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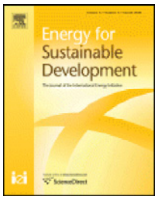

# Using objective measures of stove use and indoor air quality to evaluate a cookstove intervention in rural Uganda

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ABSTRACT

Exposure to combustion byproducts from cooking is a major health concern globally. Alternative stoves may reduce the burden of disease associated with exposure to household air pollution. We subsidized Ugastove-brand rocket stoves to 54 households in six rural Ugandan villages. We monitored kitchen concentrations of fine particles ($PM_{2.5}$) and carbon monoxide (CO) before and one month after introduction of the Ugastove. Temperature data-loggers were affixed to each Ugastove and to the traditional stove (three-stone fire) during the 1-month Ugastove acclimation period to record temporal patterns in stove use and adoption. Household surveys were administered to collect household information that may impact stove use or indoor air quality. $PM_{2.5}$ kitchen concentrations were 37% lower after introduction of the Ugastove (mean reduction: 0.68 mg/m$^3$; 95% confidence interval [CI]: 0.2–1.2; $p < 0.01$). Changes in CO concentrations were small (8% lower; mean reduction: 1.4 ppm, 95% CI: −5.2–7.9) and not statistically significant. During the 1-month acclimation period, 47% of households used primarily the Ugastove, 12% used primarily the three stone fire, and 41% used both stoves in tandem. $PM_{2.5}$ concentrations were generally lowest in households that used primarily the Ugastove, followed by households that used stoves in tandem and that primarily used a three-stone fire. In summary, introduction of the Ugastove in 54 rural Ugandan households was associated with modest reductions in kitchen concentrations of $PM_{2.5}$ but not CO. Objective measures of stove use reveal that short-term stove use varied by household.

## Introduction

Roughly half of the global population (including ~80% of rural households in the developing world) relies on biomass fuels for cooking (IEA, 2006). Exposure to the byproducts of incomplete combustion is associated with numerous adverse health outcomes including chronic obstructive pulmonary disease, acute respiratory infections (especially in children), higher blood pressure, lung cancer, low birth weight, infant mortality, and pneumonia (Baumgartner et al., 2011, 2014; Bruce et al., 2000; Dherani et al., 2008; Ezzati and Kammen, 2002; Kurmi et al., 2010; Smith-Siverstsen et al., 2009). Exposure to indoor air pollution correlates with cooking practices; in low-income countries cooking is primarily conducted by women and children (Balakrishnan et al., 2004; Bruce et al., 2000). The World Health Organization estimates that indoor air pollution is the 4th most important risk factor globally for morbidity (108,084,000 Disability-Adjusted Life Years; Lim et al., 2012).

Switching to cleaner fuels is a promising strategy for improving indoor air quality (Grieshop et al., 2011; Siddiqui et al., 2009). However, in rural areas of developing countries, access to (and ability to pay for) clean fuels is often limited. Strategies to improve indoor air quality therefore generally focus on improved combustion (i.e., more efficient stoves) or altering the cooking environment (e.g., increased ventilation or constructing detached kitchens) (Hutton et al., 2007). Emissions for a variety of alternative-design stoves have been characterized in a controlled setting (Bhattacharya, et al., 2002; Jetter and Kariher, 2009; Roden et al., 2006, 2009). Field measurements of indoor air quality for community-scale alternative stove interventions have been reported in many areas of the world (Albalak et al., 2001; Edwards et al., 2007;

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*Abbreviations:* CO, Carbon monoxide; $PM_{2.5}$, Particulate matter of 2.5 microns or less; UCB, University of California—Berkeley Particle Monitor; URF, Uganda Rural Fund.

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Smith et al., 2007). Exposure assessments have focused on a variety of strategies, including estimating kitchen concentrations before and after interventions (Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007; Pennise et al., 2009) and personal sampling of household members during a stove intervention (Clark et al., 2010; Northcross et al., 2010).

Stove use and adoption are often evaluated using information from self-report surveys; a limited number of interventions use objective measurements based on recording stove temperatures (Ruiz-Mercado et al., 2008; Smith et al., 2007). Studies of adoption rates are sparse and the factors that may influence adoption are largely unknown (Lewis and Pattanayak, 2012); there is a significant need for better collaboration between public health officials and researchers to gain clarity on what drives cookstove adoption (Gall et al., 2013). Few studies integrate real-time objective measurements of both air pollution and stove use (Ruiz-Mercado et al., 2011).

This study evaluates the introduction of a wood burning rocket stove made by Uganda Stoves Manufacturers Ltd. (hereafter referred to as the Ugastove) to 54 households in six villages in rural southwestern Uganda. We assess the effectiveness of this intervention via before-and-after measurements of indoor air quality (fine particles [$PM_{2.5}$]; carbon monoxide [CO]) and short-term (i.e., 1-month) stove use. Our study makes useful contributions in two areas: (1) deploying integrated objective measurements of indoor air quality and stove use, and (2) evaluating a widely distributed, locally manufactured stove in Uganda.

## Data and methods

### Study site description

This study was conducted in villages surrounding Kyetume Village near Masaka, Uganda (population: ~500) during June–August of 2010. Kyetume is located in southwest Uganda, approximately 50 miles west of Lake Victoria and 40 miles north of the Uganda-Tanzania border (Fig. 1). The villages lack access to basic infrastructure (e.g., drinking water, sanitation systems, health care). Electricity is available, but intermittently, in only one of the villages (Kyetume). Residents in the study area use primarily three stone fires for cooking.

