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Monitoring impacts of clean cookstoves and fuels with the Fuel Use Electronic Logger (FUEL): Results of pilot testing

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ABSTRACT

Objective, affordable, and unobtrusive monitoring tools are needed to quantify in-field performance and increase user acceptance rates of clean cookstoves and fuels. To meet this need, researchers have developed the Fuel Use Electronic Logger (FUEL), a sensor-based system that monitors the mass of a household fuel supply and cookstove temperature over time to quantify cookstove adoption and use, fuel consumption, and extrapolate to air quality and climate emissions. Following proof-of-concept studies in Honduras and Uganda, a pilot study was conducted in 44 rural Ugandan households monitoring over an average of 45 days. The purpose of these studies was to evaluate sensor usability and technical performance, inform algorithm development, and demonstrate how FUEL data can be used to quantify key stove performance metrics. Usability results indicated that the FUEL accurately monitored fuel consumption 88% of monitoring days, and 78% of households continued to use the fuel holder without the sensor 8 months after the monitoring period. Fuel consumption was reported per cooking event, day, monitoring period, household, and per capita. Results showed high daily variability in each household, suggesting that longer monitoring durations are needed, with estimation error decreasing from 72% at 4 days to 6.5% relative to a 25-day monitoring period. Cooking duration paired with fuel consumption also provided indicators of average firepower and therefore operational practices across households. Use of emission factors with fuel consumption data estimated carbon savings, showing that stacking of an improved and traditional stove will contribute to higher fuel consumption and carbon emissions per capita than households using a single improved stove. These results highlight the potential of the FUEL system to aid in more effective and accurate quantification of long-term technical performance and adoption, while increasing the transparency and impact of improved cookstove projects.

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Introduction

In recent years, improved fuels and cookstoves have been designed and disseminated in 80 million households to help mitigate the harmful health and environmental impacts of traditional open fires (Clean Cooking Alliance, 2017). Despite actions to reduce harms through technologies utilizing improved fuels and increasing heat transfer and combustion efficiencies, the long-term impacts of these efforts remain unclear, as does the extent to which improved stoves displace traditional methods because the technical performance of improved stoves in real-use settings has not been fully characterized. Therefore, to inform more strategic design and policy decisions, accurate and comprehensive field data are needed.

Historically, surveys have been used as a relatively easy and inexpensive method to estimate desired cookstove performance metrics, but are subject to bias (Brooks et al., 2016). As a result, practitioners have started to introduce quantitative monitoring and evaluation tools to increase objectivity, resulting in the development of several sensor-based technologies that monitor stove performance at the household level (Harrell et al., 2016; Lozier et al., 2016; Pillarisetti et al., 2014; Ruiz-Mercado, Canuz, Walker, & Smith, 2013; Wilson et al., 2015). These include temperature and emissions sensors that measure cookstove body temperature as a proxy for use and quantify ambient air quality or personal exposure. While these data have been helpful to inform program implementers about adoption and emissions, temperature sensors have been unreliable and difficult to interpret, while emissions sensors only monitor for short times and are subject to confounding variables. In addition, neither monitor fuel consumption, a metric that can provide additional understanding of health and environmental impacts. Despite the need to evaluate fuel consumption in real-use conditions to correlate directly to cost, emissions inventories, and health predictions, only a handful of stove projects are currently able to do so due to challenges in capturing accurate and long-term data (Adkins, Tyler, Wang, Siriri, & Modi, 2010; Gifford, 2010).

The lack of available autonomous fuel consumption monitoring tools motivated the development of the Fuel Use Electronic Logger (FUEL), a

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sensor-based system that monitors the mass of a household fuel supply and cookstove body temperature to directly quantify cookstove use and fuel consumption and extrapolate fuel consumption to emissions using pre-determined emissions factors. This system was developed using user-centered ethnographic and entrepreneurial methods over a two-year period in three countries (Ventrella, Zhang, & MacCarty, 2019). Results from preliminary studies of the FUEL in Honduras and Uganda indicated that the system was usable and 69% of sensors performed as anticipated (Ventrella & MacCarty, 2018). This paper will discuss the performance and use of FUEL prototypes to determine key performance metrics and provide a comparative analysis of existing cookstove monitoring technologies. It will also outline the methods and results of development, testing, and analysis in a field study of 68 sensors in northern Uganda.

Background

From project implementers to funding organizations, stakeholders in the global clean cooking sector are advocating for more objective, quantitative data to prove or improve project efficacy (Kees & Feldmann, 2011). There are hundreds of stove designs in existence that vary based on cultural context, fuel type, and local resources, so technical performance and adoption rates will vary based on factors such as design, user population, and training and marketing strategies. These variations require that each new stove design or program be individually evaluated to measure project efficacy.

Program monitoring & evaluation metrics

A set of standardized indicators are needed to quantify the impact of a cookstove program. Technical Advisory Group 285 of the International Organization for Standardization (ISO) is working to develop international standards for clean cooking technologies (ISO, 2018). These standards include a set of metrics and testing protocols for evaluating cookstove performance, including cookstove adoption, displacement and stove stacking, time, fuel consumption, firepower, and emissions.

Adoption and usage

Sustained adoption of a technology is a direct function of its usability (Moses, Pakravan, & MacCarty, 2019). A design that does not meet user needs will not be regularly used and therefore not generate anticipated impacts. Therefore, measuring cookstove adoption to understand usage rates is critical. For stoves and fuels, adoption can be divided into three stages, including acceptance, initial use, and sustained use or disadoption (Ruiz-Mercado, Masera, Zamora, & Smith, 2011). Assessing this evolution of technology adoption necessitates long-term monitoring to fully capture sustained use and additional non-constant factors such as seasonal variability and variation in the number of people served in the household (Bhatt & Sachan, 2004; Rehfuess, Puzzolo, Stanistreet, Pope, & Bruce, 2014; Ruiz-Mercado et al., 2011; Stevenson, Mattson, Bryden, & MacCarty, 2017).

Displacement and stove stacking

Stove stacking occurs when a household uses more than one energy device for cooking and/or heating. Stacking is more common than complete displacement of traditional cookstoves in households that have access to multiple appliances, which they use for varying tasks and seasons. Because stove stacking can greatly reduce potential health and environmental impacts when use of traditional devices continue, it is necessary to measure the use of all cooking devices in the household to fully capture the effects (MacCarty & Bryden, 2017). Displacement and stacking can be measured through survey-based methods or usage monitoring of each device present in the household.

Time

The total time expended towards cooking energy provision can be divided into several subtasks, including fuel collection, fuel preparation, fire-starting, cooking or reheating food, and tending the stove during the cooking process. If an improved stove has better combustion and heat transfer efficiency than a traditional stove, it could potentially reduce the amount of time spent collecting firewood, shorten cooking duration, or reduce tending time and allow for more free time to perform other tasks. Time spent on cooking can be measured using surveys, controlled cooking tests (Bailis, 2004), or time allocation studies where a researcher observes and records the duration of each task (Soeftestad, 1990). Sensor-based monitoring can provide a more accurate depiction of time spent on cooking-related activities.

Fuel consumption

An integral component of the cooking process is the fuel use, which represents financial, time, and energy expenditures for the user (Rehfuess and World Health Organization, 2006). The type of fuel varies based on availability and users' socio-economic status, but can include regional wood types, charcoal, coal, biogas, and liquid petroleum gas (LPG). In areas of nonrenewable wood harvest, the current status for 55% of the global wood harvest, fuel collection can also lead to environmental degradation and deforestation (Bailis, Drigo, Ghilardi, & Masera, 2015; Osei, 1993). Direct quantification of fuel consumption is needed to understand impact in these areas. Current methods to quantify fuel consumption include manual daily weighing through the Kitchen Performance Test (KPT) (Bailis et al., 2018) or survey-based methods (Granderson, Sandhu, Vasquez, Ramirez, & Smith, 2009; Osei, 1993; Smith et al., 2007). These methods often normalize fuel consumption to standard adult equivalence (SAE), which accounts for the age and gender of each household participant (Table 1) (Bailis et al., 2018; Openshaw, 1990).

