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Fuel use and design analysis of improved woodburning cookstoves in the Guatemalan Highlands

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ABSTRACT

This study examined the fuel use and design of an improved woodburning cookstove (*plancha*), in comparison to traditional cooking over an open woodfire. These cookstoves had been randomly introduced into population households in the Guatemalan Highlands that had previously used open woodfires. This research consisted of: (1) a 12-household Kitchen Performance Test (KPT) over a 4-day period and (2) single-day participant observation in five households. The KPT monitored fuel consumption and the number, age, and gender of people who were cooked for, while the participant observation was used to form a complete understanding of fuel use patterns and to examine the influence of stove condition and cooking behavior. In spite of fairly low variability in the fuel use data (coefficients of variation of about 0.34) the KPT did not show statistically significant differences in fuel use between the two cooking methods. It is possible that increased study power through a larger sample size may have resulted in a statistically significant difference in favor of the *plancha*, but it is doubtful that the size of the effect would be of any practical significance. Thus, although other studies have shown that the *plancha* is extremely effective in reducing indoor air pollution in the study area, the KPT did not indicate that it offered any benefits with respect to fuel use. Practical and experimental recommendations for future cookstove efficiency studies are presented, with directions for continued work in this area.

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1. Introduction

Several hundred improved cookstove projects currently exist worldwide, ranging from local NGO (non-governmental organization) projects to the single remaining nationwide initiative in Nepal [1]. These projects and associated research commonly focus on reducing exposure to air pollution and/or reducing fuel use, yet several other important considerations

include stove impacts on the hygiene, the time required for household tasks, and greenhouse gas emissions [2]. It is estimated that nearly half of the world population relies on biomass for household energy, accounting for about 10% of all human energy use [3] and 1.5 million premature deaths annually, through associated exposure to air pollution [4].

Reduction in fuel use is perhaps the most compelling reason for consumers to adopt an improved stove. Thus,

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whether based on government and donor programs or commercial marketing, there is a need to understand the fuel use of a proposed new stove as well as the performance of existing in-place stoves. In addition, knowledge of fuel use is necessary to evaluate the environmental benefits of stove introduction, particularly those related to reduction of deforestation and direct greenhouse gas emissions.

Reliable measurement methods are thus needed both for evaluating a new design in controlled non-cooking conditions (“efficiency” tests), controlled field conditions with cooking (“efficacy” tests), and in uncontrolled field conditions to determine the actual changes of fuel use in practice (“effectiveness” tests). These are part of a suite of tests investigating stove performance, which also include cooking speed, ease of ignition, turndown ratios, etc. Here we use the strict engineering definition for efficiency: a unitless ratio of energy applied to usable energy obtained. In this case, the efficiency is expressed as the ratio of energy in the pot to the energy in the fuel, according to the First Law of Thermodynamics, i.e. not considering energy quality.

In light of the complex interaction between fuel parameters and stove design, reliable stove comparisons should be made on the basis of fuel-stove combinations even with efficiency tests [5]. Measuring and comparing cooking efficiencies for solid-fuel stoves is surprisingly difficult, particularly in the “effectiveness mode”. Several efficiency-related tests were developed by NGOs in the early 1980s [6], and are recognized throughout the cookstove community. These tests principally comprise the Water-Boiling Test (WBT, an efficiency test), the Controlled Cooking Test (CCT, an efficacy test), and the Kitchen Performance Test (KPT, an effectiveness test). Since then there have been a number of modifications to the WBT. For example, national versions were widely deployed during the Indian and Chinese improved stove programs, which ran from the early 1980s to the late 1990s. The KPT, however, has undergone relatively little change and systematic evaluation, although there do exist ongoing efforts to improve it [7]. A search of the peer-reviewed literature revealed a single published evaluation [8], which found that existing lab-based tests, unlike the KPT, are unreliable predictors of actual household fuel consumption. In this evaluation, Bailis et al. acknowledge the difficulties of implementing field assessments such as the KPT. A central objective of the present article is to provide a more in-depth analysis of the KPT method.

As part of RESPIRE (Randomized Exposure Study of Pollution Indoors and Respiratory Effects), a randomized trial of improved wood-burning chimney cookstoves to determine health effects of woodsmoke in women and children, we conducted KPTs to evaluate the impact of the stove on household fuel use as compared to the traditional open woodfire. After describing the site and stove, we detail the implementation of the KPT and the results obtained. We end with a summary of research conclusions and recommendations for future research.

