooked the three main meals with the chimney cookstove, while household #2 took 12 days. Although the lighting of the cookstove in household #1 commenced in the second day (as seen by the rate of temperature changes), the number of cooking events (the number of peaks) increased gradually. This was a common pattern in the study population. After a few days, all households entered a stable period of sustained use.

3.1.2. Sustained use

The population level of sustained use was high, with unadjusted means of 89.5% stove-days and 2.4 average daily meals. Three households in the sample had cookstove usage consistently low through the study. Each of these three was sampled at least 14 monitoring periods. They averaged less than 10% days in use through the 2.6 years of the study and used the chimney cookstove for less than five meals in total.

The patterns of stoves used and daily meals for the fifteen monitoring periods of sustained use are shown in Fig. 3. Each point represents the percent of stoves used out of the I_t stoves monitored on that day (upper graph) and the average daily meals on that day (lower graph) across the I_t stoves. The smoothed line (locally weighted least squares) highlights the seasonal variability. The inset in Fig. 3 details the evolution of initial use during the first monitoring round for the group of newer users only. The population adoption curve shown in the inset is shaped by the average of the individual delays such as those depicted in dotted lines in Fig. 2.

In the Poisson regression and mixed effects models of sustained use only rounds 2–16 were included. The regression estimates for the groups of old and new users had no statistically significant differences ($p > 0.01$) either by round or in their 2.6-year averages. The effect of household size at baseline was not significant either.

With the mixed effects model we found that most of the total variability in stove use (76% for percent stove-days in use and 77% for daily meals) is due to the differences between households, and less due to the variability of repeated measures within each home. The estimates from the models are shown in Table 3.

3.1.3. Seasonal variability

The seasonal effect observed in the trends of stove usage in Fig. 3 proved statistically significant when included in the regression model. Table 3 shows the effect of the warm and

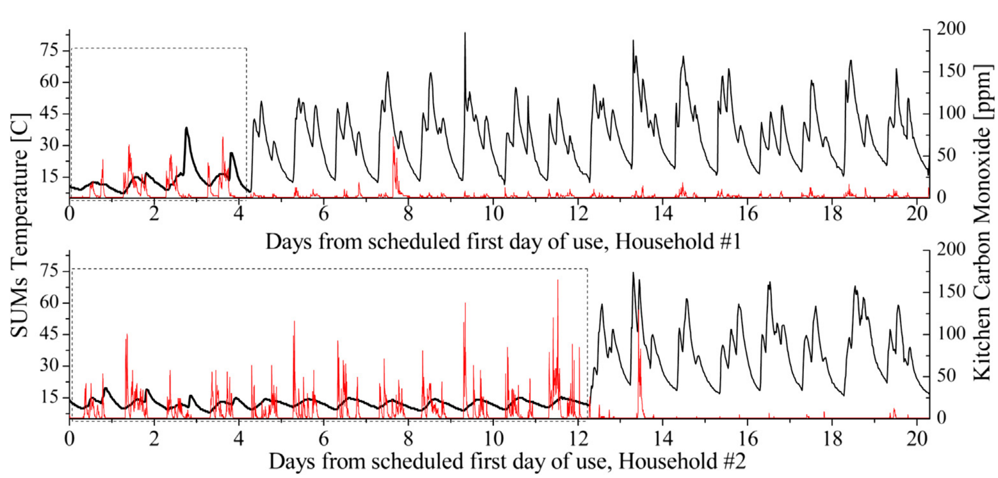

Fig. 2 – Initial adoption of a chimney cookstove after a scheduled start date as seen by the increased cookstove activity registered with the SUMs (black line, left axis) and the reduced kitchen CO levels (red line, right axis) in two different households. A rate of change higher than that of the ambient temperature indicates the lighting of the cookstoves in both households during the first four days. However, not until day 4 (household #1) and day 12 (household #2) did the homes cook the main three meals with the chimney cookstove and CO was drastically reduced. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

