AN ABSTRACT OF THE THESIS OF

Heather Miller for the degree of Master of Science in Mechanical Engineering presented on August 26, 2021.

Title: Development and Testing of an Integrated Sensor Suite for Cookstove Monitoring and Evaluation.

Abstract approved: ______________________________

Nordica MacCarty

The health and environmental impacts associated with traditional methods of household cooking and heating have driven the development and dissemination of many types of improved cookstoves and fuels. However, adoption rates, household cooking practices, and even household ventilation can directly influence the magnitude of a real-world impacts. Given the highly contextual nature of a technological intervention's impact, monitoring multiple household metrics over an extended period of time is necessary to fully understand performance in a given context.

Sensor-based monitoring can provide a means of capturing long-term, relatively objective data regarding a stove's performance within context of use. Evaluation of several metrics are needed, including adoption rates, fuel usage, and emission production. While each of these metrics have been monitored previously using individual sensors in combination with more traditional monitoring methods, such as surveys and household visits, monitoring of all three metrics simultaneously with sensors has not yet been possible.

A new integrated sensor suite has recently become available allowing for the autonomous monitoring of household air pollution, stove usage, and fuel usage. The purpose of this research was to evaluate this sensor suite as a tool for increasing accessibility and capacity for stove monitoring and evaluation by in-country projects. Training materials, data processing algorithms, and cross-sensor analysis methods were developed. The hardware used in this study were manufactured by Climate Solutions Consulting and included a wireless handheld launcher and a sensor suite consisting of an EXACT (temperature) sensor, HAPEx (particulate matter) sensor, and FUEL (fuel use) sensor. Data regarding household stove use, air quality, and fuel use was collected in Nepal between February 2021 and April 2021 by partners with the Red Panda Network. Data analysis included individual household level comparisons between monitoring periods to determine the itervention's impact on fuel consumption and household air pollution, household fuel use verification via increases in stove temperature and particulate matter concentration, and identification of cooking initiation given particulate matter (PM) concentrations.

Through cross-sensor analysis household PM data was used to verify cooking duration and flag rises in PM concentration without the increase in stove temperature. Furthermore, measured household fuel consumption using the FUEL system was verified using both household PM and stove temperature data with FUEL system compliance quantified with stove temperature data. Results suggest that the use of cross-sensor data analysis allow for single sensor validation, a more comprehensive view of household context, and an ability to develop insights on household stove performance despite data loss and/or corruption. This new, comprehensive method of household stove monitoring shows potential to increase transparency regarding real world stove performance evaluation, allow for faster stove design and iteration, increase access to results-based financing

such as carbon credits, and develop more robust metrics regarding stove impacts on both user health and the environment. Further development of the sensor suite system may increase the capacity of local projects to perform stove monitoring by providing a more accessible and effective means of data collection.

Development and Testing of an Integrated Sensor Suite for Cookstove Monitoring and Evaluation.

by

Heather Miller

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 26, 2021
Commencement June 2022

Master of Science thesis of Heather Miller presented on August 26, 2021.

APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

---

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Heather Miller, Author

ACKNOWLEDGEMENTS

To my advisor, Nordica MacCarty, thank you for tirelessly working to ensure that this opportunity was accessible to me. Your positive outlook and passion for your work is something I aspire to.

To Sunil Khanna and Joy Waite-Cusic thank you both for being such great mentors. Your insights on academia, careers, and life have been invaluable.

Thank you to my mother. Your love, unwavering support in my decisions, and complete and utter acceptance of all that I am has helped me to become the person I am today. I will forever be thankful and humbled by the sacrifices you have made for me.

To Vanessa, thank you for always being there for me. Your energy and creativity has always inspired me and made me proud to call you my friend.

To my Humanitarian Engineering lab mates, thank you for always being willing to have difficult and interesting conversations and for always reminding me to take care of myself.

To my friends Emily Klee, Parker Weide, and Derek Bean thank you all for being such amazing adventure buddies and all around great friends. Memories of our amazing adventures and anticipation for the ones to come have helped me through many uncomfortable moments.

To my partner Derek Bean. Words can not describe how much you have helped me during this time. Thank you for always making me laugh, being up for anything, and reminding me to take a breath.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

Chapter 1: Introduction

Background

Approximately 40% of the world's population still relies on open fires or simple stoves fueled by biomass for their cooking and energy needs (WHO, 2018). The high levels of exposure to emission from these forms of energy result in an estimated 1.6 million premature deaths a year (Stanaway et al., 2018). Though the ultimate goal would be ensuring all global citizens have access to clean energy, many at the bottom of the socioeconomic ladder may never see that reality. With some projections stating that approximately 2.6 billion people will still rely on traditional biomass for cooking by the year 2030 (IEA, 2012), the need for intermediate technologies such as improved biomass cookstoves and alternative fuels will persist for decades to come. Thus, there is a need for objective data regarding performance in context of use allowing for better understanding of household needs and behaviours, stove redesign or project redirection, and access to stove performance metrics that can be used to obtain results-based financing such as carbon credits.

The objective data regarding stove performance that is needed when conducting stove projects are highly specific to context (Rhodes et al., 2014). Current methods for data collection can be time consuming and expensive, limited in ability to provide long duration insight, require significant skills and training, unable to capture all of the metrics needed to fully evaluate stove performance (adoption rate, fuel usage, and emissions), and susceptible to bias (Barnes, 2010). To address these issues, development of accessible and robust monitoring and evaluation (M&E) methods regarding stove adoption and performance within their context of use are needed.

Sensor Suite

This need for accessible and robust methods of stove M&E was the driving motivation for this research. Building on previous research at Oregon State University (Ventrella & MacCarty, 2019; Ventrella, MacCarty, & Lefebvre, 2020; Ventrella, Zhang, & MacCarty, 2020), and with the continued partnership with Climate Solutions Consulting, a suite of wireless sensors and associated data analytics were developed to provide a comprehensive understanding of a stove's performance in context of use. This suite, shown in Figure 1.1 provides a comprehensive view of household context through the monitoring of stove use, household air pollution, and fuel consumption using the following sensors.

1. EXACT: Stove temperature sensor

2. HAPEx: Household air pollution sensor

3. FUEL: Household fuel consumption sensor

Figure 1.1: Sensor suite deployed in the a Nepalese household.