1.1. The site

Locally constructed *planchas* (see Fig. 1) were installed in 250 of 500 participating households in the western Guatemalan

Highlands, creating equally sized experimental and control groups for RESPIRE. The *plancha* was developed in Guatemala and has been constructed locally for over 25 years. It is a high-mass stove with an enclosed combustion chamber and a flue to remove smoke from the kitchen [5,9]. A metal door provides access to the combustion chamber at one end of the stove; a flue with a damper, allowing the user to control airflow through the combustion chamber, is located at the opposite end (see Fig. 2).

The cooking surface is constructed from a steel plate, measuring approximately 46 cm × 92 cm. Three holes are cut into this plate to allow for improved heat transfer from the combustion chamber to the pots. The holes are different sizes (approximately 28 cm, 21 cm, and 14 cm); the largest is located near the fuel access door, and the smallest is located near the flue. The stove comes with metal disks and rings that accommodate different pot sizes, and can be used to cover the holes, creating a flat cooking surface.

The *plancha* body is constructed of cement blocks, fire bricks around the combustion chamber, and dirt insulation. The working surface surrounding the steel cooking surface is faced in tile. The *planchas* in this study were constructed at a cost of more than US\$100. Although the steel plate is an important cost element (approximately 25%), it is a critical part of the stove’s attractiveness since it allows cooking of tortillas without smoke in the kitchen and provides a degree of space heating, which is desirable in the Guatemalan Highlands.

The *plancha* was compared to an open-fire method of cooking, both using the same woodfuel. Although several households indicated that they cooked directly on the floor in the past, all of the open-fire households in the study used an elevated hearth raised approximately 0.25–0.5 m above the floor, locally called a *poyo*. These hearths are typically located in a corner of the kitchen.

Improved indoor air quality is the primary motivation driving RESPIRE, and considerable resources have been devoted to measuring health benefits and pollution levels. Fuel performance in comparison to an open fire has yet to be conclusively determined, despite several studies [9–11].

Deforestation is not an immediate danger in the Guatemalan highlands, but restrictions against logging and the cost of fuel have a direct bearing on household livelihood as 56% of Guatemalans, and 76% of the indigenous population, live in poverty [12] and 97% of rural households depend on woodfuel [13]. This research was conducted in indigenous Mam Mayan population in San Marcos, one of the poorest departments in the country. Although the specific impacts of stove fuel use may change depending on region and season, assessing fuel use accurately in field conditions is an integral component to cookstove evaluation.

2. Methods

The following sections of this article review the KPT and participant observation research methods. Information from both assessments was used to develop research conclusions. We received institutional review board approval for this research from the University of California, Berkeley



Fig. 1 – Shown is the *plancha* (clockwise, beginning at top left): combustion chamber; exhaust flue; work surface; and placement in a household kitchen.

Committee for the Protection of Human Subjects. Each household that consented to participate signed a Spanish language consent form, and where necessary, Mam translations were provided by fieldworkers.

2.1. Kitchen performance test: Methods

The KPT was selected over the water boiling and controlled cooking tests because it more accurately reflects the *in situ* fuel use of the stove. In the KPT the fuel use comparison relies on consumption data from households in which normal cooking for the family is performed by the usual cook, over several days. The relative advantages and disadvantages of each test are related to the control of variation. There is an inevitable trade-off between efforts to reduce variability and the ability to apply performance results to widespread use across an entire population of stoves. Transitioning from the WBT to the KPT brings an improvement understanding of actual practice, but also introduces an increase in variability. Further, Bari et al. [14] indicate that physical monitoring permits improved estimates of fuel use at the household level when compared to estimates that rely solely on survey data.

The KPT conducted in this study was based primarily on the protocol published as part of the Shell Foundation, Household Energy and Health Project [7] and the previous pilot study conducted by Kuwabara [11]. It combined physical monitoring and surveying. The most significant difference was an increase in the number of days from four to five, and the provision of uniform firewood supplies to participant households.