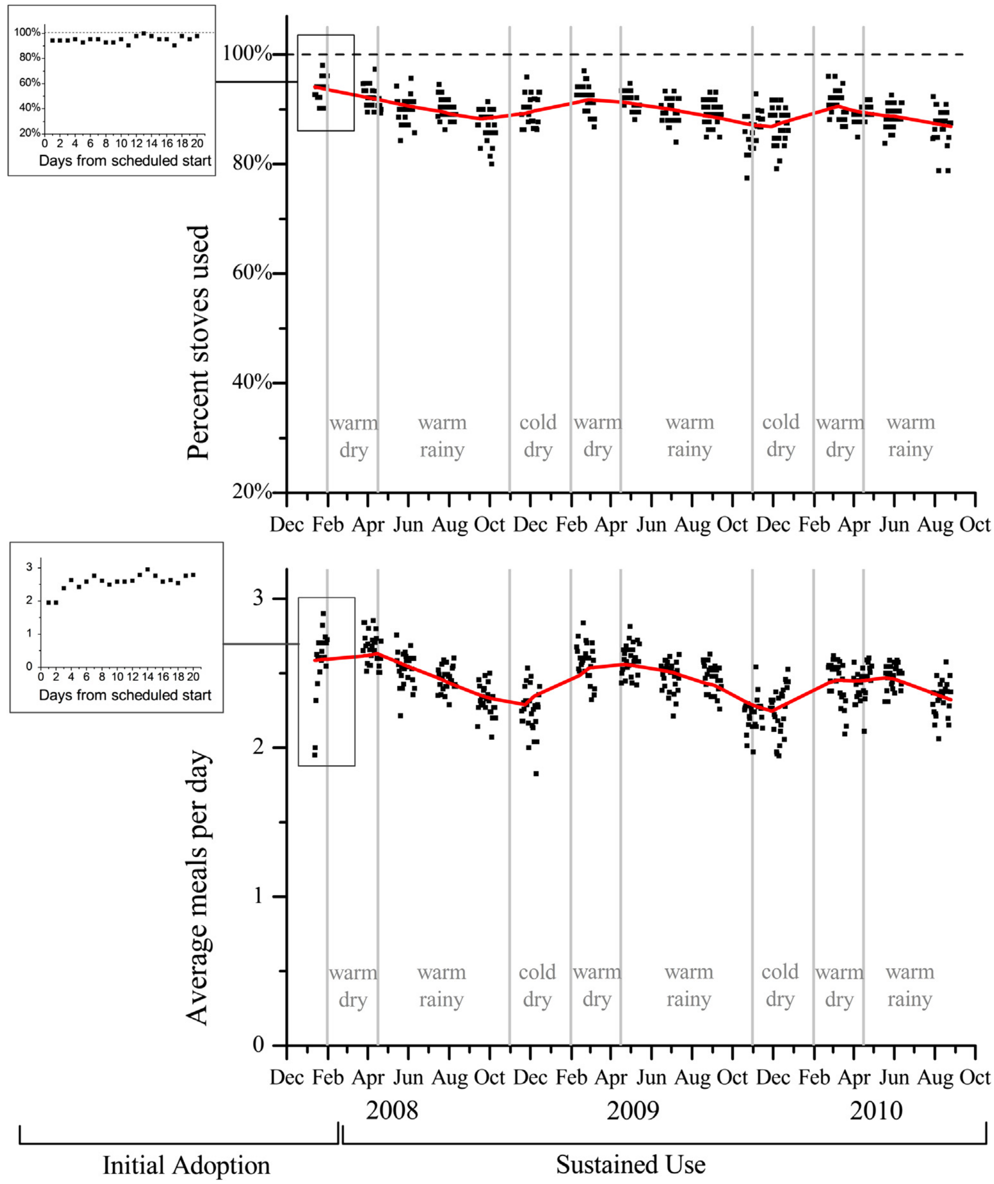

Fig. 3 – Percent stoves used (above) and average daily meals (below) measured with Stove Use Monitors (SUMs) in the CRECER Guatemala study through 32 months. Every point represents the level of use for the chimney cookstoves measured in that day and the smoothed line highlights the seasonal cycle. The insets cover the period of initial adoption for the group of newer users only, after the scheduled start date. During this initial period the percent of stoves used were kept nearly constant while daily meals gradually increased in the first few days. The vertical lines define the locally accepted annual seasons.