Firepower

Measurements of time spent cooking and fuel consumption can be used to calculate average firepower over a given time period, which provides an indicator stove-tending practices in the home (Eq. (1)) (Bailis, 2004).

$$q = \frac{m_{fuel} HHV}{\Delta t} \tag{1}$$

Here m_{fuel} is the dry equivalent mass of combusted fuel during the cooking duration, HHV is the higher heating value of the fuel, and Δt is cooking duration. Average firepower, q, is an indicator of the rate of heat output and can serve as a relative comparison metric between various stove types.

Emissions

Quantification of pollutant emissions from cooking are of interest for both climate and health impacts and are typically inventoried based on measures of emission factors and/or emission rates multiplied by fuel use and/or cooking time, respectively.

The environmental impact of cooking is represented as global warming commitment, carbon emissions, or tons of equivalent carbon dioxide ($tCO_{2,e}$). The total climate forcing contribution for any stove type, i, can be calculated in terms of global warming commitment

Table 1
Standard Adult Equivalence (SAE) factors (Bailis et al., 2018; Openshaw, 1990).

Gender and age	Fraction of standard adult
Child: 0–14 years	0.5
Female: over 14 years	0.8
Male: 15–59 years	1.0
Male: over 59 years	0.8

measured in tons of carbon dioxide equivalent (tCO_{2e}) per year, where each stove-specific emission factor, $EF_{k,I}$, is weighted by its global warming potential (GWP) and then multiplied by annual fuel use (AFU_i) measured for that stove (Eq. 2). The term f_{NRB} is the fraction of local non-renewable biomass harvest. The key input of AFU_i must be quantified in the field by manually weighing wood or through surveys (MacCarty, 2015).

$$GWC_i = AFU_i\left(f_{NRB}EF_{CO_2\ i} + \sum_k GWP_k EF_{k,i}\right) \tag{2}$$

The value of the non-renewable woody biomass fraction, f_{NRB}, can be measured or taken from literature values based on the location where the stoves are implemented. GWP is defined as the amount of emissions that will still remain in the atmosphere following one year of stove use and is typically analyzed at the 20 or 100 year time-scales (Table 2). The 20 year time-scale accounts for the more immediate impacts of the short-lived climate pollutants (MacCarty, 2015).

Existing monitoring & evaluation methods

There are several existing technologies and methods used to measure the in-field data required for the above evaluations of stove performance and impact, including household surveys, the Kitchen Performance Test (KPT), and temperature and pollutant sensors.

Surveys

Household surveys are frequently used as a low-cost option to understand attributes like household demographics, decision-making priorities, user preferences, adoption, stove stacking, and fuel use (Pakravan & MacCarty, 2019). While they provide critical data on user perceptions, surveys can introduce various biases into analyses, including recall and social desirability bias (Thomas et al., 2016). Another such bias is the Hawthorne effect, in which research participants will deviate from normal habits when they know they are being observed and often increase uptake of the intervention technology only during that period (Simons, Beltramo, Blalock, & Levine, 2017). The presence of the Hawthorne effect skews observational data for quantitative metrics like stove and fuel use, misrepresenting typical user behavior. To this end, researchers have found that self-reported survey data on cooking duration has little correlation with sensor-based usage data and that participants overestimate both cooking duration and the number of daily cooking events (Ramanathan et al., 2017; Simons et al., 2017; Thomas, Barstow, Rosa, Majorin, & Clasen, 2013; Wilson et al., 2015). Therefore, to verify results, surveys should be coupled with quantitative measurements when possible.

Kitchen Performance Test

The Kitchen Performance Test (KPT) was developed in the 1980s to provide quantitative in-field fuel use measurements (Bailis et al., 2018). The KPT combines qualitative survey methods with daily quantitative household fuel weight measurements over several days to determine household-dependent daily fuel usage. To conduct a KPT, field staff visit a sample of households to weigh a specified portion of fuel at the beginning of the testing period, and return every day for the study duration, generally 3–5 days, to manually re-weigh and determine daily fuel use. While this test does provide data on household fuel consumption, there are challenges to conducting an accurate and representative test. Barriers include biases in the survey portion, user errors, seasonal variability, a lack of standardization in measurement, logistics issues, time and resource intensiveness, and the possible disruption to daily activities from repeated intrusion into households (Granderson et al., 2009; VITA, 1985). Researchers who have used the KPT have cited the need for a method that reduces these complications (Bailis, Smith, & Rufus, 2007; Granderson et al., 2009; Osei, 1993; Smith et al., 2007).

Temperature sensors

Sensor-based monitoring has become increasingly common in stove and other development projects to provide more accurate impact data (Harrell et al., 2016; Simons et al., 2017). One example in the stove sector is the use of autonomous temperature sensors. These devices measure the temperature of a cookstove body, and the data are then analyzed to determine the duration and timing of cooking events and stove stacking if multiple cooking devices are monitored.

Challenges with temperature sensors include malfunction due to high temperatures, time-intensive training on sensor placement and data upload, and data that are difficult to interpret due to the slow warm-up and lengthy cooldown time for cookstoves before and after a cooking event (Dickinson et al., 2015; Ruiz-Mercado, Canuz, & Smith, 2012; Simons, Beltramo, Blalock, & Levine, 2014; Wilson et al., 2016). In addition, although efforts have been made to correlate temperature data to fuel consumptionusing an energy flux approach, a study utilizing the WiCS temperature monitoring system reported high uncertainty (Graham et al., 2014). Because firepower is very much location- and application- specific, accurately predicting fuel use from temperature alone is challenging.

Pollutant measurements

Air quality and emissions monitoring systems quantify household air pollution (HAP) in homes and total emissions from cookstoves, respectively. Pollutants of interest include fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and black carbon (BC). Larger hood or emissions capture systems such as E-Pod, ARACHNE (Roden et al., 2009), or the Aprovecho Portable or Laboratory Emissions Monitoring System (PEMS or LEMS) (MacCarty, Still, & Ogle, 2010; Roden et al., 2009) are used to collect and measure multiple pollutants to quantify emission factors and rates. While collection systems such as these are useful for short-term laboratory tests, portability, training, and practicality issues prevent their use for measuring over multiple days in a household.

Table 2
Global warming potential.

Emission	GWP_{20}	GWP_{100}
CO_2	1	1
CH_4	72[c]	25[c]
N_2O	289[c]	298[c]
CO	10[b]	1.9[c]
VOCs	4.9[b]	3.4[c]
BC	3200[a]	910[a]
OC	−250[b]	−75[b]

[a] Bond et al. (2013).
[b] Bond, Venkataraman, and Masera (2004).
[c] Forster et al. (2007).

Table 3
Comparison of available monitoring metrics.

	Surveys	KPT	Temperature sensors	Emissions sensors	FUEL
Usage	X		X		X
Stacking	X	X	X		X
Time	X		X		X
Fuel use	X	X			X
Pollutants				X	

Methods

FUEL system design

Current monitoring methods in the cookstove sector (Table 3) are often time and resource-intensive, subject to high uncertainty, and do not provide the range of data necessary to fully understand stove performance as an integrated system. There has been no existing technology that quantifies fuel use over time, from which impacts on time, health, and the environment are derived. For this reason, researchers and stove practitioners have called for more accurate methods to capture long-term fuel use data. To meet this need, researchers at Oregon State University in partnership with Waltech Systems and Climate Solutions Consulting developed the Fuel Use Electronic Logger (FUEL), an integrated sensor system to quantify usage and fuel consumption, (Figs. 1 and 2). The FUEL system monitors and records time-stamped data on the mass of fuel added to and removed from the holder, cookstove temperature, and ambient temperature for several months at a time. The first-generation FUEL system prototypes include:

- S-type tensile or compressive load cell
- Internal temperature sensor
- External thermocouple port
- Integrated power supply, analog-to-digital converter (ADC), and control module with internal clock
- SD card port for data storage
- Battery power supply
- Plastic housing

The second generation developed with Climate Solutions Consulting uses wireless communication with a handheld launcher that can deploy and read data integrated streams from any combination of up to twelve FUEL, temperature, and air quality sensors in a single household. Because the updated system is wireless, the location of the holder is flexible and does not have to be located directly next to the stove to record temperature data. The current manufacturing cost is approximately $75 per unit.