This research consisted of: (1) a 4-day KPT in 12 households to examine fuel use; and (2) single-day participant observation in five households to elicit qualitative design and usage data. In both portions of the study *plancha* households were compared to households using open fires for cooking. An analysis of the quantitative and qualitative data was performed to reach a set of conclusions regarding: the advantages and challenges of implementing a KPT study; the fuel performance of the *plancha* with respect to open-fire methods; and evaluation of the *plancha* design.

The wood used in the study was acquired from local sellers in two large batches. Each batch was oak, the preferred wood type in the study communities. The first batch of wood was kept indoors and dried for more than 2 weeks prior to delivery.

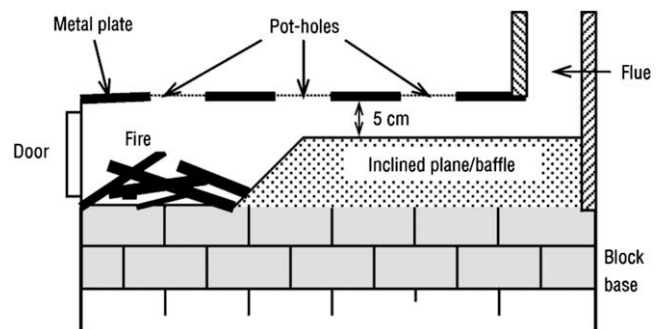


Fig. 2 – Cross-sectional view of the *plancha* taken directly from [9]. The designs evaluated in this study also contained a damper in the lower portion of the flue.

The second batch had a higher moisture content, and was delivered to households within 2 days of receipt.

Moisture affects the burn rate for wood and when moisture content is high enough can affect the ability to ignite. Moreover, fuel moisture has a complex interaction with the two major components of stove efficiency: combustion efficiency and heat transfer efficiency [5]. Although electronic moisture meters are available, we elected not to use them because of their recognized inaccuracy outside of a tight, pre-specified range. In addition, the meter measurements are location-specific across the fuel specimen, and even though moisture content can vary significantly within a given piece of wood, there is no standard protocol to estimate overall moisture content from a set of meter measurements.

During recruitment, each participating household was asked to estimate their fuel needs. This estimate was increased by 25% to determine the approximate amount of wood to deliver each day. On the first day of the study the initial supply of wood for each household was weighed and counted, and participants were reminded to only use the wood provided by the study for the remainder of the KPT. The wood was stored in a designated area in each household. On days 2–4 the delivered wood and the wood remaining from the previous day was weighed and counted (see Fig. 3). In addition, a set of questions was asked in order to determine the number of meals served the previous day, and the age gender and number of people served at each meal.

On the final day, the remaining wood was weighed and counted, and questions were asked, but no wood was delivered. Participants were aware that they would be permitted to keep any wood remaining on the final day of the study thus providing some incentive to be as careful with its use as they would be with their own fuel supply. The primary tools and hardware used in the KPT were: two spring scales with 0–100 kg range and a 1 kg resolution; ropes and harnesses for wood transport; and bags for weighing up to 15 pieces of wood at once.

Over a 2-week period, six open-fire and six *plancha* households each generated four fuel use data points, one per day. These data were averaged for each household, resulting in a total data set of $N = 12$. As the KPT included daily fuel use, the number and age of people served at each meal, and the

number of meals served, fuel use can be expressed in several ways. As consistent with the protocol, the metric reported here is kilograms of fuel per person-equivalent-meal served (kg PEM^{-1}). Comparisons are not significantly different using other common metrics. Person meals were scaled to adult male equivalents; a child under 14 years was counted as 0.5, an adult female at 0.8, and a senior adult male at 0.8, as suggested by Baldwin [15]. Two sets of analyses excluding and including *refacción* were conducted. *Refacción* is preparation of snacks, which takes place in the mid-morning typically involving preparation of a hot beverage prepared from some of the following ingredients: milk, water, rice, corn, and sugar.

2.2. Participant observation: Methods to examine design and usage

Participant observation, “a way to collect data in naturalistic settings ... [to] observe and/or take part in the common and uncommon activities of the people being studied” [16], was used to support understanding of fuel use and to examine stove design. The short-term participant observation approach in this study was similar to that presented in Sandhu et al. [17]. One researcher and one fieldworker together conducted single-day participant observation study in five households in two communities (see Table 1). Three households used *planchas* and two used open fires. The fieldworker was fluent in both Mam and Spanish, while the researcher spoke Spanish only. There was need for Mam translation at one of the five participant observation households.