rainy periods expressed as incidence rate ratios (IRR). The incidence rate ratios are the ratios of the cold to warm (or rainy to dry) stove-days or meals. Thus, for example, with the warm-dry season as a reference (which is obtained by setting in Equations (14) and (15) the season terms to $cold = 0$ and $rainy = 0$), the stove use estimates for the warm-rainy season are obtained multiplying the reference value by the IRR of the rainy_season (β_3 or γ_3) term. Usage decreased to 89% stove-days in use (95% CI: 82%, 98%) during warm-rainy seasons (a 3% reduction from the reference, $p = 0.013$), and during the cold-dry periods (3% reduction, $p = 0.002$).

For the daily meals, use decreased during the warm-rainy season by 5% ($p < 0.0001$) to 2.4 daily meals (95% CI: 2.2, 2.7) and by 12% ($p < 0.0001$) to 2.3 (95% CI: 2.0, 2.5) during the cold-dry period.

4. Discussion

We present a methodology for the quantification of the stove adoption process. By long-term deployment of SUMs we were able to visualize the dynamics during initial adoption and to

Table 3 – Regression estimates of population and mixed effects models for the percent stove-days, number of daily meals and daily fueling events in the SUMs study population. The incidence rate ratios (IRR) are the ratios of the cold to warm (or rainy to dry) stove-days or meals (warm-dry is the reference season). The intraclass correlation coefficient is the percent of total variability in the measurements that comes from differences between stoves. *p*-values: * ≤0.0001, + ≤0.013.

		Population average model	Mixed effects model
		Poisson (robust)	Random intercept
		Estimate (95% CI)	Estimate (95% CI)
Percent stove-days			
Fixed part	Warm-dry season (%stove-days)	92.0 (87.1, 96.6)+	–
	Cold_season (IRR)	0.96 (0.94, 0.99)+	–
	Rainy_season (IRR)	0.97 (0.95, 0.99)+	–
Random part:	Between-hh variance	–	0.99 (0.72, 1.36)
	Within-hh variance	–	0.31 (0.29, 0.34)
	Intraclass correlation	–	0.76
Daily meals			
Fixed part	Warm-dry season (meals/day)	2.56 (2.40, 2.74)*	–
	Cold_season (IRR)	0.88 (0.85, 0.91)*	–
	Rainy_season (IRR)	0.95 (0.92, 0.98)*	–
Random part	Between-hh variance	–	3.90 (2.85, 5.34)
	Within-hh variance	–	1.09 (0.99, 1.18)
	Intraclass correlation	–	0.78
Daily fueling events			
Fixed part	Warm-dry season (meals/day)	3.11 (2.90, 3.33)*	–
	Cold_season (IRR)	0.89 (0.85, 0.93)*	–
	Rainy_season (IRR)	0.96 (0.93, 0.99)+	–
Random part	Between-hh variance	–	5.07 (3.70, 6.95)
	Within-hh variance	–	1.36 (1.25, 1.48)
	Intraclass correlation	–	0.79

quantify the level of sustained use, magnitude of the seasonal variations in usage, and sources of variability. The learning period in the study sample consisted of a few days only. The quick uptake is due to the nature of the cookstove dissemination in the CRECER project, where all households receiving the chimney cookstove were asked to start usage on the same day. Therefore, this section focuses the discussion in the measured levels of sustained use.