International Partnership & the Global COVID-19 Pandemic

An international study was planned to deploy and evaluate this new monitoring system. This research began with the intention that Oregon State researchers would travel to the place of deployment to ensure that the best possible study outcomes could be achieved. Unfortunately, the global COVID-19 pandemic prevented all international travel subsequently changing the nature of the study. Therefore, the study was expanded to evaluate remote training capabilities and the potential for capacity building in local stove monitoring projects as well as the efficacy of the sensor system itself.

The Red Panda Network (RPN) is a non-profit organization that has been fighting to save red pandas since 2007 and is currently implementing a “Community-based

Red Panda Conservation" project in more than 50% of the red panda habitat in Nepal. RPN is committed to protecting wildlife and preserving their habitat through the empowerment of local communities by adaptive community-based research, education, and sustainable livelihood initiatives. One of their livelihood initiatives is the distribution of an improved metal biomass cookstove with a chimney to rural communities that live alongside red pandas and rely on the biomass in their habitats for their energy needs. RPN chose to partner with Oregon State researchers on this study to produce clear stove performance metrics for communication with their stakeholders.

Collaboration regarding development of study timeline and objectives was accomplished using through Zoom meetings. The written material developed for the training of the RPN field staff, shared as Appendix A, was provided along with video content as a guide for sensor use and appropriate research conduct involving human subjects. All sensors needed for the research were sent to Nepal and, with the assistance of Climate Solutions Consulting, plans were made on how best to deploy sensors within the households that would be monitored.

Once the field staff were trained and the study began, all sensor data were collected and shared after each household visit. Data were then progressively analyzed at Oregon State University. Upon the completion of the study, a report was developed for RPN for the purpose of communicating the performance of their stove program to their stakeholders which is shared as Chapter 2. Finally, a journal paper was developed to share functionality of the sensor suite and is presented in Chapter 3.

Data Analysis

Although the use of sensors in M&E for household energy projects is not a novel endeavor, the use of an integrated sensor suite that autonomously monitors household air pollution, stove usage, and fuel usage simultaneously over a prolonged periods is something that, to our knowledge, has not yet been pursued. Beyond the deployment of the sensors, this research aimed to develop a method for stove M&E that provided a potential increase in local capacity by providing an accessible method of monitoring without the usual need for the presence of a highly trained researcher and analyst. Accomplishing this objective will require the development of a data analysis platform that allows users the ability to upload sensor data files and retrieve stove performance metrics. My contribution to this effort focused predominately on the development of data management and analysis methods that can be implemented on this type of platform.

Two primary types of analysis were developed for this research. The first was general sensor metrics which included household cooking time, fuel consumption, and particulate matter readings. These values were used to evaluate differences in household contexts as well as report changes in households from one monitoring period to the next. The second method involved sensor validation through cross-sensor analysis. The FUEL sensor, which involves direct user interaction, requires the most verification to ensure that the system is being used properly by household participants. Additionally, identifying cooking events and potential usage of other non-monitored stoves in a household has been a difficult task using only single stove temperature sensors. Using cross-sensor analysis I have developed a method for identifying the initiation of cooking events as well as highlighting potential instances of cooking events that are occurring on a non-monitored stove.

Researcher Positionality

It is important to recognize that my positionality in this research may have inadvertently led to bias and uncertainty. Although I have worked closely with our partners in Nepal I have never been to households involved in this study nor have I spoken to any of the participants. This along with the fact that I am physically, socioeconomically, culturally, and racially distant from the participants results in my having a very limited understanding of their lived experience. All of the analysis methods that I developed for this study included assumptions that I made about cooking patterns and household realities that I assumed based on discussion with our partners in Nepal, household pictures, and educated guesses based on sensor data. I acknowledge the potential that some, if not all, of the assumptions made in this research may not reflect reality and are subject to debate. Furthermore, I acknowledge the power differential created between Oregon State University and RPN may have resulted in bias regarding household selection and data collection. To reduce this bias we did our best to support RPN throughout the study process while also ensuring that they were aware that our support was not contingent on the success of the study.

Thesis Contents

The remaining chapters of this thesis will proceed as follows. Chapter 2 will present a report outlining initial results regarding changes in measured household fuel consumption and household PM levels. This report was written to provide stakeholders of the Red Panda Network with indicators regarding the impact of their cookstove implementation project and does not include cross-sensor validation. Chapter 3 will present a paper in preparation for submission to *Development Engineering* regarding the insights generated by the suite of sensors during collaboration with RPN as well as the feasibility of the system as a tool capable of building local capacity for stove monitoring and evaluation. Chapter 4 concludes with overall findings from this research with an appendix presenting materials developed for training RPN field partners in the deployment of the sensor suite and data collection.

Chapter 2: Project Impact Report for Red Panda Network

Report prepared for stakeholders of the Red Panda Network

Authors: Heather Miller, Janam Shrestha, Olivier Lefebvre, and Nordica MacCarty

Abstract

The Red Panda Network and Oregon State University collaborated to monitor and analyze energy usage in households in two rural districts in the eastern Napalese mountain range. The goal of the project was to quantify the impact of an improved metal stove with a chimney on fuel consumption and indoor air quality in 48 households (22 in the Taplejung district and 26 in the Panchthar district). Fuel consumption was monitored using a Fuel Use Electronic Logger (FUEL) and relative particulate matter concentration was monitored using a Household Air Pollution Exposure (HAPEx) sensor. The data show a percent change in average total household fuel use and fuel use per person of -28.3% [-12.6%, -42.4%] and -30.5%[-10.48%, -47.9%] respectively following the introduction of the RPN stove. The average 24 hr particulate matter concentration in households were observed to have an average percent change of -54.2% [-36.2%, -69.2%]. There did appear to be disparities between the levels of impact between the two districts. Households in the Taplejung district experienced greater fuel savings than the those in the Panchthar district while households in the Panchthar district experienced greater reduction in average 24 hr particulate matter concentration levels. These results suggest that household context may play a role in the expected impacts of the RPN

stove. Additional studies may be needed to verify these results and increase statistical confidence over household types, time periods, and seasons.

2.1 Project Outline

2.1.1 Project Goals

The goal of this project was to quantify impacts of transitioning from traditional stoves (Figure 2.1) to a metal biomass cookstove with a chimney (Figure 2.2) distributed by the Red Panda Network (RPN) on both fuel consumption and indoor air quality in two rural Nepalese districts.

Figure 2.1: Stoves observed in households prior to introduction of RPN stove

Figure 2.2: RPN Metal Stove with Chimney.