### Stove selection

During an assessment trip in January of 2010, we introduced four stoves to community leaders and focus groups: two wood-burning rocket stoves (Ugastove; StoveTec), a charcoal stove (Ugastove-brand), and a solar oven (Minneapolis Solar Oven Society). Community members showed an overwhelming preference for the wood burning stoves. Between the two wood-burning stoves, the Ugastove was preferred because it is larger (most households in rural Uganda are large: ~10 people), has a fixed pot skirt (to prevent spills), and is the tallest of the alternative stove options (less bending over while cooking). Based on community feedback we chose the wood fueled

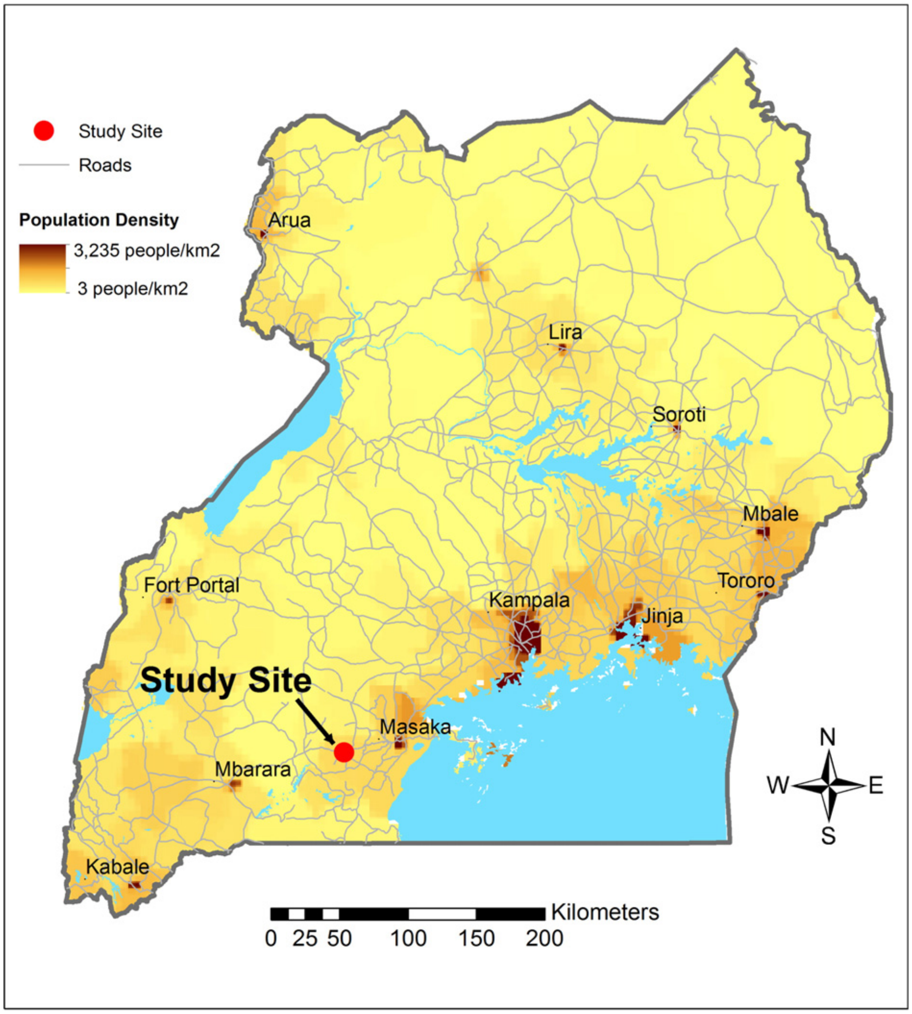

**Fig. 1.** Location of the study site (Kyetume Village and surrounding villages).

Ugastove for this intervention (see Supplemental Information for details).

Ugastove produces a variety of stoves at its manufacturing site in Kampala, Uganda (see Supplemental Information for details). Working with the USA-based non-governmental organization Impact Carbon, Ugastove secured financing from a carbon offset program (Gold Standard) and is expanding its manufacturing facilities and distribution area (Gold Standard, 2006). Best practices for design of more efficient cookstoves (e.g., that burn less fuel) have been well documented (EAP, 2004; PCIA, 2006; 2009); various organizations (e.g., Gesellshaft fur Internationale Zusammenarbeit [GIZ]) are involved in promotional and educational efforts to improve the energy efficiency of cooking in Uganda (GIZ, 2014). For example, initial field tests of the Ugastove (by Impact Carbon) in Kampala, Uganda found a ~50% reduction in fuel use compared to a three stone fire (Haigler et al., 2007).

Locally constructed alternative stoves (built from clay and ant hill dirt) cost 15,000–30,000 shillings (US$7–US$15) near Kyetume (Fig. 2). The wood-fueled Ugastove costs 35,000 shillings (US$17). We subsidized the cost of the Ugastove to meet our target sample size. Our locally-based partner organization in Uganda (Uganda Rural Fund [URF]) suggested a price of 10,000–20,000 shillings (US$5-US$10) would be affordable in all six villages. We priced the Ugastove at 15,000 shillings (US$7) for this study based on two criteria: (1) the price is affordable for most households and (2) households that see no value in the stove are unlikely to enroll.

### Study design

We used a before-and-after study design which included an intervention group but not a control group (i.e., observational study) to evaluate changes in indoor air quality associated with the introduction of the Ugastove. This approach allows for use of paired statistical tests and minimizes intra-household variability (time and resource constraints did not allow for expanding the study to include a control group). We monitored kitchen concentrations of two air pollutants (fine particles [$PM_{2.5}$], carbon monoxide [CO]) and stove adoption and usage rates, based on temperature data loggers affixed to each stove.

Following recommendations by Edwards et al. (2007), we calculated our target sample size (~50 households) to allow for detection of statistically significant differences in kitchen air pollution concentrations (based on expected reductions [~20%]). Our target sample size is consistent with similar studies in Ghana (Pennise et al., 2009), India (Chengappa et al., 2007), Mexico (Masera, et al., 2007), and Guatemala (Bruce et al., 2004).