4.1. *Measured stove adoption performance in the CRECER study*

4.1.1. *Sustained use*

The high levels of sustained use measured with the SUMs were maintained during the 2.6 years of the monitoring study. We identified that the following factors contributed to the high levels of use: 1) high initial acceptance and sustained use of this chimney cookstove in the region and its compatibility with the cultural practices and main local cooking tasks such as tortilla making, 2) familiarity of the new users with the chimney cookstove, since their neighbors or family members had received one in the previous years as part of the study, 3) abundance of fuelwood in the region and its almost exclusive use for cooking in the study population [19] (only one household of the 567 in CRECER had a gas stove, which was used only for some meals), 4) frequent contact maintained and trust built by fieldworkers and study personnel with the participants [20] through the quarterly visits for IAP (indoor air pollution) monitoring, questionnaires and medical checkups, 5) continuous encouragement to use the chimney cookstove that some of the household experienced thought the study visit. Thus, the rapid take up and sustained use of cookstoves we observed should not be assumed to occur in disseminations undertaken in different conditions.

Even under these optimum conditions for sustained use there was never a day in the 2.6-year period when 100% of the chimney cookstoves were used (Fig. 3). Even after the households with lowest use are excluded from the analysis, 100% usage was measured only in one day thought the study and an average of three daily meals was never detected. Therefore, on any given day there were always a couple of households not cooking all meals with the chimney cookstove and using instead the open cookfire or not cooking at all in the home. This suggests that 90% stove-days is a best-case for sustained use and a more realistic target goal for adoption performance than 100%, which is sometimes assumed.

4.1.2. *Seasonal variability*

Once users entered the period of sustained use only the seasonal fluctuations affected the population means. The highest levels are seen in the warm-dry season, gradually declining through the warm-rainy period. We know from the fieldworkers and participants that the chimney cookstove is particularly hard to light with wet fuel, so it is plausible that the decreased availability of dry fuelwood with the onset of the rainy season contributed to this decline (see the annual rain and ambient temperature patterns in the Supplemental material). Seasonal migration and local festivals also affected the use patterns. For instance, the two lowest levels of meals per day during sustained use (Fig. 3) correspond to

Table 4 – Quantitative metrics of stove adoption using Stove Use Monitors (SUMs). Ten of the main metrics formulated in this paper are tabulated (central cells) by increasing level of detail (first column: days in use, meals, hours in use), duration of the monitoring period (second column: one day, *T* number of days) and size of the monitored sample (third and fourth columns: one stove, group of stoves). The main applications of the metrics are summarized in the right and lower margins of the table. The factors on the right margin carry over from the top down, i.e. given an appropriate sample size and monitoring period the metrics for time in use (lower rows) could also reflect information about factors acting at the level of meals and days in use (upper rows). The corresponding absolute metrics: the number of stove-days in use, the number of meals and the number of hours can also be used to quantify the cumulative stove activity in a day or a period.

Level of detail	Monitoring period	Size of the monitored sample		
		One stove	Group of I stoves	
Days in use	One day		**% stoves used** Display patterns of use (Fig. 3).	Factors affecting whether the stove is used at all in a day: migration, fuel availability, weather, local festivals, stove break down, stove abandonment.
	T days	**% days in use in *T*** Correlate with meals to analyze the stacking of fuels/stoves (Fig. 5).	**% stove-days in use in *T*** Comparisons with usage indicators for the same *T* (Fig. 4).	
Meals[a]	One day		**Average meals per day** Display patterns of use (Fig. 3).	Factors affecting the frequency of use within days: special meal celebrations and other household needs and preferences to combine the use of multiple fuel/stoves.
	T days	**Average daily meals** Correlate with % days in use to analyze the stacking of stoves/fuels (Fig. 5)	**Average meals in *T*** Comparisons with usage indicators for the same *T* (Fig. 4).	
Time in use[b] (hours)	One day	**% day in use** Correlate with meals to understand cooking dynamics.	**% hours per day in group** Display patterns of use.	Factors affecting the duration of stove use on a day: household routines, type of cooking tasks performed, amount and type of fuel consumed, stove type, stove operation and maintenance practices and environmental conditions.
	T days	**% daily hours in *T*** Correlate with days in use and meals to analyze the stacking of stoves/fuels.	**% hours in group** Comparisons with usage indicators for the same *T*.	
		Individual temporal patterns: seasons and increasing/decreasing trends of sustained use.	Longitudinal group patterns: acceptance, initial adoption, sustained use trends and seasons.	↑ ← Applications