To operate, the system is installed as shown in Fig. 2 in the kitchen or cooking area being monitored. If there are no existing support beams to install the holder, an external support structure may be constructed. Each cook is trained to store all or a portion of his or her fuel supply in the storage holder, remove fuel as it is needed for cooking, and restock with additional fuel when needed. Each reduction in weight recorded by the load cell as fuel is removed for cooking is integrated over a specified time period to determine total fuel use. The FUEL system can operate in tension or compression depending on factors such as kitchen size and the fuel type. For example, heavy LPG canisters that have a direct gas line to the stove are more easily weighed on compressive scales. An external thermocouple generates a continuous temperature profile over the logging period, which is analyzed to determine cooking events and duration. The temperature profile also serves to corroborate the weight data and identify user error by checking that the cookstove temperature is elevated when a weight reduction is detected.

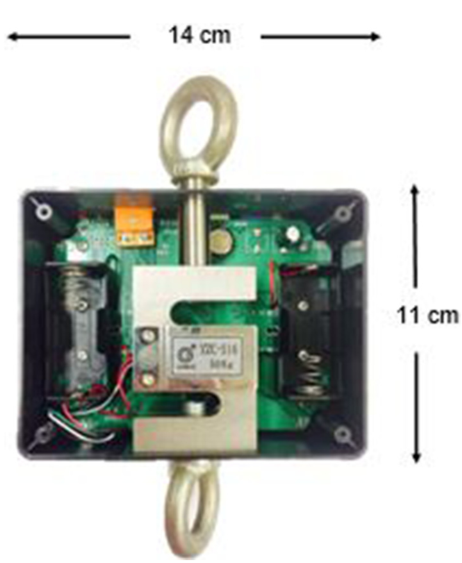

Fig. 1. FUEL sensor (1st gen).

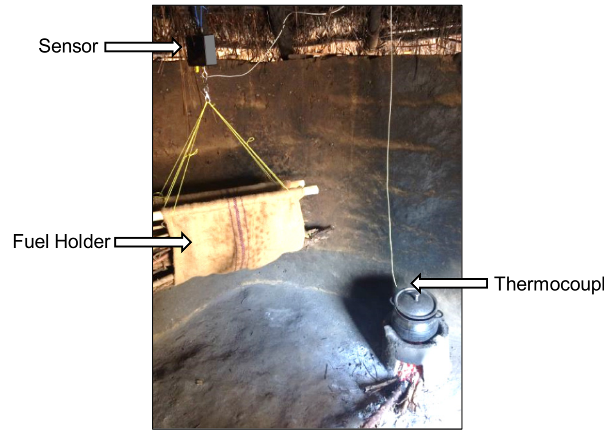

Fig. 2. FUEL system installed in Apac, Uganda.

Data from the FUEL are intended to report multiple metrics of cookstove performance, including adoption, stove stacking, time spent cooking, and fuel use, and extrapolate these metrics to health and climate impacts. This study seeks to determine if the FUEL system can work as intended to provide robust, quantitative data for more accurate, transparent, and verifiable measurements of cookstove performance.

Field testing

A series of studies was conducted between 2017 and 2018 to test the technical feasibility of the FUEL and then pilot test once the feasibility was verified. During Phase 1 in April of 2017, the first five prototypes of the FUEL system were tested in rural Honduras with StoveTeam International, a non-government organization (NGO) that distributes improved stoves in Central America. The purpose of this testing was to evaluate the in-field technical system performance and the usability of the fuel holder design. Results of this study aided in proof of concept of the existing design and were also used to inform firmware updates such as logging rate. In August 2017, the research team partnered with International Lifeline Fund (ILF), a D.C.-based NGO that manufactures and distributes low-cost, increased-efficiency wood and charcoal stoves in east Africa. In collaboration with ILF, the team conducted Phase 2, a preliminary study in northern Uganda to evaluate usability and technical feasibility with 100 sensors. Following these preliminary studies, a pilot study, Phase 3, was conducted in July 2018 to analyze

Table 4
FUEL research phases.

Phase	Timeframe	Purpose	Location	N households	N sensors	t (days)
1	April 2017	Preliminary	Honduras	4	5	30
2	August 2018	Preliminary	Uganda	85	100	30
3	July 2018	Pilot	Uganda	44	68	45

metrics such as carbon emissions, firepower, and comparative fuel consumption between stove types. The time frame, location, sample size, and monitoring duration of each research phase are listed in Table 4. All research with human subjects was conducted with oversight from the Oregon State University Institutional Review Board under study number 7257.

Lessons learned from the preliminary studies were used to inform the pilot study. These included selecting thermocouples with a higher rated temperature,higher quality SD cards, and using stainless steel brackets to attach thermocouples to the stoves.

Sample households

In the pilot study, a total of 68 sensors were installed in 44 households and logged for an average of 45 days. Stoves included the intervention stove, the Rural Wood Stove (RWS) and two traditional stoves, including a locally mudded stove (LMS) and a three stone fire (TSF) (Fig. 3). The distribution of stove types in sample households is shown in Table 5. To measure stove stacking in households with two stoves, two FUEL sensors, each with their own temperature sensor, were used.

Training

Prior to the monitoring period, an hour-long training session was conducted to inform users about the purpose and method of use for the FUEL system. Participants were told the overall intent to better understand the impacts of stoves on their health and environment, the function of each system component, and details of operation. Following these operational details, questions and concerns were addressed to ensure clarity of instructions, which included:

- Place any collected wood in the holder before cooking
- Remove wood from the holder as needed for cooking
- Do not place partially burned wood (or extra wood removed) back into the holder. Leave out for the next cooking event.

Equipment, installation, and calibration

The FUEL systems were installed by hanging the sensor from preexisting support beams in the cooking area roofing structures and attaching the thermocouple to the stove. Each FUEL system was left to log for the specified monitoring period, with routine visits to check on households during the first week. After the logging period, local field staff returned to collect sensors, and data were uploaded to a local computer and sent to researchers for analysis. To account for variation in household size using the SAE chart (Table 1), the age and gender of each household member was collected as part of a survey conducted on Magpi, a mobile data collection platform.

Each load cell was calibrated individually to account for variation in calibration curves using a 2-point calibration at 1 kg and 30 kg. The sensor logging rate was reduced from Phases 1 and 2 to increase battery life and programmed to record data every 49 s until a threshold weight change is detected, at which point the sampling rate increases to every 7 s until no additional changes in mass are sensed. These values were arrived at with the intent of capturing quick additions/removals of wood, which was observed to happen in several instances, while still enabling long-term monitoring without significant battery drain. A resident local to the Apac region produced the storage holders to reduce manufacturing and transportation costs and provide an opportunity for income generation in the community. They were made from readily available recycled burlap coffee sacks and dowels cut from wood traditionally used as housing supports and sized to reduce intrusiveness (Fig. 4).

Table 5
Sample distribution and stove type.