### Household selection

We worked with URF to identify households interested in purchasing a subsidized Ugastove and participating in the study. URF facilitated this process via monthly meetings with women's empowerment groups which were already established in each village. The study team worked with students at the URF-sponsored primary and secondary schools to establish a group of student community mobilizers called the “Clean Air Team”. The Clean Air Team participated in several lectures on indoor air pollution and learned how to properly use the Ugastove. Since the students lived in the study villages, they acted as liaisons between the study team, URF, and community members.

Members of the study team and Clean Air Team visited each household and administered a screening survey to ensure that all households were willing to participate and that they were appropriate candidates for inclusion; namely, if households were (1) currently using wood fuel for cooking, (2) willing to pay for a new stove, and (3) willing to participate in air quality and stove use monitoring. We administered questionnaires to determine which household members were primarily responsible for cooking and cooking-related activities.

Prior to our study, most households used a three stone fire for cooking. A small number of homes had a large stove built from clay and ant hill dirt; however, owing to their size these stoves are typically used only for special occasions (holidays). Cooking is performed mostly in poorly ventilated detached kitchens to protect the fires from wind or rain and to conserve wood use. Materials and construction of kitchens varied; some kitchens were vented near the roof while others were only open via a doorway (see Fig. 3). Typical cooking durations are 1–5 h per event. Descriptive statistics of reported cooking habits are listed in Table 1.

### Air pollution monitoring and exposure assessment

Air quality monitoring occurred for 48 hours ($PM_{2.5}$) and 24 hours (CO) per session; monitoring sessions occurred once before and once after introduction of the Ugastove. A 1-month acclimation period was scheduled before carrying out the “after” monitoring period to allow households to adjust to use of the new stove.

Our study involved fifteen sets of monitoring equipment; each set contained one particle monitor (UCB; Berkeley, CA) and one CO data logger (Dwyer®; DW-USB compact series) deployed in tandem in each household. The UCB was designed specifically for use in studies like ours, i.e., measuring concentrations in cooking environments with an open fire. Dwyer CO data loggers were used because of their small size, long battery life, and price. The UCB has been validated in field and laboratory tests (Chowdhury et al., 2007; Edwards et al., 2006; Litton et al., 2004) and deployed in a variety of studies measuring indoor air quality (Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007; Pennise et al., 2009). Air pollution measurements were logged in 1-minute (2-minute) intervals for $PM_{2.5}$ (CO) during each monitoring period.

We followed the methods presented in previous studies to deploy our air pollution equipment (Dutta et al., 2007; Pennise et al., 2009).

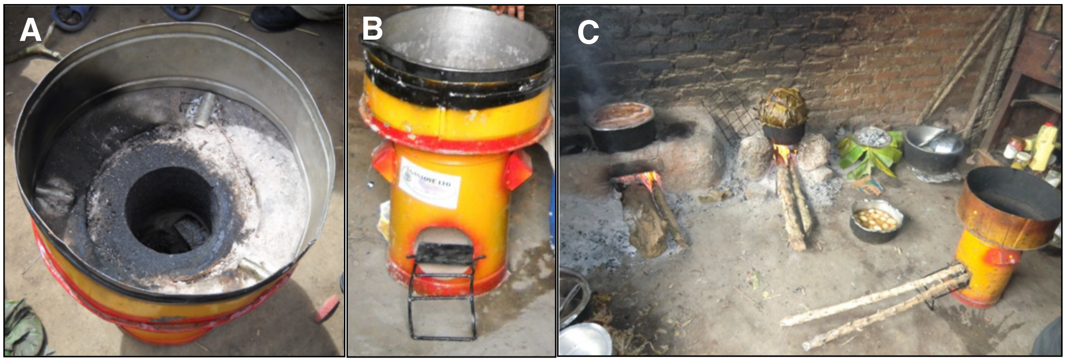

**Fig. 2.** The wood-fueled rocket stove (Ugastove) used in this intervention (A & B). Three types of stoves present in each study village (C) from left to right: locally produced clay and anthill dirt stove, three stone fire, and the Ugastove.

**Fig. 3.** Examples of a more open (A) and a more closed (B) kitchen. Monitoring equipment in a kitchen (C).

Our aim was to locate the instruments in the breathing zone of the cook. Each monitor was placed in the same location before and after introduction of the alternative stove.

### *Short-term adoption rates of alternative stoves*

We evaluated 1-month use and adoption of the Ugastoves via temperature data loggers (ThermoChron ® iButtons) placed on each stove and near each three stone fire to differentiate when one or both of the stoves were being used. The temperature data loggers were placed in close proximity to (but not in contact with) each stove. The data loggers were attached to the Ugastove handle using metal wire and were 2–3 inches from the stove; for the three stone fire, data loggers were attached to a ¾ inch steel pipe and driven into the ground ~24 inches from the center of the fire and 2–3 inches above the ground. Temperature data points were logged in 22-minute intervals allowing for a ~1-month monitoring period without a researcher visiting the site. The iButton temperature data loggers have been used in other similar studies (Ruiz-Mercado et al., 2008).