[a] The definition of "meals" requires special attention to ensure consistency between the interpretation of SUMs signals and the particular stove type, cooking practices and cultural context of the monitored population (e.g. to ensure that the stirring of fuel is not counted as multiple meals and that short tasks like tea preparation and longer tasks such as tortilla making are weighed as desired). In this paper we used information about the number and length of meals from recall questionnaires [13] to ensure the consistency of our meal definition.
[b] The use of differential-temperature signals [13] is required in most cases to accurately estimate time in use (e.g. to avoid counting the cooling-down of the stove as time in use and to correct for the influence of ambient temperature or external heating sources).

the local Christmas celebrations on December 24th, when people are cooking additional food or traditional dishes in the open cookfires or eating with relatives in other households. Despite this variability, the stove-days and meals per day did not decline significantly over the 2.6-year period. Therefore, changes in the personal exposure and kitchen IAP levels found during this period will not be due to cookstove use but rather caused by changes in frequency of open-cookfire use, deterioration or incorrect use of the chimney cookstoves or changes in the distribution of personal time-activity budgets [21].

4.1.3. *Partition of variances*

Remarkably, the levels of sustained cookstove use in the groups of newer and older users were not significantly different, despite that their adoption processes started 2–4 years apart. This could also be related to the nature of the dissemination and reflects the attractiveness of this chimney cookstove to this population and the stability of the sustained use process. A review of the baseline fuel and cooking characteristics and socioeconomic factors of the two groups reveals no statistically significant differences either (data not shown).

We estimated the fractions of between and within household variance of measured usage to characterize at what level the factors influencing this stage of the adoption process operate. This was also done to prioritize individual and group strategies for improved sustained use. The intraclass correlation coefficient from the mixed effects model indicated that differences in usage between households accounted for 76% of the total variability in the 2.6-year population averages. Baseline covariates did not explain these differences, and thus in our case, they are likely to arise from non-seasonal migrations or from the distinct preferences that each household has for using the chimney cookstove for all cooking needs or only for some tasks (and potentially, for continuing using the open cookfire). Therefore, in our case, it would be more efficient to increase the population-mean cookstove use with actions that reduce the between-household variability and that focus on the homes with the lowest cookstove usage (providing different or additional stove designs tailored to the cooking tasks still performed on the open cookfires, and teaching how to light, operate and maintain the cookstove to those that did not learn). Strategies that influence all households equally (technical improvements to the chimney cookstove, homogeneous incentives, generic messages) will be less efficient at the population level. Sample size calculations from the estimated variances are briefly discussed in A.2 in the Supplemental material.

4.1.4. Metrics of stove use

We found that metrics of sustained use such as the percent of days in use (for a single stove) and the percent stove-days in use (for a group of stoves, Equation (8)) can summarize the number of stoves active in a monitoring period. Therefore these metrics are enough to count the stoves completely abandoned and to quantify population seasonal patterns at the daily level, such as those due to migration, fuel availability, weather and special events. These metrics alone, however, are insufficient to differentiate how frequently the stoves are used every day. Measuring the number of daily cooking events and the daily time of stove use is important to identify the homes that cook all tasks with the new stove from those that combine it with other stoves and fuels to fulfill all their needs. In this regard, metrics such as the average meals in T (Equation (10)), the meals per days in use (for a single stove), the meals per stove-day in use (for a group of stoves, Equation (13)) and other metrics of time of use such as the hours of usage or the degree-days could be more useful to quantify the level of stove activity at individual or population levels with higher resolution. These metrics can be helpful to study correlations with other parameters of stove performance such as fuel use, emissions and exposure reductions. In Table 4 we tabulate the metrics discussed in this paper and highlighting the usefulness of each.