Though other households in these communities had participated in the KPTs, none of the KPT households were included in this portion of the study. This eliminated biases that may have existed if a household had participated in both studies. Participant observation typically spanned two complete meals per household. The goal was to gain an understanding of behaviors relevant to fuel use and *plancha* design. The three research questions guiding the participant observation were: (1) What behaviors impact fuel use?; (2) How do these behaviors differ between stove and fire households?; and (3) How do participants interact with different features of the cookstoves and fires?



Fig. 3 – KPT daily delivery bundles (left) and in-home weighing process (right).

Table 1 – Details of the five participant observation households.

Date	Community	Household type	Household Size			Start time	End time
			Men	Women	Children		
25-Jul-05	A	Open fire	2	2	5	06:00	16:30
26-Jul-05	A	Plancha	1	1	4	06:05	12:30
27-Jul-05	A	Open fire	0	2	3	12:50	19:00
28-Jul-05	A	Plancha	0	1	7	06:20	13:25
29-Jul-05	B	Plancha	1	1	6	07:00	11:30

Data collection consisted of short-term participant observation, including informal interviews and direct observation. Photographs addressing each of the three research questions, and measurements of stove surface temperature and airborne particulates were used to supplement fieldnotes. Surface temperature was quantified using a handheld infrared thermometer, and particulates were monitored with sensors that use an LED (light-emitting diode) and collection chamber to measure optical scattering. The unstructured nature of the observational portion of the study was critical to understanding fuel use and *plancha* design, as both were poorly understood prior to this study. In contrast, studies that utilize direct, structured observation make assumptions about important behavior in advance of fieldwork [18].

Data analysis of fieldnotes and photographs began with iterative codebook development [19]. The final codebook contained 17 unique, descriptive codes and was used to index the entire data corpus. Using the data analysis framework of Miles and Huberman, this was followed by: data reduction; display of textual, photographic, and code frequency data; and “conclusion-drawing” [20].

During the first week of measurements, it was noted that one of the spring scales was reading incorrectly. Review of the fieldnotes indicated that the scale experienced an acute reduction in function. A linear relationship between measurements afterwards and those before was found by comparing weightings from both the damaged and undamaged scale. The correction factor found was used to adjust the data used in all presentations and analyses.

3. Results

Table 2 and 3 summarize the results of the KPT tests. Including *refacción* as a full meal in the calculation of person-equivalent-meals (PEM), the KPT data showed that the average consumption of the *plancha* was 1.36 kg PEM⁻¹, while that of the open fire was 1.24 kg PEM⁻¹; i.e., the *plancha* used approximately 10% more fuel than the open fire. Excluding *refacción*, as shown in Table 3, the average fuel use of the *plancha* was 1.69 kg PEM⁻¹, while that of the open fire was 1.57 kg PEM⁻¹, representing an 8% increase in fuel use for the *plancha*. t-Tests indicated that both results were highly insignificant, with $p > 0.65$ and $p > 0.72$, respectively).

As the results with and without *refacción* are similar and participant observation and informal interviews of KPT households suggested that the amount of wood used to cook *refacción* varies only slightly with number served, the summary

data in Table 2 and the rest of the analysis here does not consider the *refacción* as a separate meal. Table 3

Cohen's effect size was calculated to gauge the magnitude of the observed difference in fuel usage. Cohen's effect size is defined as the difference between means divided by the (pooled) standard deviation, and is a commonly used measure in t-test analyses. Convention holds that an effect size of 0.2 is “small,” 0.5 is medium, and 0.8 is large [21]. In the KPT Cohen's effect size was approximately 0.23, representing a small difference in fuel use between the *plancha* and the open fire. Effect size can also be viewed as an indicator of the degree to which two data sets overlap. The effect size in the KPT corresponds to roughly a 15% overlap. Finally, an effect size/power analysis was performed to determine the approximate number of households that would be required to detect an effect size of the magnitude found in the KPT. Assuming that the effect size measured in the KPT were maintained, results of 10% significance and 80% power would require 176 total households to reach significance.