2.1.2 Project Details

Fuel consumption and indoor air quality of 48 households in 2 districts were monitored. Weight sensors (FUEL) were used to track fuel usage and household air pollution sensors (HAPEx) were used to monitor indoor air quality. Each household was monitored for a minimum of 10 days before the introduction of the RPN stove to establish a baseline for fuel consumption and air quality within the homes. After the initial monitoring period, the homes were provided with the RPN stove and given a minimum of 2 weeks to become accustomed to using it. Sensors were then reinstalled in the households and the same parameters were monitored again for a minimum of 10 days. Mid-monitoring check-ins occurred during both monitoring periods to ensure that the sensors were operating correctly and to allow field staff the opportunity to address any questions the participants might have had and correct any issues. During each household visit fuel moisture readings were collected with a MO210 moisture meter. Table 2.1 shows the dates of sensor deployments, check ins, and data collection for each of the monitoring periods in both districts.

Table 2.1: RPN household monitoring dates in 2021.

		Before RPN Stove			After RPN Stove		
District	**Households**	**Sensor Deployment**	**Mid Check-In**	**Data Collection**	**Sensor Deployment**	**Mid Check-In**	**Data Collection**
Taplejung	22	Feb. 20th	Feb. 28th	March 5th	March 25th	April 2nd	April 6th
Panchthar	26	March 8th	March 15th	March 22nd	April 9th	April 15th	April 21st

2.1.3 District Details

Table 2.2 shows the number of households monitored in each district along with the number of households that could be considered for analysis. Incomplete data was due to sensor malfunction as well as absence of household members during data collection.

Table 2.2: Complete HAPEx and FUEL data availability

District	**# HH**	**HAPEx Data**	**FUEL Data**	**Fuel & Feeding Data**
Taplejung	22	19	15	15
Panchthar	26	19	24	23

The location of each district are shown in Figure 2.3. Household in both districts exist within rural mountainous regions of eastern Nepal, however household context differs significantly. The Taplejung district is located on a popular tourist route with many of the households represented in the sample being tea houses that cater to tourists as they pass through. Alternatively, Panchthar district consisted of more traditional households feeding only household members and occasionally using their cookstoves for animal feed preparation. Because of this difference in context, households in Taplejung district fed on average more people in total than those households in Panchthar district (see Figure 2.4).

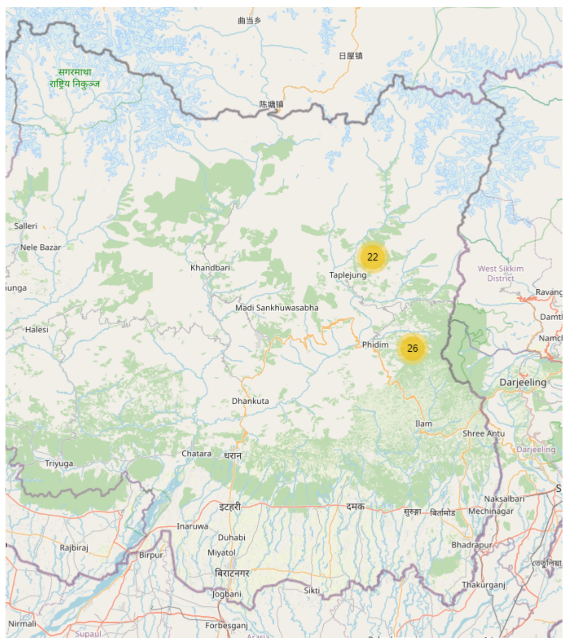


Figure 2.3: Locations of districts studied. Numbers representing the number of households in Taplejung district (22) and Panchthar district (26).

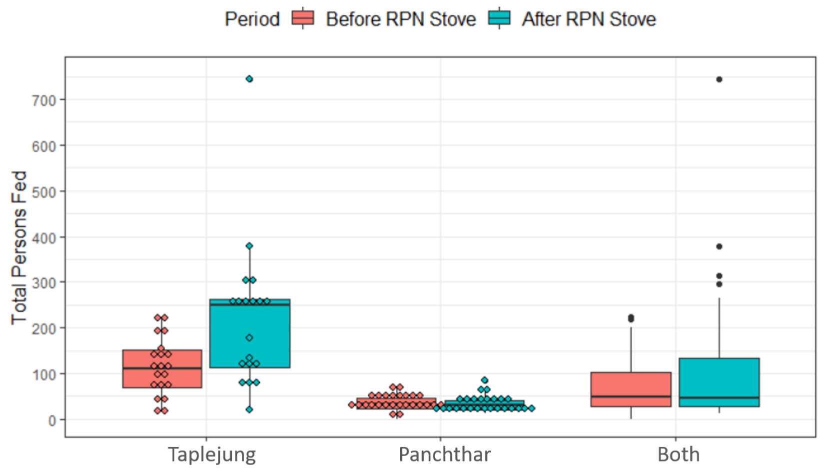


Figure 2.4: Total number of standard adult equivalent people fed in each household during each monitoring period.

2.2 Data and Analysis

2.2.1 Fuel Use

The fuel consumption in each household was measured using a Fuel Use Electronic Logger (FUEL) (Ventrella & MacCarty, 2019; Ventrella, MacCarty, & Lefebvre, 2020; Ventrella, Zhang, & MacCarty, 2020). The FUEL system, which was constructed and installed in every household, monitors and records time stamped mass data every two minutes. Study participants were asked to store any fuel they intended to use for cooking in the FUEL system. They were also instructed to remove only what they planned to use for a particular cooking event, to never put fuel back on the system after it was removed, and to fill the system only when it was empty or close to empty. Assuming that participants complied with these instructions, we are able to calculate the amount of fuel consumed over a given monitoring period. Figure 2.5 shows an example of the FUEL system in use in a household with Figure 2.6 illustrating an example of the resulting sensor data.

Figure 2.5: A FUEL system installed in one of the Nepalese Households. Red square indicates the actual FUEL sensor.