Fig. 4 shows the correlation between the percent days in use (x-axis) during each monitoring period and its average daily meals. It illustrates that among households with stable 100% days in use (A and B) some may cook only one of the main meals on the chimney stove (A), others cook all three meals with it (B) and others abandoned the stove (C), in this case because they migrated. This highlights the necessity to measure usage at the meal level to understand adoption dynamics, and the need to monitor the prevalent use of open cookfires to quantify the total impacts brought by the cookstove.

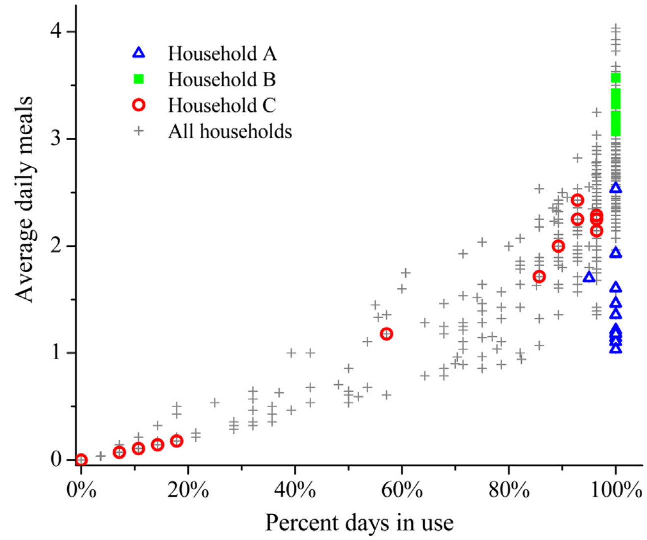

Fig. 4 – Percent of days in a SUMs-monitoring period that households in the CRECER study used the chimney cookstove (x-axis) in relationship with the average daily meals in the period that they cooked with it (y-axis). Both households A and B score the same intensity of cookstove use as measured in percent stove-days. However, through the 16 monitoring rounds B consistently cooked all main meals with the chimney stove, while A cooked only 1.4 meals on average, presumably combining the use of an open cookfire. Household C gradually disadopted the chimney cookstove.

4.2. Comparison of stove use indicators

We compared the SUMs measurements against recall questionnaires and field surveys (Fig. 5) since the latter two are the main indicators currently used in household energy projects. The purpose of this comparison was to examine the consistency between SUMs and questionnaires, and to discuss the usefulness of each to quantify the stove adoption process.

Two questions were compared against the actual SUMs-measured use recorded during the 15 days and three months preceding the questionnaire: Question 1 (Q.1) “Are you using the Plancha stove for cooking?”, with responses: “Yes” or “No”, and Question 2 (Q.2) “In the past three months, how often did you use the open cookfire?” With responses: “Daily”, “2–4 times per week”, “once per week”, “twice per month” or “once per month”. The last three categories were clustered. Fig. 5 shows the distribution of binary responses for cookstove use (Q.1, upper graphs) and the ordinal categories for frequency of open-cookfire use (Q.2, lower), compared against the SUMs measurements.

In this population, reported cookstove use was consistent with the SUMs measures, even for the cases when the chimney cookstove was not used. The variances of the group of admitted users are small and in only one case cookstove use was over-reported (Fig. 5, Q.1). The six households that reported not using the chimney cookstove had a median of meals smaller than one meal. The consistency between the methods is noteworthy considering lower recall accuracies found in similar study populations for measures of HAP exposure [22] and for health outcomes not related to HAP [23]. We consider that the high agreement is associated with the frequent interaction and long-term relationship of the RESPIRE/CRECER field personnel with the study participants, and that there was no direct incentive to exaggerate or under-report usage.