In addition to statistical significance, the relationship between daily fuel consumption (kg PEM⁻¹) and person-equivalent-meals cooked was investigated. As reflected in Fig. 4, fuel consumption decreases monotonically with an increase in person-equivalent-meals. The data are not sufficient to determine whether this is due to a statistically significant economy of scale, which would indicate a *nonlinear*

Table 2 – KPT data, *refacción* included.

Household	Average fuel use (kg PEM ⁻¹)
Plancha1	1.81
Plancha2	1.21
Plancha3	0.936
Plancha4	2.02
Plancha5	1.29
Plancha6	0.903
Average	1.36
Standard deviation	0.459
Coefficient of variance	0.337
Open Fire1	1.78
Open Fire2	1.69
Open Fire3	1.34
Open Fire4	1.00
Open Fire5	0.845
Open Fire6	0.785
Average	1.24
Standard deviation	0.431
Coefficient of variance	0.348

Table 3 – KPT data, *refacción* excluded.

Household	Average fuel use (kg PEM ⁻¹)
Plancha1	2.31
Plancha2	1.19
Plancha3	2.51
Plancha4	1.28
Plancha5	1.70
Plancha6	1.13
Average	1.69
Standard deviation	0.604
Coefficient of variance	0.357
Open Fire1	2.34
Open Fire2	1.85
Open Fire3	1.81
Open Fire4	1.21
Open Fire5	1.20
Open Fire6	1.04
Average	1.57
Standard deviation	0.497
Coefficient of Variance	0.316

relationship. Were this trend significant, the units of person-meal should be modified to eliminate the implication of a linear relationship.

3.1. Participant observation: Design and usage findings

The findings presented in this section derive primarily from the participant observation households, yet they also draw upon observations and interviews in the 12 KPT households. Given that the goal was to examine social and behavioral factors related to fuel use and *plancha* design, the main limitation of the dataset for the observational study was not the household sample size, but rather the limited number of communities that were involved. Recognizing that single-season observation was a limitation of our study, we asked direct and indirect participants about seasonal variations in practices.

In the developing world, the most common form of open combustion consists of “three rocks or brick holding the pot

above an open fire” [5]. In our study’s households, 2–3 concrete blocks were used around open fires. Open-fire houses universally used a *comal* (round flat earthen or metal pan) solely for cooking corn tortillas (Fig. 5). As with the *plancha*, a solution of lime and water is applied to the surface prior to use to clean and to prevent the (dough) from sticking.

On a typical day, a woman starts the first fire around 6:00 a.m., independent of season. Throughout the day, the *plancha* will be operated by this woman, possibly with the assistance of other women. *Plancha* households maintain different schedules for cleaning the flue and the combustion chamber despite specific maintenance instructions from the RESPIRE project. The combustion chamber is not cleaned daily, but when it is, it is usually cleaned by hand before the first fire.

In both open-fire and *plancha* households, matches are used to light kindling or a small candle is used in place of kindling. In *plancha* households, the fuel is placed inside the combustion chamber via the door and the pot hole closest to the door. In both household types significant bellowing is often required to start the fire, suggesting similar exposure to pollutants during this brief period for both cooking methods.

Breakfast is cooked between 6:00 and 8:00 a.m. and is followed by *refacción* about an hour later, and lunch is started just before noon. Some households cook food for tortilla dough or for the animals only in the afternoons, while others do so while preparing other meals for the family. Dinner preparation begins around 6:00 p.m. and the fire is extinguished at approximately 8:00 p.m. Some *plancha* households maintain a fire for much of the day, effectively “warm-starting” the *plancha* (see Fig. 6). At least one household let the fire die out completely after each meal. Such differences in cold-starting and warm-starting can confound fuel use data since much of the heat generated by fuel combustion is lost into the mass of the stove.

To measure the presence of harmful airborne particulates for the cookstove intervention, sensors were installed in participating households. Fig. 7 contains a plot that reflects airborne particulates in a *plancha* household over a 24-h period. Several of the findings from the observation portion of this research are replicated in the plot, reinforcing the validity of the observational results. The first spike indicates a cooking event at 8 a.m.; this is a bit later than the majority of households, but within the approximate 6–8:00 a.m. range identified during observation. The smaller set of peaks from 12 to 2:00 p.m. confirm the observations that placed lunchtime around noon. The observations also noted that dinner began around 6:00 p.m. and that the fire is generally extinguished by 8:00 p.m. The final two spikes in the plot reflect similar timing, to within an hour.