Stove Type	Households	Percentage
ILF Rural Wood Stove (RWS)	20	45%
Three stone fire (TSF) and Rural Wood Stove	10	30%
Locally mudded stove (LMS) and Rural Wood Stove	13	23%
Rural Wood Stove and Rural Wood Stove	1	2%
Total	44	

Type K thermocouples rated at 750 °C with 3 m extensions were used to monitor cookstove temperature and calibrated in ice (0 °C) water and boiling (100 °C) water. Stainless steel brackets with several holes to thread the thermocouple wire through and attach to the stove body were manufactured (Fig. 5). In the study locations, the FUEL sensor was hung directly from each household roofing structure, enabling a streamlined installation process that eliminated the need for additional hardware, such as support beams. Participants were asked to specify the desired placement and height of the holder.

Algorithm development and analysis

Data analysis algorithms were developed to analyze usage, integrate fuel mass reductions to determine fuel consumption, corroborate system accuracy by checking that elevated temperatures correspond to reductions in fuel load, and extrapolate these data to overall energy use, firepower, and carbon emissions.

Stove usage

To determine usage, a combination of peak detection and time-window clustering was used to determine cooking events and duration following a similar method used by (Ruiz-Mercado et al., 2012). Peaks were clustered in time windows based on average reported cooking time per meal from a survey of 20 participants over four days. If a gap

Fig. 3. Household stove types.

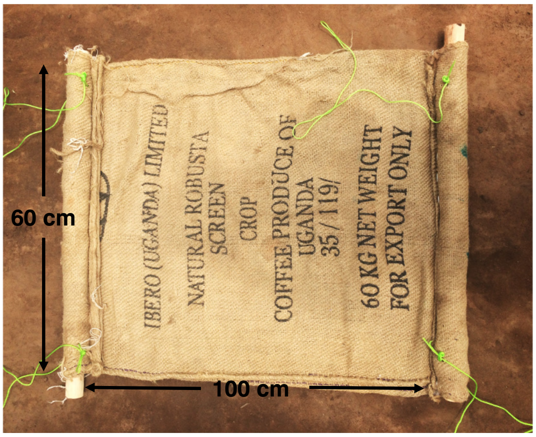

Fig. 4. Fuel holder and dimensions.

between two temperature peaks was greater than approximately 3 h, the algorithm would consider those as two separate cooking events.

Fuel consumption

Fuel use on a wet basis is calculated by integrating mass reductions over a specified time period (Fig. 6). A mass reduction is identified by assigning a weight threshold value, W_0, for the difference, ΔW, between two consequent data points, W_i and W_{i-1}. To detect fuel changes and avoid noise-related fluctuations, a threshold value was set for ΔW. If ΔW is above a specified threshold value, it is then checked against the temperatures, T, within range $T_i - T_{i+25}$, to see that it is elevated above the baseline (non-cooking temperature) to verify an actual cooking event. The temperature range accounts for the time it takes for the cookstove temperature to rise to a detectable difference from ambient following a cold start. If a weight reduction is not verified or a cooking event occurs with no corresponding weight reduction, it may require manual interpretation, corrective action, or correlating temperature and energy flux to account for unrecorded fuel weight (Graham et al., 2014). There are three conditions that can be applied to account for potential errors:

(1) when weight decreases, temperature increases. If false, discount this weight value and flag.
(2) when temperature increases, weight decreases. If false, flag.
(3) there is a temperature increase above ambient any time during a 24-hour period. If false, consider a non-cooking day.

Fig. 5. Thermocouple installation.

To illustrate, a 24-hour data sample from a household in El Eden, Honduras, Phase 1 is shown in Figs. 7A and B (Ventrella, 2018). In Fig. 7A, the thermocouple temperature is above ambient, indicating a cooking event, but there is no corresponding decrease in fuel weight, indicating condition (2). This signifies that the cook has used fuel that was not stored in the holder and would require using temperature data to calculate the energy flux and correlating it to fuel consumption (Graham et al., 2014). Fig. 7B represents a logging period with accurate FUEL monitoring, in which decreases in weight are corroborated with a thermocouple temperature elevation. The algorithm also looks for temperature spikes directly before and after the weight decrease is detected to account for occasions when the fuel is removed a short time after the stove is lit. Although not represented in Fig. 7, there is also the potential use error in which there is a decrease in fuel weight but not a corresponding temperature increase, indicating that fuel was removed but not used in the stove, condition (1). Identification of events that will lead to inaccurate fuel calculations in the algorithm allows for verification of accurate data and flagging of suspect data that does not reflect real fuel use, which can be omitted and/or alert researchers to the need for corrective action.

Observational and survey data from Phase 2 showed that instead of storing their fuel in the holder after collection, some households would chop their wood into smaller pieces only directly before cooking, place the wood in the holder for a short time period, and then remove the entire portion for cooking (Zhang, Zhao, & Ventrella, 2018). This resulted in near-instantaneous, linear spikes in data that were originally attributed to noise. These could then be differentiated from unintentional interaction with the system, which generally resulted in a discrete point above a certain threshold. After determining this use case, the algorithm was updated to identify spikes in weight data using a rolling median filter and replace each spike with a nearby point. Outlier fuel use days were also removed from the dataset and were calculated as 1.5 interquartile ranges from the third quartile (Montgomery & Runger, 2014).

Measurements of cookstove use and fuel consumption could then be analyzed to report energy use per person and extrapolated to firepower, carbon emissions, carbon credits, and aDALYs. Emission factors (EF) determined through lab or field testing are needed and shown as the mass of each pollutant emitted per MJ of fuel consumed (Table 6) and used to calculate the mass emission of various pollutants, k, for a given stove, i, and fuel consumed (Eq. 3). In this study, EF values for the three stone fire and improved stove were not available under local conditions and were therefore chosen from the literature. The EF values for the LMS were estimated as the average between a three stone fire and a general rocket stove. The value for higher heating value (HHV) was selected for *Eucalyptus camaldulensis*, a common wood-type in northern Uganda (Kilimo Trust, 2011).

$$m_k = m_{fuel} HHV_{fuel} EF_{k,i} \tag{3}$$

Results and discussion

The objectives of this study were to evaluate the usability and technical performance of the FUEL system and report findings of metrics including comparative fuel consumption, firepower, and carbon emissions between various stove use cases.

Preliminary qualitative data from community meetings and household surveys suggested that the system was usable for households and that storing fuel in the holder was not an issue (Ventrella, Zhang, & MacCarty, 2019). Interviews revealed the weighing of wood was intuitive to users as the concept of the scale was well understood from purchasing weighed food items at the market. A large portion of the sample population reported that they considered elevating the fuel in the holder as a positive attribute. Observation corroborated these findings, as some households elevated their wood supply on rocks to keep it off the ground and away from moisture and termites. Post-study surveys

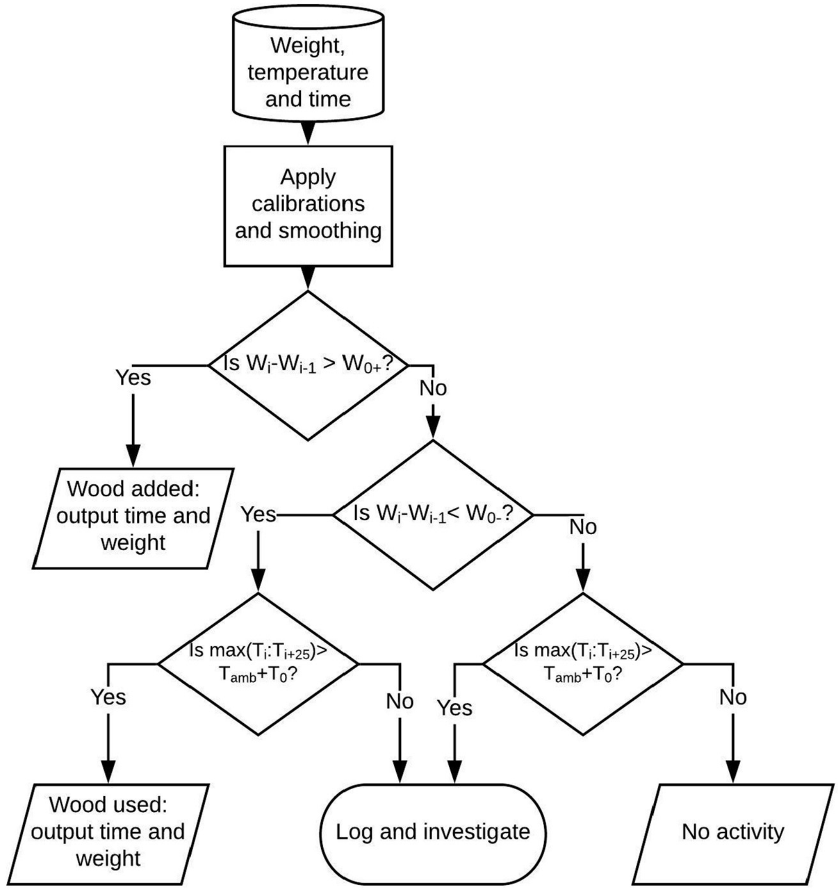

Fig. 6. Algorithm to convert raw weight data to fuel use.