**Table 1**
Self-reported cooking behavior ($n = 54$ households).

| Survey question | Mean or frequency |
|---|---|
| *Mean age (primary cook)* | 40.3 |
| *Mean household size* | 7 |
| *Sex (primary cook)* | |
| Male | 2% |
| Female | 98% |
| *Time spent tending fires (h/day)* | |
| <1 | 6% |
| 1–3 | 32% |
| 4–5 | 23% |
| >5 | 38% |
| *Firewood collection rate (collections/week)* | |
| <1 | 4% |
| 1–3 | 53% |
| 4–6 | 10% |
| >6 | 33% |
| *Firewood collection time (h/collection)* | |
| <1 | 13% |
| 1 | 18% |
| 2 | 31% |
| 3 | 11% |
| >3 | 27% |
| *Firewood collection time (h/week)* | |
| <2 | 11% |
| 2–9 | 57% |
| 10–20 | 18% |
| >20 | 14% |

Surveys were given simultaneously with the deployment of the temperature and air quality monitors as well as after the 1-month acclimation period. Our surveys focused on: (1) household demographics (size of household, cooking and firewood collection responsibilities), (2) cooking behavior (number of meals, cooking duration, fuel use, cooking outdoors), (3) self-reported health impacts (change in smoke, coughing, and irritated eyes), (4) feedback on the Ugastove performance, and (5) characteristics of the kitchen (construction material, size, presence of windows or other ventilation). See the Supplemental Information for the full surveys.

### *Statistical analysis*

#### *Indoor air quality*

We distributed Ugastoves to 54 households; of those 54 households, we obtained complete data (i.e., no equipment malfunction) for 42 households (78%) for $PM_{2.5}$ and 48 households (89%) for CO. To provide the most meaningful comparison for a consistent set of households, we exclude 3 households (6%) that did not complete payment and 11 households (20%) whose kitchens could not be classified as an indoor environment (for example, some kitchens had only a roof and no or few walls). Our final sample sizes for statistical analysis are $n = 28$ ($PM_{2.5}$) and $n = 34$ (CO).

We calculated 48-hour ($PM_{2.5}$) and 24-hour (CO) mean kitchen concentrations for each sampling period and each household. We used a parametric statistical test (paired $t$-test) to assess whether there were statistically significant reductions in kitchen concentrations among all households.

#### *Temperature data loggers*

We collected ~1 month of stove usage data for the Ugastove and three stone fire for 32 households. An additional 4 (6) households had

**Table 2**
Summary statistics of pre- and post-intervention air pollution measurements.

| Pollutant[a] | $n$ | Before |  | After |  | $p$-Value[b] | % change in mean |
|---|---|---|---|---|---|---|---|
|  |  | Mean | SD | Mean | SD |  |  |
| $PM_{2.5}$ ($mg/m^3$) | 28 | 1.84 | 2.21 | 1.16 | 1.28 | $0.007^{***}$ | 37% |
| CO (ppm) | 34 | 16.6 | 10.8 | 15.3 | 16.4 | 0.68 | 8% |

[a] $PM_{2.5}$ measurements are 48-hour mean kitchen concentrations; CO measurements are 24-hour mean kitchen concentrations.

[b] Asterisk denotes level of significance (paired $t$-test). $^{*}$ for $p < 0.1$, $^{**}$ for $p < 0.05$, and $^{***}$ for $p < 0.01$.

data for the three stone fire (Ugastove) only. We define any measurement that was >30 °C as a period of stove use (all ambient daily high temperatures were <30 °C during the sampling period). Since we do not have data on ambient kitchen temperatures we may misclassify stove use if stoves are placed in very close proximity. We performed a sensitivity analysis on our choice of 30 °C as the threshold for use; we report the base-case here (see the Supplemental Information for details on the sensitivity analysis).

We calculated mean minutes of stove use per day for each stove and for each week to compare trends in short-term adoption rates. We classified households as primarily Ugastove users if ≥80% of total household stove use minutes during the 1-month acclimation period were from the Ugastove; similarly, if ≥80% of total stove use minutes were from the three stone fire, households were classified as primarily three stone fire users. If neither stove accounted for ≥80% of total stove use minutes, households were classified as tandem stove users.

## Results

### *Kitchen air quality pre- and post-intervention*

Table 2 shows mean kitchen concentrations before and after introduction of the Ugastove (see the Supplemental Information for a sample of the real-time household data). We observed a statistically significant 37% reduction in $PM_{2.5}$ concentrations ($p$-value < 0.01). The reduction in CO concentrations (8%) was not statistically significant ($p$-value = 0.68; Table 2); we did not quantitatively measure fuel use to explore if the amount of wood burned differentially affected $PM_{2.5}$ and CO concentrations. Scatterplots of before vs. after measurements for each pollutant are shown in Fig. 4.

We did not find strong correlations between mean $PM_{2.5}$ and mean CO concentrations among households (before measurements: $R^2 = 0.16$; after measurements: $R^2 = 0.10$; Fig. 4). We found slightly stronger correlations when removing two outlier households (before measurements: $R^2 = 0.30$; after measurements: $R^2 = 0.53$).

### *Temperature data loggers and short-term stove adoption*

Short-term stove use patterns varied by household. Based on our classification scheme (cutoff: ≥80% of total stove use minutes), during the one month of data collection the Ugastove was the primary stove in 47% of households, the three stone fire was the primary stove in 12% of households, and the Ugastove and three stone fire were used in tandem in 41% of households. On our survey, 65% of households reported using a stove other than the Ugastove during the acclimation period; that value is similar to our objectively-based classification (i.e., 53%