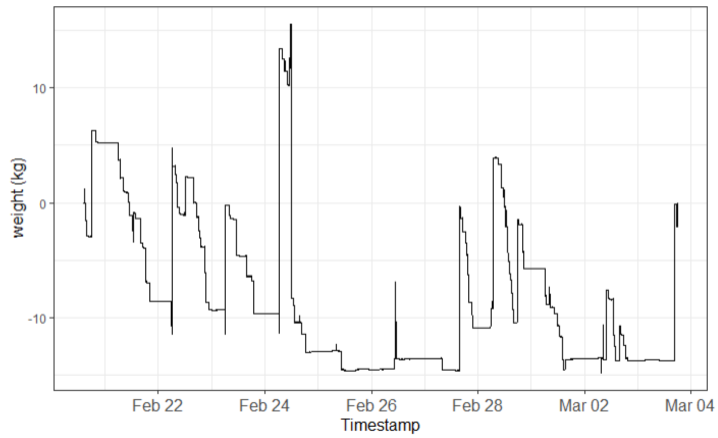


Figure 2.6: Example of FUEL system data output.

2.2.2 Standard Adult Equivalent

Simply comparing the amount of fuel consumption before and after the introduction of the RPN stove does not take into consideration the variation in the number of people fed during each monitoring period. This variation may occur in households who entertain visitors (like the tea houses described in the Taplejung district) or if a member of the household is only present for a portion of the monitoring. To account for these variations, each household was given a printed chart similar to that of Figure 2.7 and were asked to indicate the category of age range and gender of each person fed. Having participants track the people fed in this way allows the calculation of a standard adult equivalent (see Table 2.3) each day of monitoring per standard methods in the Kitchen Performance Test (Bailis, Smith, & Edwards, 2007). During mid-monitoring check-ins, the field staff would check the list and remind participants to indicate how many had been fed each day if they had forgotten. Although there is potential of recall bias, particularly in tea houses with many guests, these estimations allow for the approximation of both the amount of fuel used per person fed as well as total fuel use.

	Child: 0-14 years	Female: over 14 years	Male: 15-59 years	Male: over 59 years
Day 1				
Day 2				
Day 3				
Day 4				
Day 5				
Day 6				
Day 7				
Day 8				
Day 9				
Day 10				

Figure 2.7: Household feeding chart.

Table 2.3: Standard Adult Equivalence (SAE)

Gender & 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

2.2.3 Household Air Quality

Data regarding indoor air quality in households were collected using Household Air Pollution Exposure (HAPEx) sensors. The HAPEx sensors are real-time, passive particulate matter (PM) loggers that use light scattering technology to estimate PM concentrations within a given space logging PM concentration units every minute. Figure 2.8 shows a HAPEx sensor installed in a household with Figure 2.9 illustrating an example of the PM data collected within a household during one of the monitoring periods.

Figure 2.8: Installed HAPEx sensor.

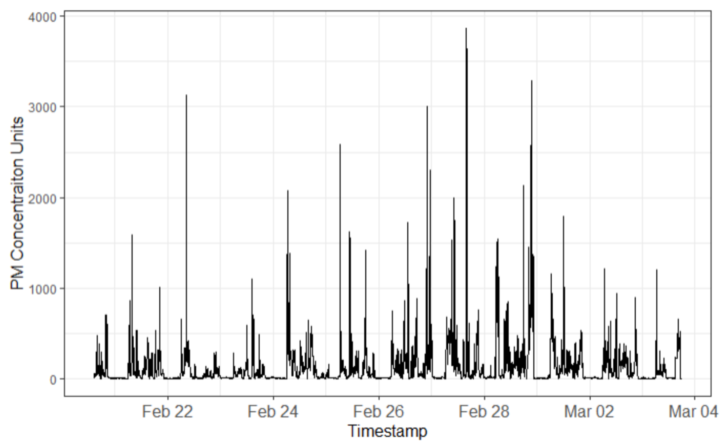


Figure 2.9: Example of HAPEx sensor data output

Determining the concentration ($\mu g\, m^{-3}$) of a specific aerosol (i.e. $PM_{2.5}$) within a household requires calibration of the light scattering against a gravimetric standard for the specific type of aerosols present. Due to constraints in the project, we were unable to collect gravimetric measurements and so we will be reporting differences in the estimated 24 hour particulate matter concentration units. While these measurements cannot be used to consider compliance or non-compliance with the World Health Organization's guidelines, it can provide insight on the magnitude of relative changes in PM concentration before and after the introduction of the RPN stoves.

2.3 Results

2.3.1 Fuel Usage

Figures 2.10 and 2.11 illustrate the amount of total and per person fuel use respectively in each district independently as well as combined.

Figure 2.12 shows the actual dispersion of percent change in both total and per person fuel consumption among the households. The Taplejung district households showed a median change in per person fuel consumption of -72.5% and a median total fuel consumption change of -56.3%. The Panchthar district households showed a median fuel consumption change per person of 3.4% and a median total fuel consumption change of -14.2%. When considering all monitored households a combined median fuel consumption change per person of -21.1% and a median total fuel consumption change of -22.4% was observed.

Figures 2.13 represent the expected average percent change in fuel use and fuel use per person with a 95% confidence interval (CI) if we assume that the households monitored are representative of other households within the larger rural Nepalease population. These figures show that overall we would expect both the average total fuel consumption and the average fuel use per person to change -28.3%[-13.1%, -42.3%] and -30.7%[-11.1%, -47.8%] respectively. However, households with environments that more resemble those in the Taplejung district may experience higher total fuel reductions with an average percent change of -45.4%[-13.6%, -70%] and an average percent change of fuel use per person of -68.0%[-47.4%, -83.6%]. Alternatively, we would expect households that more closely resemble Panchthar district households to have an average percent change in total fuel use of -16.9%[-2.0%, -30.5%] and an average percent change in fuel use per person of only -1.0%[-21.0%, 21.3%].

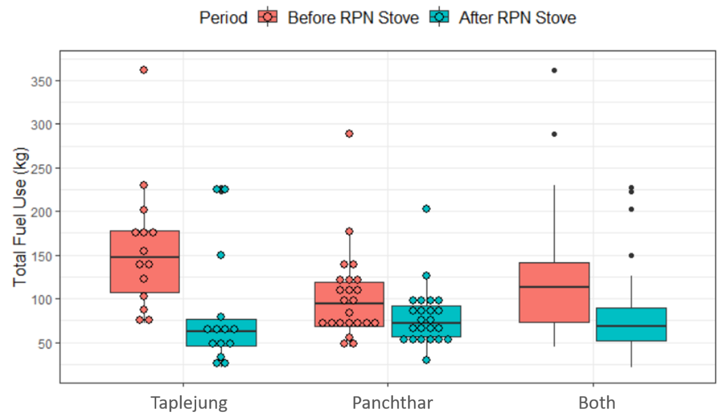


Figure 2.10: Total kg of fuel use measurements for both districts individually and together before and after the introduction of the RPN stove.