conducted eight months after the end of the monitoring period indicated that approximately 80% of participating households were still using the holder to store wood with no sensor attached (Ventrella, Zhang, & MacCarty, 2019). Willingness to use the holder beyond the duration of the study period indicated that storing wood in an elevated holder would not require significant habit change and is desirable in this context, however this will vary depending on fuel storage needs.

Usability for the program staff was also acceptable compared to similar monitoring methods in the sector. Installation of the FUEL system took two staff members approximately 15 min per household on

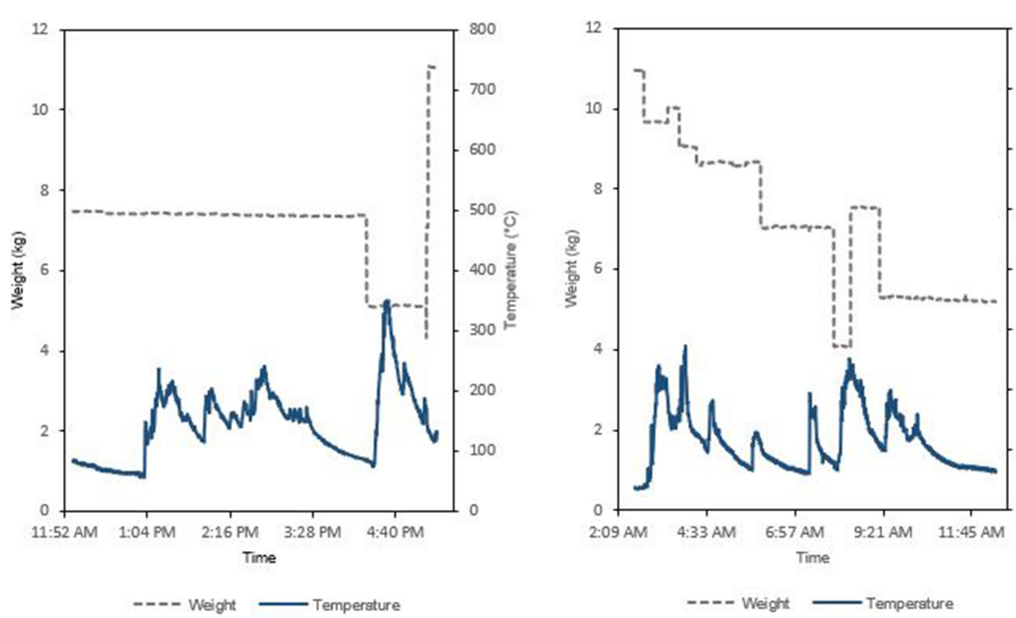

Fig. 7. (A) Inaccurate FUELmonitoring; (B) accurate FUELmonitoring (Ventrella, 2018).

Table 6
Emission factors (g/MJ).

Stove type	EF CO_2	EF CH_4	EF N_2O	EF CO	EF NMHC	EF BC	EF OC	Source
Three stone fire	101.9	0.240	0.012	5.16	0.458	0.073	0.169	a–n
Locally mudded stove	99.8	0.220	0.014	4.01	0.500	0.080	0.150	Average
Rural wood stove	97.7	0.200	0.016	2.85	0.533	0.089	0.124	b,c,f,h,i,j,l,n,o

Compiled by MacCarty (2015).
a Brocard, Lacaux, and Eva (1998); b Smith et al. (2000); c Venkataraman and Uma Maheswara Rao (2001); d Bertschi, Yokelson, Ward, Christian, and Hao (2003); e Ludwig, Marufu, Huber, Andreae, and Helas (2003); f Bailis, Ezzati, and Kammen (2003); g Johnson, Edwards, Alatorre Frenk, and Masera (2008); h MacCarty, Ogle, Still, Bond, and Roden (2008); i Roden et al. (2009); j MacCarty et al. (2010); k Christian et al. (2010); l Grieshop, Marshall, and Kandlikar (2011); m Akagi et al. (2011); n Jetter et al. (2012); o Zhang et al. (2000).
CO2 (carbon dioxide); CH4 (methane); N2O (nitrous oxide); CO (carbon monoxide); NMHC (non-methane hydrocarbons); BC (black carbon); OC (organic carbon).

average, including walking time between households. Although transporting the fuel holders was cumbersome at times, this issue could be mitigated by distributing the holders to participants during the initial community meeting.

From the 68 sensors installed in this phase, a total of 53 sensors functioned as anticipated throughout the duration of the monitoring period, logging a cumulative 37,392 h of data. Due to various prototype hardware failures, 25% of the sensors did not log data for the entire monitoring period. Of the 68 sensors, three did not initiate logging. Another eight stopped logging after a short period, five had noisy signals, and one data set was not transferred to the researchers. The uninitiated or terminated logging could have occurred from coin cell battery discharge, the 1.5 V batteries becoming dislodged from the holder, or faulty SD cards, which are issues that can be resolved in future deployments. These data points were therefore not included in the analysis.

Analysis of the remaining sensor data showed that with temperature check applied when possible, 88% of sensors were used consistently in Phase 3, compared to 82% in Phase 2. Consistent use was defined as removing a threshold amount (1 kg) of wood for at least 60% of the monitoring days, to account for days when no cooking is conducted in the household.

Temperature/fuel use corroboration

To understand the effect of temperature corroboration on the algorithm output, the average daily fuel with and without condition (1) temperature check was compared. When temperature check was available, a change in fuel weight would not be integrated unless it was detected during or soon before a corresponding temperature increase. Fig. 8 and Table 7 show that using the temperature/fuel corroboration had no significant difference on results, indicating that temperature measurements are not needed to check reported decreases in weight. However, this analysis does not account for the events flagged when a cooking event is detected without any change in fuel weight, condition (2).

Temperature and fuel use corroboration, conditions (1) and (3), were also evaluated for algorithm output of sensor usage. Percent use with and without temperature/fuel use corroboration was compared for all sensors with working thermocouples and was defined as the ratio of days where a change in fuel mass was detected to total cooking days and total logging days, respectively, where total cooking days was counted as days when cookstove temperature was elevated above a specified threshold, indicating that the stove was on and in use.

Condition (1) was found to have no significant effect. However, without applying condition (3), the algorithm classified all days where

Table 7
Average daily fuel consumption with and without temperature corroboration.