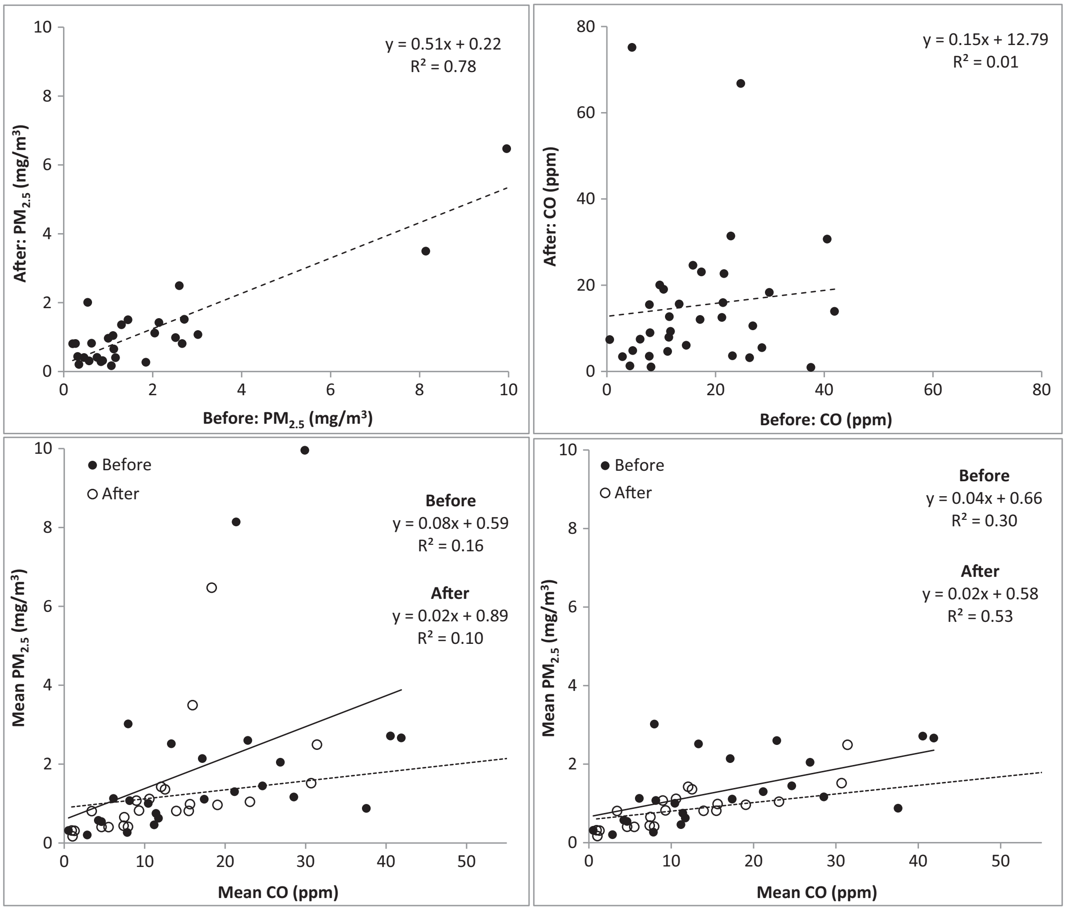

**Fig. 4.** Top panels (left: $PM_{2.5}$; right: CO): correlation between mean concentrations before and after introduction the Ugastove for households with full data. Bottom panels (left: full data; right: two outliers removed): correlation between mean CO and $PM_{2.5}$ concentrations during air quality sampling periods.

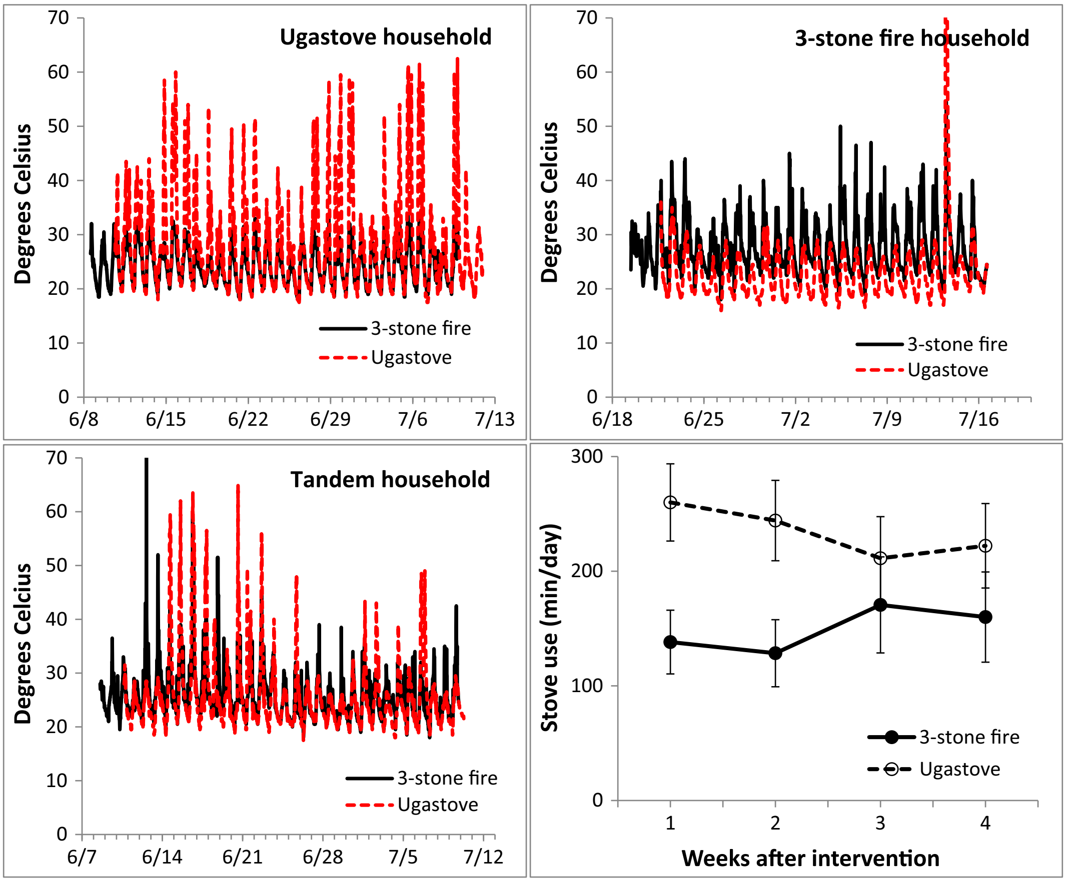

**Fig. 5.** Example household data from temperature sensors using a temperature threshold of 30 °C to indicate stove use. Top-left panel: a household that primarily used the Ugastove; top-right panel: a household that primarily used the three stone fire; bottom-left panel: a household that used both stoves in tandem. Bottom-right panel: Stove use by week after introduction of the Ugastove ($n = 32$; error bars are 1 SE). Stove use is defined as minutes per day that the temperature data logger reported temperatures >30 °C.