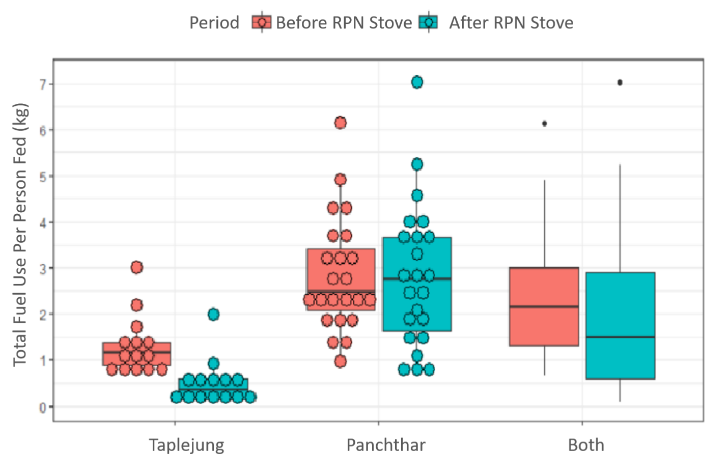


Figure 2.11: Total kg of fuel use measurements per standard adult equivalent person fed for both districts individually and together before and after the introduction of the RPN stove.

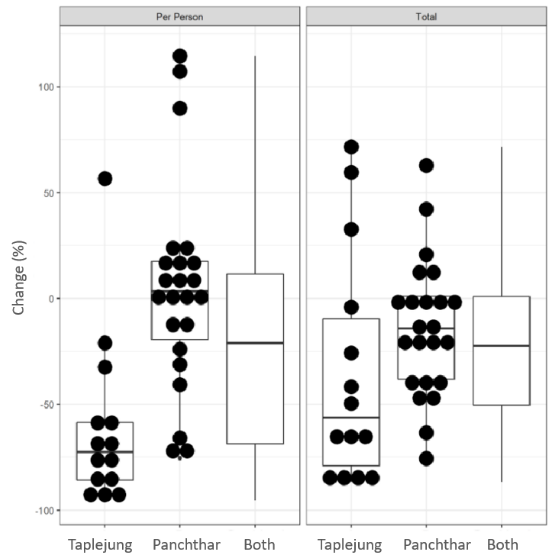


Figure 2.12: Actual change in total and per person fuel consumption in both districts. Median Fuel change per person, Taplejung: -72.5%, Panchthar:3.4%, Both: -21.1%. Median Total Fuel Change, Taplejung: -56.3%, Panchthar: -14.2%, Both: -22.4%

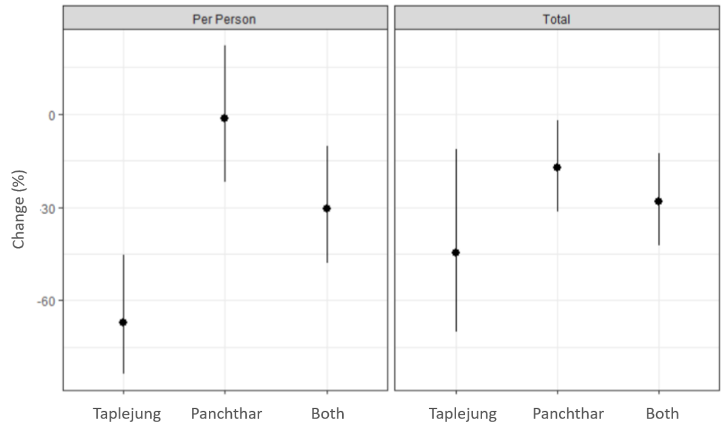


Figure 2.13: Percent change in fuel use per person and total fuel use after the introduction of the RPN stove. The point represents the average percent change with the error bars representing the 95% CI.

2.3.2 Particulate Matter

Figure 2.14 represents measured 24 hr PM concentration units in both districts whereas Figure 2.15 represents the change in average 24 hr PM concentration units within individual households in each district. There was an observed average percent change in average 24 hr PM concentration units across both villages of -54.2%[-36.2%,-69.2%] with households in the Panchthar district experiencing a more pronounced average percent change of -69.9%[-57.0%, -80.4%] and households in the Taplejung district experiencing an average percent change of -35.3%[-3.90%, -65.3%].

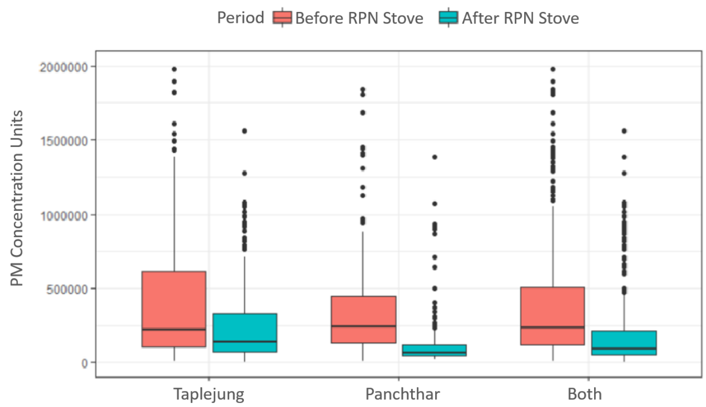


Figure 2.14: 24 hr particulate matter (PM) concentration unit measurements for both districts before and after the introduction of the RPN metal stove with chimne.

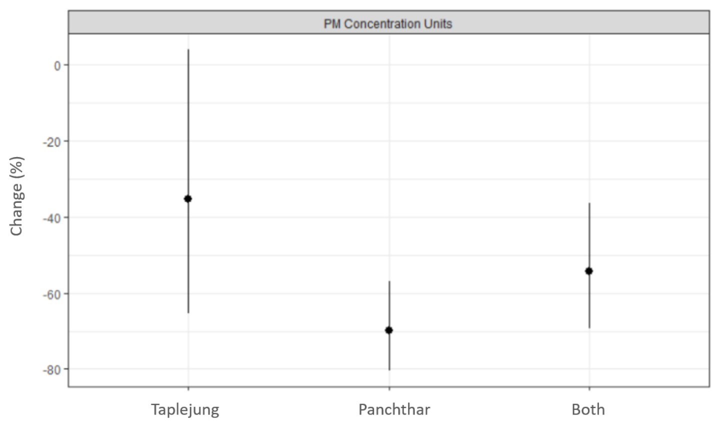


Figure 2.15: Percent change in average Particulate Matter (PM) concentration units after the introduction of the RPN stove. The point represents the average percent change of 24 hr PM concentration unit with the error bars representing the 95% CI.