Interestingly, the six households that reported not using the cookstove responded affirmatively to question: Q.4 “Is the family happy with the cookstove?”. Indeed, there was no negative answer to this question in the full CRECER population of 557 participants. Conversations with the local staff at the end of the study suggested that participants perceived Q.4 as a question about their happiness with the fact that a chimney cookstove was given to the family, not a question about their actual satisfaction with the cookstove. In the space provided for observations in the recall questionnaires, the fieldworkers noted that three of the six nonusers did not like the cookstove,

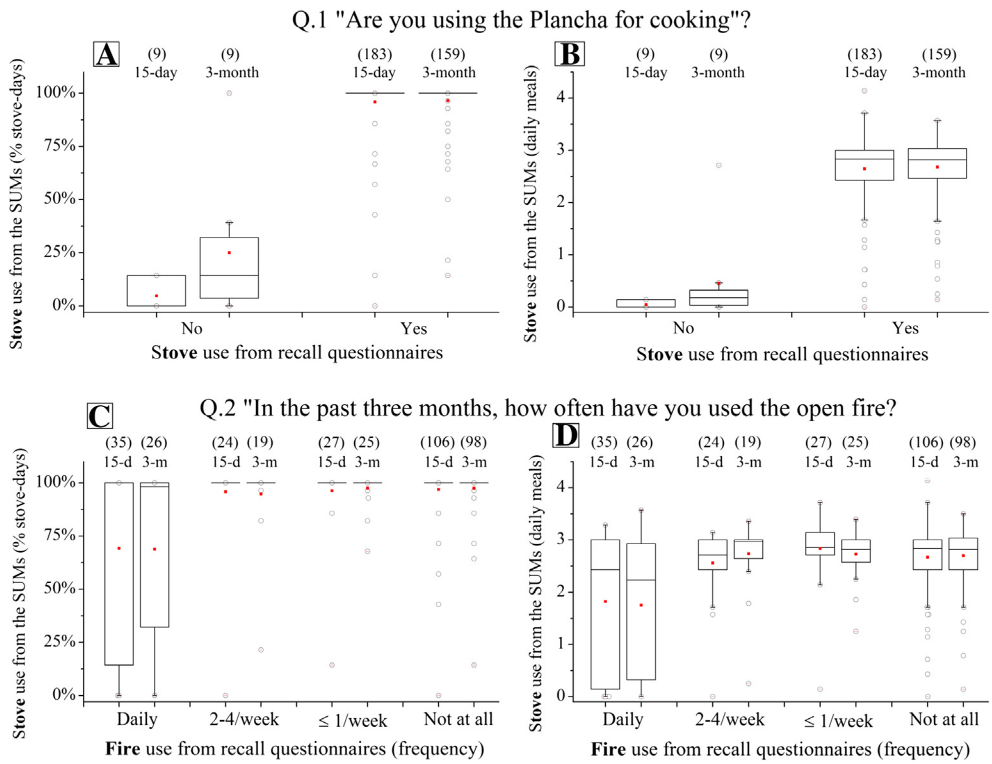

Fig. 5 – Compared cookstove usage from recall questionnaires (horizontal axes) and SUMs measurements (vertical axes) in the CRECER study. The SUMs usage was quantified in percent stove-days compared to total possible in the period (A and C) and in average daily meals (B and D). The binary reports of cookstove use (A–B) are consistent with the SUMs measures of the 15-day (left boxplot) and 3-month (right boxplot) periods that preceded the questionnaire. The reported frequency of open cookfire (C–D) followed an inverse relationship with measured cookstove usage, with daily cookfire users contributing most of the variance in cookstove use. The estimates for the 15-day and 3-month periods were not significantly different. In the boxplots the red dot represents the mean, the center line the median and the box encloses the interquartile range (25th–75th percentile). The whiskers show the 5th and 95th percentiles of the distribution and the hollow circles outside this range are outliers. The sample size in each category is displayed in parentheses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and that other three did not have dry wood to use it. Of these six, only one cookstove was classified as "in bad shape" upon a brief inspection by the fieldworkers. Although the sample size of nonusers is small in our study, these comparisons illustrate that household surveys can complement the stove use indicators from the SUMS and the questionnaires. They highlight as well that the right indicators of stove status must be selected to differentiate between abandonment of the stoves, incorrect operation by the households, lack of maintenance and normal wear. In short, some stoves could be found in good shape because they have not been used at all. These objective measures possible with the SUMs can help reduce misclassification errors, enabling stove use or stove status rather than stove type as the explanatory variable in future analysis for health effects and other impacts.