Heating, and to a lesser degree, lighting usage are important aspects of cookstove design. In the study communities, cooking and lighting tasks were typically independent. The kitchen was typically located in a separate structure apart from the living quarters, so that the *plancha* and open fire did not contribute to lighting or heating the home. About half of the homes in our study - compared with 76% of all RESPIRE all households - had electricity, but they used their electric bulbs sparingly. Participants reported that electric lighting was commonly used for 2–3 h in the evening, and sometimes on winter mornings before the men went to work. The

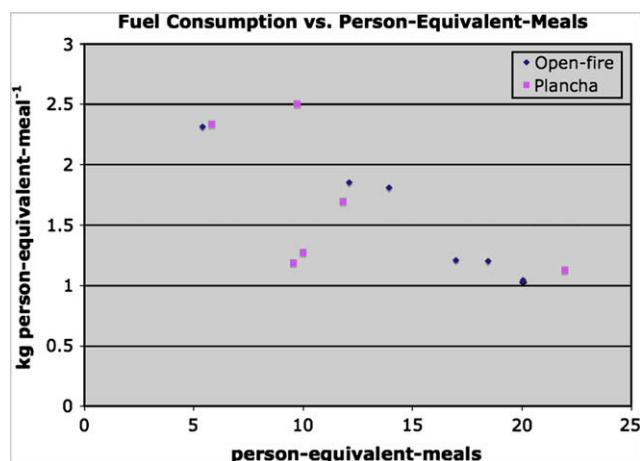


Fig. 4 – Fuel consumption versus person-equivalent-meals cooked for both *plancha* and open-fire households.



Fig. 5 – (Left) an open-fire household uses concrete blocks and a metal rack to support pots. (Right) cooking of tortillas.

households without electricity used homemade lamps constructed from a glass bottle, wick, and kerosene.

The *plancha* and open fire are not used directly for heating, yet heating still plays a role. Participants were witnessed sitting near the open *plancha* door in order to warm themselves. In this same household, the fire was used to heat towels to warm a newborn child. Based on the study observations, modifications to the *plancha* design that affect the ability to heat by reducing thermal losses, or changing the location of the access door, might affect the acceptability and ultimate adoption of the technology.

Leveraging the results of a fuel survey undertaken in the RESPIRE study area [22], we asked questions about wood use and acquisition behaviors. Obtaining such information is a challenge given the “sensitivity of disclosing locations and harvesting practices of fuelwood” [22], particularly for more formal methods such as surveys and structured interviews. Participant observation, including informal interviews and researcher participation in illegal tree felling, suggests a combination of acquisition methods including, but not limited to formal purchase. Independent of how wood was obtained, participants emphasized the significant investment of time, effort, and resources that the task required. This implies that a stove that significantly decreases fuel use would be of substantial benefit.

Vigilant tending of an open fire can drastically alter fuel performance [5]. Observations suggest that behavioral effects on fuel performance include: selective placement of wood during open-fire burning, parallel management of cooking tasks, and saving partially burned wood for future use. Study participants from both household types often indicated a perception that the *plancha* is more efficient than the open fire, most often citing the ability to conduct more tasks in parallel.

A surprising variety of wood-drying techniques were observed in the study households. That is, there was a higher degree of inter-household variation for wood-drying in comparison to other cookstove-related behaviors. One participant indicated that she dried wood by placing it in the sun. Another simply stored the wood in a dry location. Other techniques included above-fire rafter storage, placing wood very near the fire, and placing wood on the *plancha*. Different drying and storage practices are expected to drastically alter the moisture content of the wood, which in turn affects fuel

combustion and emissions, and time to burn. The KPT did not measure time of cooking tasks, but others have established that the *plancha* takes longer than the open fire for standardized tasks [9,10].

Interaction with and use of specific features of the *plancha*, was also observed. The removable damper was not often used, and in one case had been lost for several months. The door, though perforated, was left open for most of the day in every observed household. Multiple participants echoed the sentiment that the fire doesn’t burn if the door is closed, especially with “green” wood. When closed the metal door became extremely hot, which is potentially dangerous, as the door is located at the head height of a 3–5 year-old child.