Figure 2.16 represents the relationship observed between the average 24 hr PM concentration units and the average 24 hr fuel use recorded in each household. This shows the introduction of the RPN stove resulted in fewer occurrences of days with high PM concentration units across all fuel amounts.

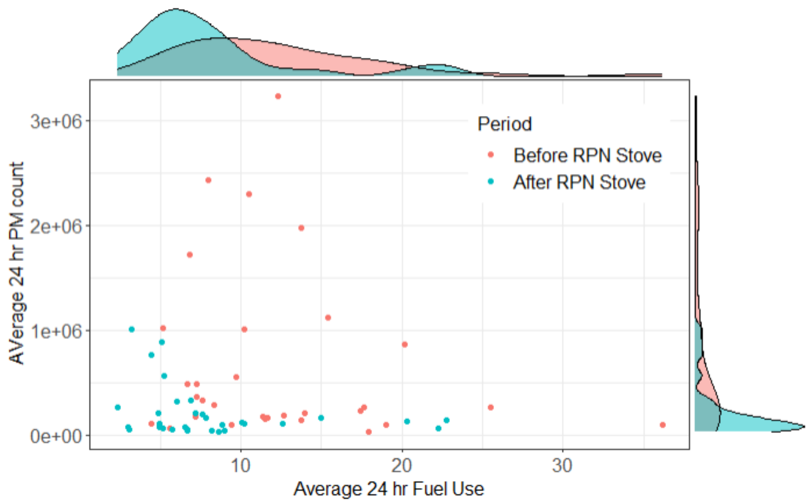


Figure 2.16: Average 24 hr particulate matter (PM) concentration unit measurements and fuel use measurements for the same 24hr period for households in both districts before and after the introduction of the RPN stove.

2.4 Conclusions

The data presented shows evidence that the introduction of the RPN metal stove with chimney into Naplese households reduced both total fuel consumption and per person fuel consumption by approximately 30%. There is evidence that households in the Taplejung district experienced a greater average total as well as per person fuel savings than households in the Panchthar district. This is likely due to the greater number of people that Taplejung district households serve as well as the potential that some households in the Panchthar district used a portion of the fuel for animal feed preparations.

Additionally, an average 24 hr PM concentration unit reduction of approximately 54% was observed across all households. However, households in the Panchthar district experienced a greater reduction in their average 24 hr PM than households in the Taplejung district. This is likely due to many households in the Taplejung district already having access to other clean cooking stoves whereas households in the Panchthar district did not. Because of this it is reasonable that households in the Panchthar district experienced a greater change in PM concentration when compared to households in the Taplejung district.

This analysis highlights the importance of understanding context of use when attempting to quantify stove impact. Results suggest that households in both districts experienced benefits in terms of fuel savings and improvement in indoor air quality, however the magnitude of those improvements were influenced by the household context.

2.4.1 Data Limitations

Although these data show promise for the RPN stoves to reduce household fuel consumption and improve indoor air quality in rural Nepalese households, additional studies may be needed to verify these results and increase statistical confidence over household types, time periods, and seasons.

Chapter 3: Evaluation of an integrated suite of sensors to monitor fuel consumption, air quality, and usage of household cooking stoves.

For submission to *Development Engineering*

Authors: Heather Miller, Janam Shrestha, Olivier Lefebvre, and Nordica MacCarty

Abstract

The rise in sensor-based monitoring in the clean cookstove sector has been driven by the need for objective quantitative stove performance evaluation within the context of use. Metrics including adoption rates and user exposure levels have been available previously through separate measurements such as stove temperature and particulate matter concentration, while information regarding fuel consumption has been collected through surveys and daily visits to households to conduct measurements. For many, these separate data streams and methods have been prohibitively difficult to use and analyze. With the advent of a suite of integrated sensors for stove use, air quality, and fuel consumption, a comprehensive analysis of a stove intervention's impact is now available. This research explores the insights that can be gained from the use of these sensors individually and in combination. Longitudinal performance metrics of an improved biomass metal stove with a chimney within its context of use were obtained using sensor suites consisting of stove temperature sensors (EXACT), household air pollution sensors (HAPEx), and fuel

use sensors (FUEL) deployed in 48 households in the Taplejung and Panchthar districts of eastern Nepal. Through cross-sensor analysis household PM data was used to verify cooking duration and flag rises in PM concentration without the increase in stove temperature. Furthermore, measured household fuel consumption using the FUEL system was verified using both household PM and stove temperature data with FUEL system compliance quantified with stove temperature data. Households were monitored for a minimum of 10 days before and after the introduction the stove with results showing a median reduction of 61.2% (n = 38) in household PM concentration and a median reduction of 16.5% (n = 37) in total measured household fuel consumption reported by the FUEL sensor. Household context appears to have played a significant role in household impact with households in the Panchthar district experiencing greater median reductions in household PM concentrations while households in the Taplejung district experienced greater median fuel reductions.

3.1 Introduction

Approximately 40% of the world's population continues to rely on open fires or simple stoves fueled by biomass for their cooking and energy needs (WHO, 2018). The high levels of exposure to emission from these forms of energy are associated with increased blood pressure, dyspnea, childhood pneumonia, lung cancer, low birth weight, and cardiovascular disease (Pratiti, Vadala, Kalynych, & Sud, 2020). These health impacts contribute to an estimated 1.6 million premature deaths a year (Stanaway et al., 2018). Additionally, fuel collection/purchasing and its use can result in significant time, financial, and physical burdens for users. Though providing increased access to clean energy alternatives would likely improve overall health outcomes as well as reduce environmental impact (Rehfuess, 2006), the lack of affordable clean energy infrastructure has led to projections that 2.6 billion people will still rely on traditional biomass for cooking by the year 2030 (IEA, 2012). Technologies designed to reduce the health and environmental impact associated with traditional energy services without the need for large scale infrastructure change may provide an intermediate solution.