either three stone fire or tandem users). We employed a sensitivity analysis to test our method for classifying stove use (i.e., incrementally increasing the threshold temperature used to define stove use). The sensitivity analysis resulted in classifying more households as primarily Ugastove users and fewer households where both stoves were used in tandem (see Supplemental Information); this result is likely attributable to the fact that we could not place the temperature data loggers as close to the three stone fire as we could to the Ugastove.

Examples of real-time temperature data for households that primarily used the Ugastove, primarily used the three stone fire, and used both stoves in tandem are shown in Fig. 5. Stove use was relatively consistent during the 1-month acclimation period. There was a statistically significant difference in stove use between the Ugastove and three stone fire (paired *t*-test; $p < 0.05$) for weeks 1 and 2. We did not observe a statistically significant difference in mean minutes per day of stove use between stove types during the last week of the acclimation period. There was only one week to week difference which was statistically significant: week 2 to 3 for the three stone fire.

### *Factors influencing kitchen air quality*

To explore how short-term stove use patterns affected kitchen air quality, we stratified our sample by our stove-use classification. Particulate and CO concentrations were lowest in households that primarily used the Ugastove (mean $PM_{2.5} = 0.9$ mg/m$^3$, $n = 10$ households; mean CO = 13.2 ppm, $n = 11$ households), followed by tandem stove users (mean $PM_{2.5} = 1.3$ mg/m$^3$, $n = 8$; mean CO = 17.9 ppm, $n = 10$), and the three stone fire users (mean $PM_{2.5} = 2.6$ mg/m$^3$, $n = 4$; mean CO = 20.2 ppm, $n = 4$). However, stratifying on stove use reduces the sample size; changes in kitchen concentrations (before versus after the intervention) were not statistically significant if analyzing each stove use group separately (Table 3).

## Discussion

Our study observed short-term (1-month) patterns of stove use and indoor air quality associated with the introduction of an alternative cookstove in rural Uganda. We looked at how stove use changed during the weeks of our study (see Fig. 5, bottom-right) but were unable to examine long-term stove use patterns.

Our study design (i.e., matched-pair measurements of indoor air quality) accounts for intra-household variability (e.g., differences in housing structures, household size, income, behavior, etc.) but does

**Table 3**
Pre- and post-intervention kitchen concentrations by stove use classification.

| Household classification | Pollutant[a] | *n* | Before | | After | | *p*-Value[b] | % change in mean |
|---|---|---|---|---|---|---|---|---|
| | | | Mean | SD | Mean | SD | | |
| Primarily Ugastove | $PM_{2.5}$ (mg/m$^3$) | 10 | 1.11 | 0.89 | 0.69 | 0.51 | 0.07* | −38% |
| | CO (ppm) | 11 | 12.2 | 11.5 | 14.2 | 19.4 | 0.66 | 16% |
| Primarily three stone fire | $PM_{2.5}$ (mg/m$^3$) | 4 | 3.30 | 3.29 | 1.94 | 1.34 | 0.31 | −41% |
| | CO (ppm) | 4 | 23.5 | 3.5 | 16.9 | 10.9 | 0.35 | −28% |
| Tandem stove use | $PM_{2.5}$ (mg/m$^3$) | 8 | 1.52 | 1.07 | 1.05 | 0.50 | 0.29 | −31% |
| | CO (ppm) | 10 | 20.5 | 12.9 | 15.3 | 21.6 | 0.60 | −25% |

[a] $PM_{2.5}$ measurements are 48-hour mean kitchen concentrations; CO measurements are 24-hour mean kitchen concentrations.

[b] Asterisk denotes level of significance (paired t-test). * for $p < 0.1$, ** for $p < 0.05$, and *** for $p < 0.01$.

**Table 4**

Comparison of kitchen concentrations reported in the present study to select previous studies.

| Study | Country | Stove type | $PM_{2.5}$ (mg/m$^3$) | | | | CO (ppm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *n* | Before | After | Reduction | *n* | Before | After | Reduction |
| Chengappa et al. (2007) | India | Fixed-stove (with chimney) | 30 | 0.52 | 0.33 | 36% | 37 | 7.88 | 5.38 | 32% |
| Dutta et al. (2007) | India | Fixed-stove (mixed chimney use) | 87 | 1.25 | 0.94 | 24% | 98 | 10.82 | 6.65 | 39% |
| Masera et al. (2007) | Mexico | Fixed-stove (with chimney) | 33 | 1.02 | 0.34 | 67% | 32 | 8.88 | 3.02 | 66% |
| Northcross et al. (2010) | Guatemala | Fixed-stove (with chimney) | 138 | 0.9 | 0.34 | 62% | 145 | 7.73 | 2.81 | 64% |
| Pennise et al. (2009) | Ghana | Rocket stove | 36 | 0.65 | 0.32 | 50% | 36 | 12.3 | 7.4 | 40% |
| This study | Uganda | Rocket stove | 28 | 1.84 | 1.16 | 37% | 34 | 16.6 | 15.3 | 8% |

not account for differences that affect all households over time (e.g., seasonal fluctuations in fuels used, moisture content of fuel, differences in foods cooked). Our study was performed during a single dry season, which should mitigate many of the seasonal effects. For example, daily temperature and humidity were relatively constant during the study period and foods cooked (and thus cooking and emission patterns) in this area of Uganda (e.g., matooke [steamed green plantain], rice, beans) remain relatively constant throughout the year.