At times, mispositioned pots allowed visible quantities of smoke to enter the kitchen through the pot holes. Cracks in the tiles at the edges of cooking surfaces and one water-rotted flue also allowed smoke to enter the kitchen. Such wear and damage on these relatively new stoves (all less than 3 years) suggest that differing physical conditions could have negatively affected stove performance. This was not observed in the efficacy study done earlier in Guatemala, which first screened out poorly maintained stoves [9].

The tiled worksurface surrounding the cooking surface was used frequently and was viewed by participants as a key advantage over the open fire. Consistent with anecdotal reports from the RESPIRE project, the *plancha* was highly desirable and accepted across all study households. The primary reasons cited were the reduction in smoke, the increased space for cooking tasks, and the comfort of cooking while standing.

4. Discussion

The confounding variables most likely to have impacted this study were the differences in the moisture content of household wood supplies and low-quality scales. Given the small difference in fuel use that was measured, 12 total households was not sufficient to bring the comparison to 10% statistical significance. A simple statistical power calculation shows that for the small effect size observed in the KPT (0.23), roughly 175 households would be required to reach 10% significance and 80% power. However, were it proven significant, the small difference in fuel use obtained in this sample simply may not

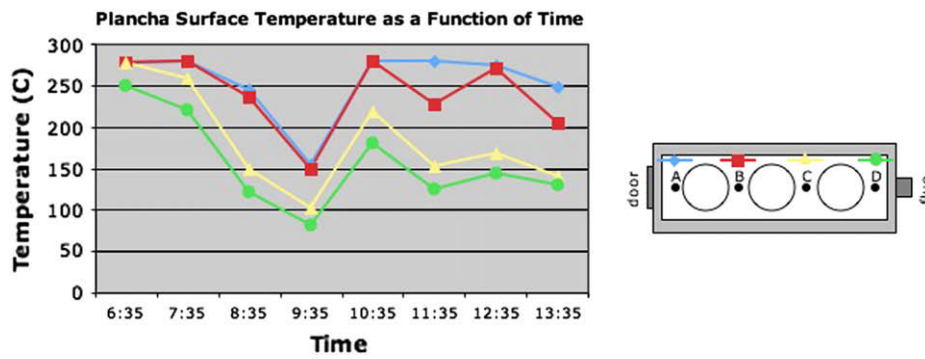


Fig. 6 – Plancha temperature measured hourly at four different points on the cooking surface (A is closest to access door, D is closest to flue) for a household with “warm-starting” behavior. Between the early-morning and mid-morning meals, the plancha surface never fully cools.

be high enough to motivate household changes, donor funding, or promotion by an outside agency.

Interestingly, in interview households women reported that the *plancha* was noticeably more efficient than traditional methods. The discrepancy with our results may be for any of the following reasons, in decreasing order of likelihood based on our findings: (1) the community implicitly assumed that contained fires are more efficient than open fires; (2) participating households were reluctant to offer negative feedback to researchers working for a project that had given them the stoves, free medical care, and other benefits; (3) community members understood the concept of efficiency differently than did the researchers; (4) as a study spanning only a few days, the KPT did not capture cooking practices which vary across seasons, festivals, and days of the week.

Although the participant observation provided useful behavioral and technological insights regarding fuel performance, the findings are based on households sampled from only two communities. The overall sample size is less of a concern than the small number of sites from which these households were drawn. Selecting households from a broader set of communities would likely provide a richer qualitative

understanding of cookstove design and fuel performance. This research could be strengthened by a micro-analysis of the actual cooking events, focusing on time-to-cook and cooking subtasks. Such a micro-analysis would have relevance both to performance (understanding utilization) and design (e.g. enclosed cookstoves with two instead of three pot holes have been shown to be much more efficient [15]). Finally, a focus on understanding the cultural perceptions of this technology and of efficiency could possibly explain the discrepancy between our results and household reports of *plancha* efficiency.