Intermediate technologies such as improved biomass cookstoves designed to increase combustion and heat transfer efficiency or stoves that use alternative fuels such as pellets or LPG have been developed to reduce the many negative impacts of traditional cooking methods (Manoj Kumar, Sachin Kumar, & Tyagi, 2013). In practice, many variables regarding fuel supply, usability, and adoption rates may limit the magnitude of an interventions impacts creating challenges for accurate measurements of real-world performance. Objective performance data within context of use is needed for a more holistic understanding of household needs and behaviours; technology and project design support; and obtaining results-based financing such as carbon or health credits.

Calls for stove performance metrics obtained within their context of use have grown over the years (Wilson et al., 2016; Thomas, 2017; Abdelnour & Pemberton-Pigott, 2018) but current methods for data collection can be time consuming and expensive, limited in ability to provide long duration insight, require significant skills and training, unable to capture all of the metrics needed to fully evaluate stove performance (adoption rate, fuel usage, and emissions), and susceptible to bias (Barnes, 2010). A rise in sensor-based monitoring in the clean cooking sector has led to new methods of stove monitoring and evaluation (M&E) that have the potential for increased accountability and transparency regarding real world stove impact while limiting subject reactivity (or changes in participant behavior caused by observation) (Thomas et al., 2016). As these methods develop, ensuring that they are accessible to stove project implementers has the potential to increase the efficacy of stove dissemination and ensure that stoves are reaching their design impact potential. This research aims to develop existing sensor-based stove monitoring methods and data analysis through the development and testing of the deployment of a new wireless integrated sensor suite and its resulting data.

3.1.1 Stove Monitoring and Evaluation

Understanding a stoves performance within its context of use often requires that more than one metric be monitored (Harrell et al., 2016). It is commonly accepted that stove usage and displacement of traditional methods, household air pollution, and fuel consumption are the three most important metrics in determining stove performance and potential long term impact. Each of these metrics should be considered during stove M&E either through more traditional methods or with sensor-based monitoring.

Stove usage is a key indicator of usability, desirability, and (when paired with efficiency and emissions data) a predictor of impact. Usage sensors provide data on cooking patterns and time spent cooking on one or more stoves (also known as stove stacking) and can provide important insights on the level of displacement of traditional methods. Though various temperature loggers are available, including iButtons, Geocene Dots, and EXACT infrared sensors, all stove usage sensors require careful positioning to ensure robust response and prevent damage from heat (Ruiz-Mercado, Canuz, & Smith, 2012; Wilson et al., 2016).

Measuring household air pollution (HAP), specifically fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and black carbon (BC), can provide direct insight into impact on both short and long term health outcomes for stove users. Large hood or portable emissions capturing systems, which quantify emission factors by collecting and measuring multiple pollutants, produce reliable and detailed results but are not suitable for long term exposure monitoring. Additionally, they require the prolonged presence of a trained individual and large equipment in homes during cooking which can be expensive and cumbersome for the users. Gravimetric systems are the standard for quantifying health impacts against air quality guidelines. These systems utilize pump and filters to provide accurate readings of average concentration over the monitoring duration. Alternatively, real-time data from PM and CO sensors, such as devices like University of California at Berkeley's particle monitor (UCB) (Chowdhury et al., 2007) and the Climate Solutions Consulting's Household Air Pollution Exposure sensor (HAPEx), can shed additional insight on the timing and nature of particulate exposure.

The fuel requirements associated with a household's cooking and energy needs have direct implications on household finances, time allocation for fuel collection, and health outcomes. Furthermore, non-renewable biomass harvesting can lead to environmental degradation and deforestation (Bailis, Drigo, Ghilardi, & Masera, 2015). Direct quantification of changes in household fuel consumption following the introduction of a stove can provide a stove performance metric important to both end users and stake holders interested in stove impact. Beyond collecting fuel consumption data through kitchen performance tests (KPT) (Bailis et al., 2007) or survey-based methods, the only sensor-based monitoring tool currently available (to our knowledge) is the Fuel Use Electronic Logger (FUEL) (Ventrella & MacCarty, 2019; Ventrella, Zhang, & MacCarty, 2020; Ventrella, MacCarty, & Lefebvre, 2020). This sensor requires users store their fuel supply in a logging tensile or compressive scale, depending on the type of fuel. Although this system requires user engagement and compliance to report accurate fuel consumption metrics, it allows for the autonomous monitoring of household fuel consumption for longer durations than is possible through the KPT or other methods. This provides the capacity for greater data collection with less time commitment of both researcher as well as study participants. Furthermore, the FUEL monitoring system could potentially reduce bias by allowing for fewer household interruptions by stove monitoring enumerators.

3.1.2 Sensor Suite

With sensors available for autonomous monitoring of stove temperature, air quality, and fuel consumption over long durations, there is potential for a more holistic and nuanced understanding of performance within context of use. The partnership between Oregon State University and Climate Solutions Consulting has resulted in the development of a suite of wireless sensors that consists of 3 sensors:

1. EXACT: Stove temperature sensor

2. HAPEx: Household air pollution sensor

3. FUEL: Household fuel consumption sensor

Figure 3.1a illustrates the sensor suite deployed in a household. Figure 3.1b shows the wireless hand held launcher used to deploy the sensors, check household compliance regarding stove and FUEL system usage during mid-monitoring check ins, and sensor data collection. The ability to check sensor performance and usage compliance in real time allows for immediate sensor malfunction mitigation as well as directed engagement with household members based on real time sensor use metrics. Additionally, this system combines all household sensor data into a single file allowing for ease of data analysis. These features were designed to allow field staff to perform household stove monitoring at a larger scale while also reducing the time and cost traditionally associated with M&E efforts.

(a) **(b)**

Figure 3.1: (a) Sensor suite deployed in a Nepalese household. (b) Climate Solutions Consulting sensor suite Launcher

3.1.3 Red Panda Network Partnership

For this study, Oregon State University researchers partnered with the Red Panda Network (RPN), a non-profit organization that has been working to save red pandas since 2007 and is currently implementing a "Community-based Red Panda Conservation" project in more than 50% of the red panda habitat in Nepal. RPN is committed to protecting wildlife and preserving their habitat through the empowerment of local communities by adaptive community-based research, education, and sustainable livelihood initiatives. One of these initiatives includes the distribution of an improved metal biomass cookstove with a chimney to rural communities that live alongside red pandas and rely on the biomass from their habitat for energy. RPN's goal in participating in this study was to determine their stove's impact on household fuel consumption and air pollution.