Sensor	Temperature Corroboration	No Temperature Corroboration
1	7.56	8.06
2	5.98	5.95
3	3.6	3.62
4	3.59	3.8
5	1.97	2.37
6	3.96	4.05
7	5.31	5.61
8	5.86	6.2
9	8.16	8.37
10	3.75	3.89
11	3.47	4.03
12	5.04	5.06

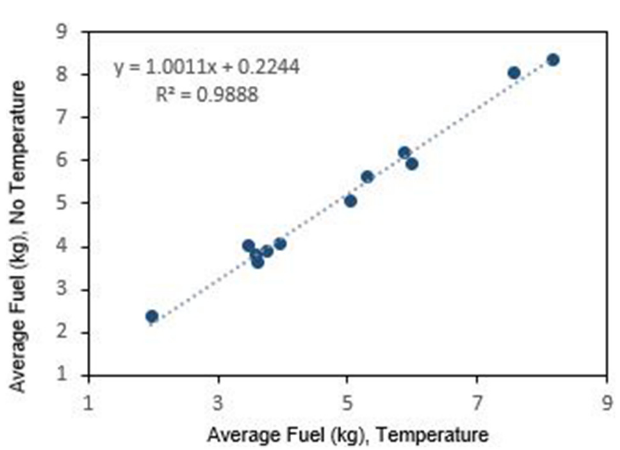

Fig. 8. Comparison of daily average fuel calculated with and without temperature/fuel use corroboration (absence of cooking event only), $R^2 = 0.998$, offset = 0.22, slope = 1:1.

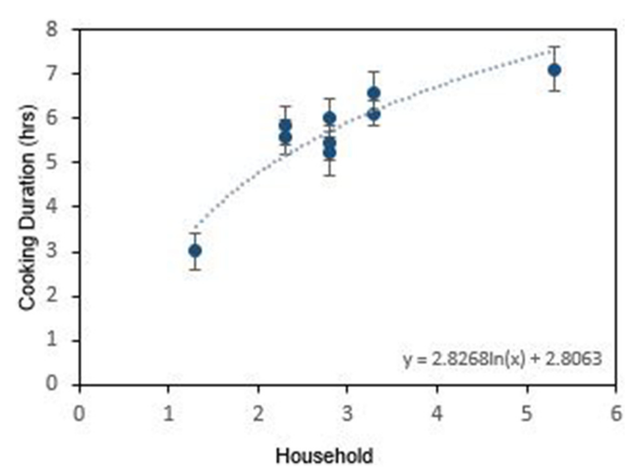

Fig. 9. Daily cooking duration vs. household size normalized to SAE, with standard error.

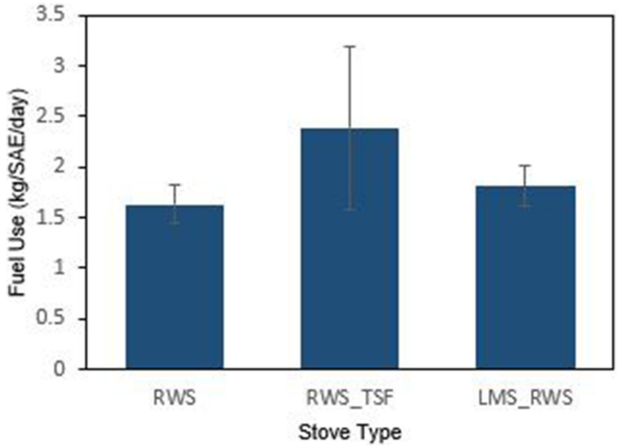

Fig. 10. Daily average fuel consumption normalized to SAE, aggregated by stove type, with standard error.

no fuel was used, regardless of if the stove was used, as inaccurate FUEL monitoring days. When temperature check was available, days where no fuel was used would not be counted as inaccurate FUEL monitoring days if there was no corresponding temperature increase on that day. Calculated average percent usage with and without condition (3) temperature corroboration was 85.1% and 79.4%, respectively, which indicates that non-corroborated fuel data underestimated accurate FUEL monitoring by about 5%.

Cooking duration

To understand the correlation between household size and daily cooking time, a logarithmic regression of daily cooking hours per family size was computed, as shown in Fig. 9. Daily cooking time increases but begins to plateau as household size increases, illustrating economies of scale for larger families. On average, cooking occurred for 5.36 ± 2.67 h per day. This agrees well with collected concurrent survey data of reported cooking time per meal in the study community, where users reported an average 5.9 h of cooking per day. Shorter cooking times could correspond to days where cooks quickly reheated food for a meal, which was found to occur in the Apac district, as one participant and the field staff reported.

Fuel consumption

The daily average fuel consumption per person adjusted for household size and aggregated by cookstove type is shown in Fig. 10. Results report an average daily fuel consumption per person aggregated for all stoves present of 1.63 ± 1.12 kg for RWS households, 1.84 ± 0.66 kg for RWS and LMS stacking households, and 2.51 ± 1.93 kg for RWS and TSF stacking households. These results imply that in this study population, households that cook with more than one stove use on average 0.88 kg more fuel per person when stacking the RWS with the TSF, and 0.21 kg more fuel per SAE when stacking the RWS with the LMS.

Because each stove is monitored with its own sensor, results from households that stove stack may also be disaggregated to report fuel consumption and additional metrics for individual stoves. Disaggregation can be useful to compare stove use and adoption within each household. For example, Fig. 11 illustrates the daily variation in fuel use for a single, stove stacking household of 3.4 SAE that uses both a RWS and LMS. Results show a total average fuel consumption of 8.65 ± 3.65 kg/day, 5.96 ± 2.88 kg/day for the RWS, and 2.68 ± 3.49 kg/day for the LMS. Data also show that the RWS was used 98% of logging days, while the LMS was used only 67% of days, implying that while daily average fuel use was higher for the RWS than the LMS, this could be attributed in part to higher usage as opposed to lower fuel efficiency.

To examine variability in day-to-day fuel use, Fig. 12 shows a box and whisker plot of the spread of daily average fuel use per person for each household over an average of 45 days each. Fuel consumption was aggregated for households with multiple stoves. The overall average daily fuel consumption was 1.61 kg/SAE/day ± 1.22 kg/SAE/day, with a minimum of 0.06 kg/SAE/day and maximum of 8.31 kg/SAE/day. Single RWS users reported an average of 1.75 ± 1.28 kg/SAE/day. These wide data spreads show that there was significant variation in day-to-day fuel use in most households. Daily variation could be caused by several factors, including consumption factors such as changes in the number of people cooked for or number and type of meals cooked each day, or measurement factors such as a cook removing more wood than needed for a single cooking event and using some the next day. For example, Fig. 13 shows the daily variation of fuel use and cooking duration in household 1 (Fig. 13). This high day-to-day variability in fuel use and

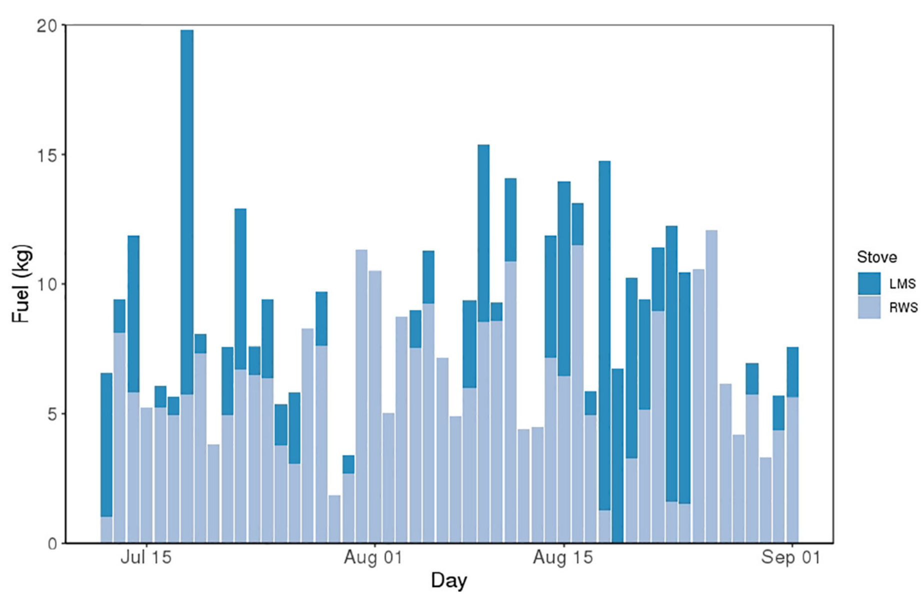

Fig. 11. Fuel use (kg) per day for a single, stove stacking household, SAE = 3.4.