5. Conclusions

Although this study was conducted in a specific location with specific communities we believe there are lessons for evaluating fuel consumption of wood-fired cookstoves in diverse environments. The measures taken to reduce the variance in data (consistency in woodfuel, regular timing of wood distribution, use of person-meals counts, etc.) seemed fairly successful, resulting in coefficients of variance of only about

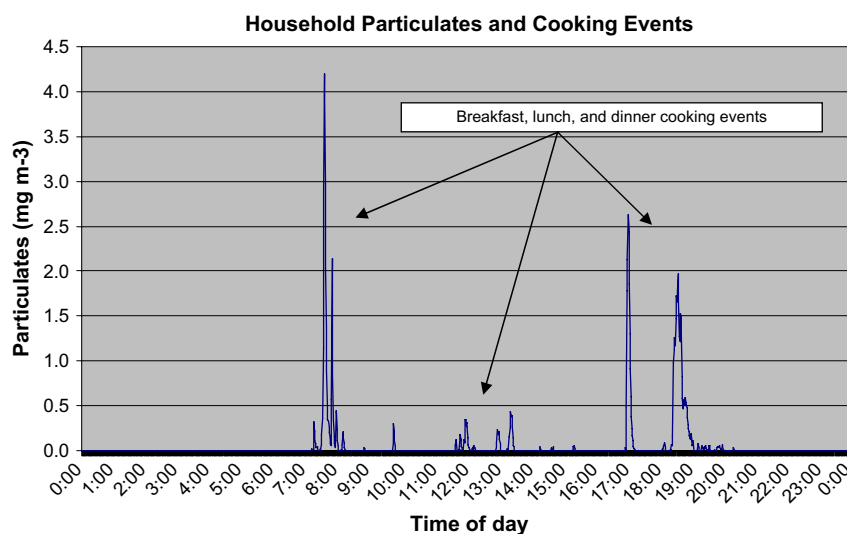


Fig. 7 – Airborne household particulates as an indication of cooking events.

one third. Any further reduction would likely require measures that would reduce the applicability of the results to target communities.

Although the KPT can be difficult to control, it has the advantage of reflecting *true* fuel consumption in study households as they proceed with their everyday cooking activities. Laboratory-based investigations such as the water-boiling test can be employed as a screening procedure to identify inefficient stove designs early on, yet should not be relied upon as the only method of fuel use assessment. Therefore it is worthwhile to consider changes in the KPT protocol that could be adopted to generate results of higher significance.

To more tightly limit the sources of uncertainty inherent in the KPT, it is recommended that the protocol be revised to reflect a more careful consideration of the households participating in the study. The simplest means of reducing variance in the data is to match study participants based on household size, thus mitigating any potential economy of scales effects. In addition to matching households based on size, it is recommended that the protocol be changed from a between-subjects design to a within-subjects design. Each household in the study should use both cooking methods rather than being restricted to one method, if possible. This would reduce the impact of individual differences in cooking practice by providing a measure that better preserves fuel consumption in individual households, as opposed to grouping households with the same cooking method. Such data pairing requires that each household have access to both methods of cooking, implying that the KPT be performed both before and after implementing the cookstove intervention. Further, users should be well accustomed to the both methods of cooking. This was a limitation of the KPT performed by [9]: *plancha* users who were unaccustomed to cooking with an open fire were asked to use an open fire for the study.

Given seasonal variations in temperature, fuel usage, and cooking, the test should be performed under uniform seasonal conditions. In conjunction with the within-subjects recommendation, this may require that the study be conducted during the same season in different years. This is the ideal experimental case based on the results of this study, and is acknowledged to pose logistical challenges. A reasonable alternative is to use simpler household matching based on household size and community characteristics.

The qualitative aspects of this study contribute to an improved understanding of human behaviors that impact fuel use and stove design. A key recommendation emerging from this work is to formally incorporate short-term participant observation into the published KPT protocol [7]. This integration would help to ensure appropriate interpretation of KPT results. If it is possible to conduct the participant observation, including analysis, before the KPT the results can be used to adapt the field experiment to local conditions.

6. Future work

The most important future work is related to the above recommendations regarding statistically significant and pragmatic KPT results. Several other potential projects are

engendered by this work. Quantifying the effects of local drying practices on reducing moisture content would help researchers understand the relevance of moisture testing during the KPT and would provide a better understanding of how different drying practices impact fuel combustion and emissions. The combined effects of differences in *plancha* design and wear of key components on indoor particle levels, as well as stove performance, should also be examined. Finally, future research might survey *plancha* design and usage patterns across different regions of the country. This research would permit the formulation of a set of design recommendations to improve stove dissemination and/or marketing.

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