Not surprisingly, the group of six households that reported not using the chimney cookstove reported using the open cookfire daily. The reported frequency of open-cookfire use followed an inverse relationship with the averages and medians of the SUMs-measured cookstove use (Fig. 5C–D), with most of the variability in the SUMS measurements being introduced by those reporting an open cookfire on a daily basis. Still, the group of daily cookfire users had medians close to 100% stove use and 2.5 meals cooked in the stove. Fig. 5D provides evidence of the stacking of cooking devices and depicts how high population-levels of cookstove use can consist of diverse individual profiles of combined chimney-cookstove and open-cookfire use. Therefore, although quantifying the intensity and variability in cookstove usage is important to understand stove adoption, it is also critical to simultaneously verify the reductions in open-cookfire practices.

In Fig. 5C–D the sharp difference between the daily cookfire users and the other three cookfire frequency categories suggests an important tipping point in the behavior of cookstove use. If the responses to the cookfire frequency question were as accurate as those about chimney-cookstove use, it would seem that an effective starting point to improve cookstove usage in this population is to focus in helping daily cookfire users to limit their cookfire activity by switching to the chimney cookstove the cooking tasks still performed with the open cookfire. As discussed in Section 4.1.3, this would reduce the between household variance and would be one of the most effective strategies to increase the population average of cookstove usage. Of course, the cooking needs, cultural practices and other factors associated with daily cookfire use must be considered to determine the specific strategy to accomplish this change.

In both questions Q.1 and Q.2 there were no statistically significant differences between the 15-day and 3-month statistics of use, even though Q.1 was not specific about the time period. This reflects the high correlation between repeated measures brought by the stability of cookstove use behavior in this population and the small magnitude of the seasonal variations. SUMs analyses like this one can also be useful to determine questionnaire accuracy and to gain insights about the mental accounts of respondents to recall questionnaires of cooking practices.

5. Conclusions

Stove use is a critical link between access to the improved stoves and the actual delivery of their benefits to the users. Therefore, impact assessment of stove programs requires to clearly differentiate between the number of stoves initially accepted (simply brought in to the household) and those actually used through the years. Although central, the role of the stove user in the cooking system is often overlooked and there have been no quantitative metrics to assess adoption dynamics and understand the factors that affect user behavior to assess and design dissemination strategies. In this paper we introduced metrics for the objective quantification of cookstove usage with small low-cost temperature dataloggers as SUMs. The SUMs enable a new analytic framework that places sustained use as a cookstove performance parameter that can be measured, systematically monitored and evaluated together with fuel use, climate-altering emissions, air pollution exposures, and other stove-related impacts.

Households with high levels of sustained cookstove use could still be exposed to elevated concentrations of air pollutants from the continued use of open cookfires or from other open-fire practices. Therefore, quantifying and monitoring the residual use of these fires are crucial to understanding the dynamics and evaluate the impacts of the stove adoption process. Placement of SUMs in all the stoves and fires present in the home and co-location of SUMs and air pollution monitors (Fig. 2) can enable identification of the stoves that are used inside the kitchen environment. These measurements can also help characterize other behavior-factors related to exposure such as kitchen ventilation, stove operation and stove maintenance practices. These issues are explored in an upcoming publication that incorporates simultaneous measurements of the continued usage of open cookfires in each household.

The relevance of our study is three-fold: it outlines a methodology for the use of the SUMs, demonstrates its accuracy and resolution, and illustrates the application of its results to study design and to select strategies for improved use based on the variability and dynamics of the adoption process. It also can herald a new era of research to elucidate the behavioral determinants of usage, which has not been possible previously at larger scales due to a lack of an objective measure of that usage.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2013.07.002.

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