Measuring stove use via temperature data loggers may result in misclassifying stove use under certain conditions. We used temperature sensors in close proximity to each stove as a proxy for stove use; however, when one stove is used, temperatures of the sensors on the other stove are likely elevated too, which may result in misclassification of stove use for the stove not used at that meal. Recognizing that this type of misclassification would be more common in households where stoves are in close proximity to each other, the sensors were located as far apart as possible in these situations.

Objective measurements of stove use allowed for insight into differences in kitchen concentrations when stoves are used alone or in tandem. In future studies that employ objective measures of stove use, it may be beneficial to focus survey questions on supplementary information that may impact exposure (rather than focus questions on stove use and adoption). For example, we asked households whether they cooked outdoors during either of the air quality sampling periods (i.e., moved stoves outdoors to cook). Fourteen households reported cooking outdoors at least once. To test the sensitivity of our core results to outdoor cooking events we removed those households from our dataset and recalculated mean changes in kitchen concentrations among remaining households; we found little difference in the core results: 36% reduction in $PM_{2.5}$ ($n = 21$; $p$-value $= 0.03$); 3% reduction in CO ($n = 27$; $p$-value $= 0.91$) (see/Supplemental Information for full results). Another aspect that warrants future research is objectively assessing fuel use. We did not observe a decrease in CO concentrations as would be expected when fuel use is decreased; exploring how fuel use affects emissions of different pollutants in future studies would be helpful.

Our study population was subject to biases demonstrated in other similar studies (Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007; Northcross et al., 2010). For example, our study population may show selection bias since users were pre-screened and interested in using the Ugastove; therefore, short-term adoption rates may be higher than in the general population. Similarly, our results may be affected by participant bias since stove user's behavior may have been altered in the presence of the research team. Despite these limitations our study offers useful information on short-term stove adoption rates (and associated impacts on indoor air quality) for a locally produced stove in rural Africa.

Table 4 compares our findings against select prior publications. We observed relative reductions in kitchen concentrations that are consistent with similar studies for $PM_{2.5}$ and less than previous studies for CO. In general, we found higher mean kitchen concentrations than other studies; that finding could be attributable to factors such as poor kitchen ventilation or longer cooking events than other study areas. Kitchen concentrations in our study were significantly higher than World Health Organization guidelines for $PM_{2.5}$ (final [interim] target: 10 [35] μg/m$^3$) and CO (24-hour average target: 7 mg/m$^3$ [~6 ppm]; WHO, 2014).

## Conclusion

We evaluated one-month adoption rates and changes in indoor air quality associated with the introduction of a locally produced alternative stove in rural Uganda (Ugastove). We successfully recruited and distributed the Ugastove to 54 households in six villages. We found statistically significant reductions (37%) in kitchen $PM_{2.5}$ concentrations among the households that received the Ugastove; CO did not exhibit a statistically significant change. We found that objective stove use data has the potential to describe patterns of stove adoption and use. Our sample suggests that not all households initially adopt alternative stoves and that a significant share of households will use traditional and alternative stoves in tandem.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2014.12.007.

## References

Albalak R, Bruce N, McCracken JP, Smith KR, Gallardo T. Indoor respirable particulate matter concentrations from an open fire, improved cookstove, and LPG/open fire combination in a rural Guatemalan Community. Environ Sci Technol 2001;35(13):2650–5.

Balakrishnan K, Sambandam S, Ramaswamy P, Mehta S, Smith KR. Exposure assessment for respirable particulates associated with household fuel use in rural districts of Andhra Pradesh, India. J Expo Anal Environ Epidemiol 2004;14(Suppl. 1):S15–25.

Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, Patz J, et al. Patterns and predictors of personal exposure to indoor air pollution from biomass combustion among women and children in rural China. Indoor Air 2011;21(6):479–88.

Baumgartner J, Zhang Y, Schauer JJ, Huang W, Wang Y, Ezzati M, et al. Highway proximity and black carbon from cookstoves as a risk factor for higher blood pressure in rural China. Proc. Natl. Acad. Sci. 2014;111(36):13229–34.

Bhattacharya SC, Albina DO, Abdul Salam P. Emission factors of wood and charcoal-fired cookstoves. Biomass Bioenergy 2002;23:453–69.

Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. Bull World Health Organ 2000;78(9):1078–92.

Bruce N, McCracken J, Albalak R, Schei M, Smith K, Lopez V, et al. Impact of improved stoves, house construction and child location on levels of indoor air pollution exposure in young Guatemalan children. J Expo Anal Environ Epidemiol 2004;14(Suppl. 1):S26–33.

Chengappa C, Edwards R, Bajpai R, Shields K, Smith K. Impact of improved cookstoves on indoor air quality in the Bundelkhand region in India. Energy Sustain Dev 2007;11(2):33–44.

Chowdhury Z, Edwards R, Johnson M, Naumoff-Shields K, Allen T, Canuz E, et al. An inexpensive light-scattering particle monitor: field validation. J Environ Monit 2007;9(10):1099–106.

Clark ML, Reynolds SJ, Burch JB, Conway S, Bachand AM, Peel JL. Indoor air pollution, cookstove quality, and housing characteristics in two Honduran communities. Environ Res 2010;110(1):12–8.