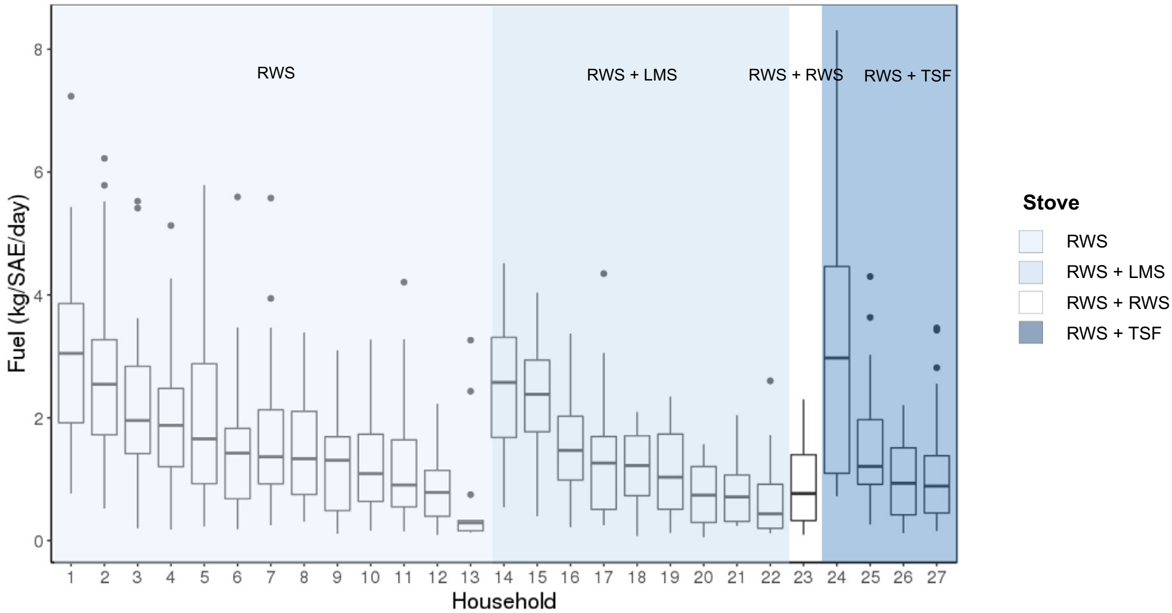

Fig. 12. Variation in daily household fuel use per person, normalized for household size.

cooking duration may require longer duration measurements to capture accurate fuel use averages, suggesting that the KPT, which typically includes only 3–5 days of measurement, may be insufficient.

Average firepower is a measurement of the overall rate of fuel consumption and therefore cooking power of the fire. Fig. 14 shows the operational firepower calculated as the total fuel consumed per day divided by the cooking duration in the 11 RWS households, indicating a mean of 4531.5 ± 1398 W over an average 30-day monitoring duration. The stoves are mass-produced and the combustion chambers are fairly uniform, indicating that the variability in firepower between stoves of the same model is mainly caused by variation in fire tending habits and cooking power needs varying from household to household. The values are well aligned with expected values, suggesting that the FUEL system can accurately monitor firepower through a combination of fuel and temperature (cooking duration) measurements.

Carbon emissions

Projections of annual tCO_{2e} per household normalized for an average household SAE of 3.84 over 20 and 100 years are shown in Fig. 15. On a 100-year time frame, the use of both an RWS and LMS will emit 10% more carbon equivalent than the use of a single RWS, while stacking a RWS with a TSF will emit 218% more than the use of a single RWS. On the 20-year time frame, these values are 9% and 58%, respectively. Although these preliminary results are not statistically significant due to low sample size, initial data suggest that continuing to use traditional stoves alongside improved stoves can result in higher climate-forcing emissions and negate health and environmental benefits of switching to an improved stove, and demonstrate the type of data available when using FUEL. As these results are preliminary, a larger sample size will be required to draw any definitive conclusions.

Monitoring duration

Analysis of the effects of monitoring duration on average daily fuel consumption results was conducted to determine the variation in average fuel as a function of time. Daily average fuel consumption was calculated over durations of the initial 4, 10, 15, 20, and 25 days and compared to the average fuel consumption over 30 days. Percent error was calculated using the difference between average fuel use after

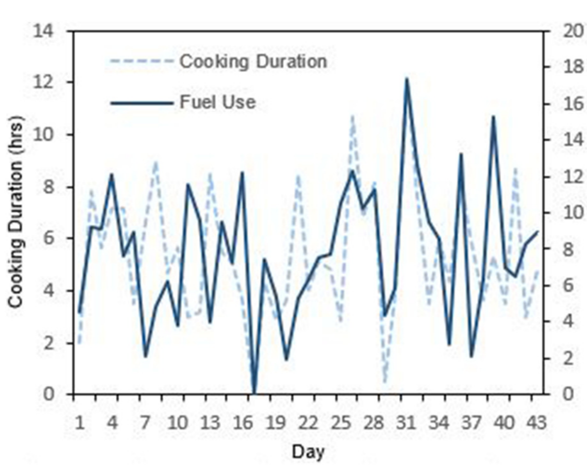

Fig. 13. Daily variation of fuel use and cooking duration for three-person, single RWS household.

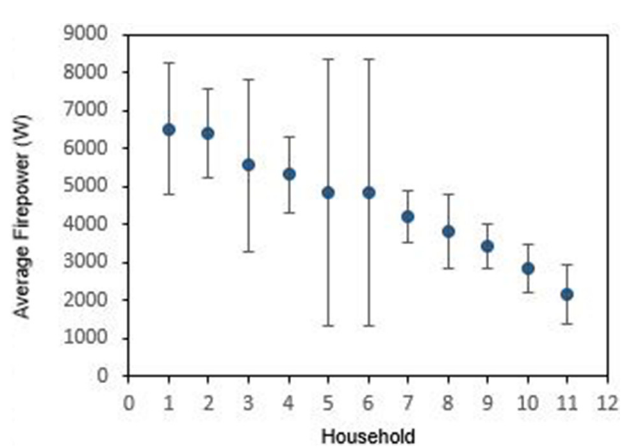

Fig. 14. Average firepower of RWS in each household, with standard error.

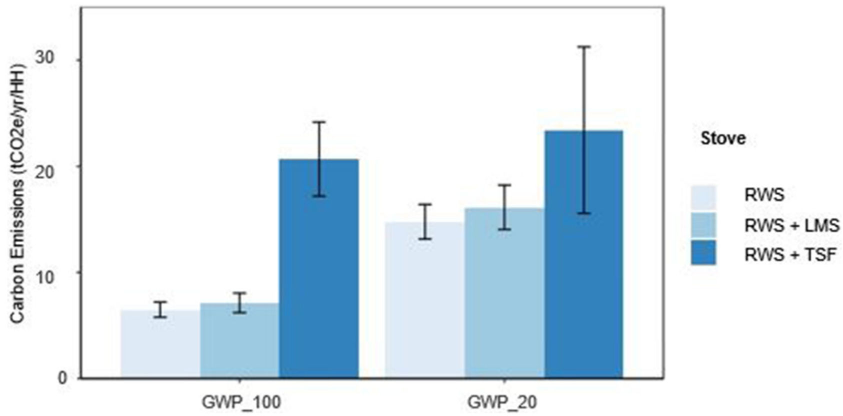

Fig. 15. Carbon emissions per household projected over 20 and 100 years for various stove combinations, with standard error.

monitoring for four days and the average fuel use after monitoring for 25 days, where 25 days was considered the most accurate as it accounted for more daily variation. Results from Fig. 16 show that the standard deviation decreased from 1.20 kg over a four-day monitoring period to 0.093 kg for a 25-day monitoring period. The average percent error also decreased between the four-day and 25-day monitoring period, from 72% to 6.5%, respectively. Temperature data were not available for all datasets, and therefore some days that reported no measured fuel use but were cooking days are not always accounted for.