Dherani M, Pope D, Mascarenhas M, Smith K, Weber M, Bruce N. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. Bull World Health Organ 2008;86(5):390–8.

Dutta K, Shields K, Edwards R, Smith K. Impact of improved biomass cookstoves on indoor air quality near Pune, India. Energy Sustain Dev 2007;11(2):19–32.

Edwards R, Smith K, Kirby B, Allen T, Litton C, Hering S. An inexpensive dual-chamber particle monitor: laboratory characterization. J Air Waste Manag Assoc 2006;56:789–99.

Edwards R, Hubbard A, Khalakdina A, Pennise D, Smith K. Design considerations for field studies of changes in indoor air pollution due to improved stoves. Energy Sustain Dev 2007;11(2):71–81.

Energy Advisory Project (EAP). How to build the improved household stoves. Republic of Uganda: Ministry of Energy and Mineral Development; 2004 (Available: http://stoves.bioenergylists.org/scottimproved [4 Nov 2014]).

Ezzati M, Kammen DM. The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. Environ Health Perspect 2002;110(11):1057–68.

Gall ET, Carter E, Eamest M, Stephens B. Indoor air pollution in developing countries: research and implementation needs for improvements in global public health. Am J Public Health 2013;103(4):e67–72.

GIZ (Gesellshaft fur Internationale Zusammenarbeit). Promotion of renewable energy and energy efficiency programme. German Federal Ministry for Economic Cooperation and Development; 2014 (Available: http://www.giz.de/en/worldwide/19268.html [4 Nov 2014]).

Gold Standard: Premium Carbon Offsets. Efficient cooking with Ugastoves. Project design document: voluntary offset projects; 2006.

Grieshop AP, Marshall JD, Kandlikar M. Health and climate benefits of cookstove replacement options. Energy Policy 2011;39(12):7530–42.

Haigler E, Ndemere JA, Pennise DM, Charron D. Investigation of fuel use for urban community development association's wood and charcoal domestic stoves. Center for Entrepreneurship in International Health and Development; 2007.

Hutton G, Rehfuess E, Tediosi F. Evaluation of the costs and benefits of interventions to reduce indoor air pollution. Energy Sustain Dev 2007;11(4):34–43.

International Energy Agency (IEA). World energy outlook. Chapter 15 Energy for cooking in developing countries; 2006 (Available: http://www.iea.org/publications/freepublications/publication/cooking.pdf [25 Sep 2014]).

Jetter JJ, Kariher P. Solid-fuel household cook stoves: characterization of performance and emissions. Biomass Bioenergy 2009;33(2):294–305.

Kurmi OP, Semple S, Simkhada P, Smith WCS, Ayres JG. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. Thorax 2010;65(3):221–8.

Lewis JJ, Pattanayak SK. Who adopts improved fuels and cookstoves? A systematic review. Environ Health Perspect 2012;120(5):637–45.

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 2012;380:2224–60.

Litton C, Smith K, Edwards R, Allen T. Combined optical and ionization measurement techniques for inexpensive characterization of micrometer and submicrometer aerosols. Aerosol Sci Technol 2004;38:1054–62.

Masera O, Edwards R, Arnez C, Berrueta V, Johnson M, Bracho L, et al. Impact of Patsari improved cookstoves on indoor air quality in Michoacan, Mexico. Energy Sustain Dev 2007;11(2):45–56.

Northcross A, Chowdhury Z, McCracken J, Canuz E, Smith KR. Estimating personal PM2.5 exposures using CO measurements in Guatemalan households cooking with wood fuel. J Environ Monit 2010;12(4):873–8.

Partnership for Clean Indoor Air (PCIA). Design principles for wood burning cookstoves. Aprovecho Research Center; Shell Foundation; 2006. Available: http://www.pciaonline.org/design-principles [4 Nov 2014].

Partnership for Clean Indoor Air (PCIA). Cooking with less fuel: breathing less smoke. Aprovecho Research Center; World Food Programme; Shell Foundation; 2009 (Available: http://www.wfp.org/content/cooking-less-fuel-breathing-less-smoke [4 Nov 2014]).

Pennise D, Brant S, Agbeve S, Quaye W, Mengesha F, Tadele W, et al. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. Energy Sustain Dev 2009;13(2):71–6.

Roden CA, Bond TC, Conway S, Pinel ABO. Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. Environ Sci Technol 2006;40(21):6750–7.

Roden CA, Bond TC, Conway S, Pinel ABO, MacCarty N, Still D. Laboratory and field investigations of particulate and carbon monoxide emission from traditional and improved cookstoves. Atmos Environ 2009;43(6):1170–81.

Ruiz-Mercado I, Lam N, Canuz E, Davila G, Smith K. Low-cost temperature loggers as stove use monitors (SUMs). Boiling Point 2008;55:16–8.

Ruiz-Mercado I, Masera O, Zamora H, Smith KR. Adoption and sustained use of improved cookstoves. Energy Policy 2011;39:7557–66.

Siddiqui AR, Lee K, Bennett D, Yang X, Brown KH, Bhutta ZA, et al. Indoor carbon monoxide and $PM_{2.5}$ concentrations by cooking fuels in Pakistan. Indoor Air 2009;19:75–82.

Smith KR, Dutta K, Chengappa C, Gusain PPS, Masera O, Berrueta V, et al. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project. Energy Sustain Dev 2007;11(2):5–18.

Smith-Siverstsen T, Diaz E, Pope D, Lie RT, Diaz A, McCracken J, et al. Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: the RESPIRE randomized trial, Guatemala. Am J Epidemiol 2009;170(2):211–20.

World Health Organization (WHO). WHO guidelines for indoor air quality: household fuel combustion. Geneva, Switzerland: WHO Document Production Services; 2014.