The percent error and standard deviation decreased logarithmically as monitoring duration increased, indicating that shorter monitoring periods may not capture longer term variability.

Fig. 17, which compares the average daily fuel consumption across households and the coefficient of variation (CoV) for increasing monitoring duration, indicates that increasing the monitoring duration did not decrease the CoV significantly, but average daily fuel use did decrease by 20% on average between day 4 and day 35 of monitoring, suggesting that longer term monitoring is of value.

Conclusions and future work

These proof-of-concept and pilot studies demonstrate that the FUEL system operates as intended, is accepted by households in this study context, and that data from FUEL can be used to calculate key cookstove performance metrics including fuel consumption, cookstove usage, carbon emissions, and firepower for each household or an entire community on a per-meal, daily, monthly, or annual basis. Stove stacking can be identified and quantified, as can potential errors introduced when monitoring with the FUEL system. As compared to temperature measurements on their own, integrated FUEL data provide a more comprehensive understanding of cookstove impacts, cooking habits, and stove usage. Monitoring fuel consumption enables direct prediction of potential emissions reductions for health and climate as well.

Data generated in the pilot study suggest that the FUEL can quantify the effects of stove stacking, indicating as expected that households continuing to use their traditional stove in addition to an improved stove will use more fuel per person than households using a single improved stove and cooking for the same amount of people. Disaggregated stove stacking results for a single household indicate that daily average fuel consumption for the RWS was higher than the LMS for that household, but that the RWS was also used for 31% more monitoring days as compared to the LMS. This points to the value in obtaining data on cooking duration to make accurate comparisons of fuel consumption over a known cooking time between different stove types. Monitoring conducted before and after an intervention is needed to draw additional conclusions about the net change when adopting an improved stove model as compared to the traditional stove and will be the subject of future studies. Results also illustrated the significant variability in day-to-day fuel use in households, firepower, and frequency and duration of cooking events. Even daily fuel use per person varied from an average of 1.75 ± 1.28 kg/SAE/day across households using the same stove (RWS). This implies that longer duration monitoring and larger sample sizes than are traditional practice in the cookstove sector may be beneficial.

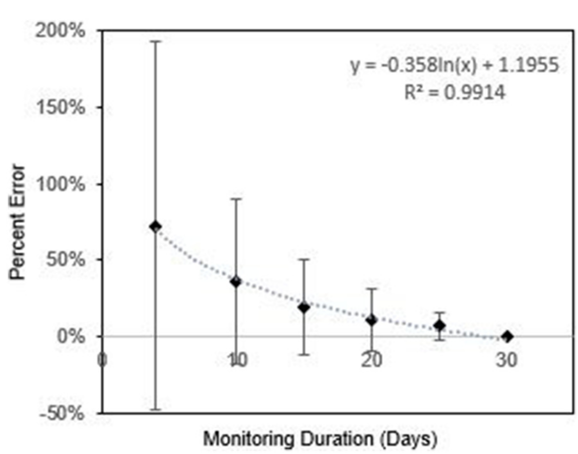

Fig. 16. Percent error vs monitoring duration up to 30 days.

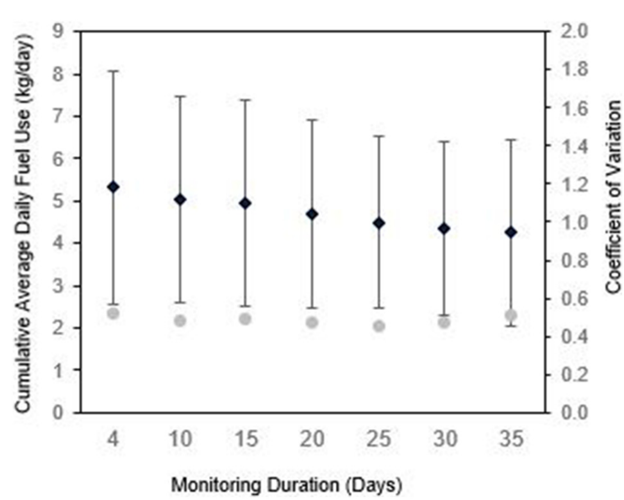

Fig. 17. Cumulative average daily fuel use and coefficient of variation vs monitoring duration.

Obtaining accurate data from the FUEL system requires systematic strategies. Initial challenges with prototype models using SD cards and thermocouples have been resolved with an updated wireless system manufactured by Climate Solutions Consulting. Issues with installation and obtaining accurate readings must be addressed in each new application. In addition to those presented in (Ventrella, Zhang, & MacCarty, 2019), a list of several considerations for conducting an effective study with the FUEL system includes:

- before conducting a study, identify the most effective method of hanging the FUEL system in the kitchen, as well as any necessary temperature sensor attachment methods for each stove type
- before installation, hold a training session with all participants to answer any questions or concerns and demonstrate how to use the system. This includes important guidance for participants such as:
  - o when adding wood, fill holder with as much wood as possible, refill when near empty
  - o all wood used for cooking must be stored in the holder for at least 1 min before putting in stove
  - o do not put unused or partially burnt wood back in holder after removal – leave out and usein the next cooking event

- arrange several check-ins from field staff to ensure accurate FUEL readings and troubleshoot potential issues
- if conducting a study with participants who have not previously used the FUEL system, conduct a usability survey and preliminary data analysis approximately 1 week into the monitoring period to ensure the system is accurately monitoring fuel consumption and is being used consistently.

Although the algorithm to determine cooking events and duration was modeled from previous research, the algorithm could be further refined for increased accuracy using specified positive and negative slope thresholds to identify the stop and start times of each cooking event, instead of peak clustering. Slope thresholds will be stove-dependent and can be best calculated through observation of the cooking process, recording when cooking starts and ends, and comparing that to the temperature profile slopes at those times.

While temperature data can help corroborate the accuracy of the FUEL readings and account for times when fuel is taken from a location other than the holder when cooking occurs or when fuel is removed when no cooking occurs, a limitation of the system is that it cannot account for every error. For example, for households that stove stack, there is the potential for error to be introduced if a household uses fuel from one holder in a different stove. If only one stove is being used, the algorithm can use temperature data to detect that fuel was being taken from the non-designated holder. However, if more than one stove is being used for cooking simultaneously, the algorithm will not be able to detect this error. Further validation is needed to demonstrate the FUEL system and algorithm can produce accurate results without placing additional burden on the user. In addition, a single holder could be used for all stoves using the same fuel to provide a measure of aggregated household fuel consumption, reducing the likelihood of this error.

Although the sensors are generally installed in households only for a short time, there is still the concern of invasiveness to the user. In a usability study conducted in Uganda with 85 households, it was found that 80% of users continued to use their holders eight months after the initial study had ended (Ventrella, Zhang, & MacCarty, 2019), pointing to high usability. However, this will differ based on study context and location. Future work should investigate mechanisms for further incentivizing users to engage with the system. Similar models have been deployed with usage data from temperature sensors to reward the use of improved cookstoves (Nexleaf Analytics, 2019). In addition, more research is needed on identifying and evaluating best practices for data dissemination to participants in a way that is of value to them.

It is expected that FUEL can be used equally as effectively for other fuels such as crop residues, coal, charcoal, and LPG. Therefore, future work includes a validation comparing the FUEL system to the KPT with a variety of fuel types (Ventrella, LeFebvre, & MacCarty, 2019). The long-term goal of this work is to develop a system that is available and usable for cookstove practitioners and researchers to more easily monitor and report long-term impacts of clean cookstoves and fuels in diverse settings.

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