3.1.4 Research Objectives

To address the needs of both RPN and Oregon State researchers, this study had two main research objectives; 1) To determine the impact of the RPN stove on rural household fuel consumption and HAP and, 2) To determine the functionality and feasibility of this sensor suite being deployed in rural households by field staff with limited previous experience in sensor deployment and data collection. To address these objectives this study looks to answer the following questions.

1. Does the introduction of the RPN stove reduce overall household fuel consumption and HAP?
2. Can the implementation of sensors and data collection be reliably conducted by field staff with limited prior experience in sensor deployment and data collection?
3. Can cross-sensor analysis improve and validate data from individual sensors?

3.2 Methods

This study was planned and conducted during the COVID-19 global pandemic, preventing Oregon State researchers from traveling to Nepal and working directly with RPN partners. With limited direct project oversight by Oregon State researchers, it was possible to test of the usability of the sensor suite and its ability to build M&E capacity in local communities using only remote training. Virtual meetings were held between

RPN staff and OSU researchers to develop a study timeline, procedures, and to answer questions regarding sensor use. All sensors needed for the study along with training materials were provided by Oregon State researchers and Climate Solutions Consulting.

Data collection in two rural mountainous districts of eastern Nepal, the Taplejung and Panchthar district (Figure 3.2) was overseen by OSU IRB 7257. Data were collected on air quality, stove, and fuel usage for 10 days before and 10 days after the introduction of an RPN metal biomass cookstove with a chimney (Figure 3.3f). The Taplejung and Panchthar districts exist in similar climates but exhibit difference in income generating activities that contribute to significantly differing household context. The households in the Taplejung district rely primarily on hosting guests and tourists heading to worship at the Pathibhara temple, whereas household monitored in the Panchthar district reflect more of a traditional Nepalese household practicing livestock herding.

Figure 3.2: The districts in which households were located in this study. Green is the Taplejung District and Orange is the Panchthar district.

3.2.1 Stoves

Each household used a range (and at times combinations) of traditional cooking stoves. Table 3.1 provides the names, descriptions, and number of stove observations in each district while Figure 3.3 shows an example of each stove type along with the RPN stove that was disseminated to the households.

Table 3.1: Biomass stoves monitored in study households.

Stove Type	**Stove Description**	**Taplejung**	**Panchthar**
Traditional Open Fire	A metal frame open fire indoor cookstove (Figure 3.3a).	7	7
Three Stone	An open fire cookstove constructed of three large stones. Both indoor and outdoor (Figure 3.3b).	0	8
Mud Stove	Stove made of stone and mud, often attached to a specific place within household. Can be located in or outside (Figure 3.3c).	4	10
Metal Frame Mud Stove	Framework made of iron surrounded by mud on three sides. Cement occasionally used as an alternative (Figure 3.3d).	10	0
Mud Stove with Chimney	Similar to a mud stove but with an inbuilt chimney (Figure 3.3e).	1	1

Figure 3.3: Study stoves. (a) Traditional Open Fire (b) Three Stone (c) Mud Stove (d) Metal Frame Mud Stove (e) Mud Stove with chimney (f) RPN stove

3.2.2 Monitoring Timeline

Before the collection of data, a community workshop was arranged in both districts. These workshops were held to inform study participants of the purpose of the study, gain their initial consent in study participation, and provide instructions on how to properly install and use the stoves. Participants were also provided with a pictorial user manual ("Installation and User Manual of Metallic Improved cookstove") that included instructions on RPN stove installation and usage. A fully installed RPN stove was set up for participants to observe, consult and follow instructions to encourage proper usage.

Sensors were deployed in households between February 2021 and April 2021. Table 3.2 provides detailed date ranges regarding the monitoring periods for the 22 Taplejung district households and the 26 Panchthar district households. Households were monitored using the sensor suite for 10 days before the introduction of the RPN stove to develop a baseline metric for household fuel consumption, cooking patterns, and HAP. After the introduction of the stove the households were given a minimum of 14 days to grow accustomed to the stove before the sensor suite was re-installed in the households for another 10 days.

During each monitoring phase, households were visited 3 times. The initial visit involved sensor installation, deployment, and training on sensor use. Explicit instructions shared with households' members regarding FUEL sensor usage included:

- All firewood for cooking must be stored in the holder before using it in a stove.
- The holder must be filled with as much firewood as possible and only refilled when near empty.
- Do not put firewood back in holder after its removal including the partially burnt firewood (leave out for next cooking event).
- If additional wood is added, it must be in holder for at least 1 minute before removal for cooking.

A mid-monitoring check-in was performed to ensure proper sensor performance and as a means of providing guidance to households as needed. The final check-in was focused on data collection and sensor removal. Fuel moisture readings were collected by taking three moisture readings each on three pieces of wood and reporting the average value during each household visit.

Table 3.2: RPN household monitoring dates in 2021.

		Before RPN Stove			After RPN Stove		
District	**Households**	**Sensor Deployment**	**Mid Check-In**	**Data Collection**	**Sensor Deployment**	**Mid Check-In**	**Data Collection**
Taplejung	22	Feb. 20th	Feb. 28th	March 5th	March 25th	April 2nd	April 6th
Panchthar	26	March 8th	March 15th	March 22nd	April 9th	April 15th	April 21st

During the initial visits, households were provided with a feeding chart and asked to track the number of people fed each day in each category. Figure 3.4 shows an English translation of the charts provided to the household participants. These data were collected to estimate standard adult equivalence when calculating fuel usage per person fed (Bailis et al., 2007). During the mid monitoring and final visits these charts were checked for completion. If the households had not consistently tracked people fed, the field staff assisted the households in filling in the charts as accurately as possible.

	Child: 0-14 years	Female: over 14 years	Male: 15-59 years	Male: over 59 years
Day 1				
Day 2				
Day 3				
Day 4				
Day 5				
Day 6				
Day 7				
Day 8				
Day 9				
Day 10				

Figure 3.4: Household Feeding Chart

After the study, RPN field staff were provided with a survey that asked for their feedback regarding the provided training materials, sensor use, sensor deployment, household training, and data collection.

3.2.3 Equipment Deployment

Deployment of the EXACT sensors (Figure 3.5a) in households were done using either metallic U-nails, tent stakes, or metallic tape depending on the type of stove being monitored and the household configuration. HAPEx sensors (Figure 3.5b) were zeroed prior to their household deployment following the procedure outlined in the user manual (Climate Solutions Consulting, 2018). Once in households, HAPEx sensors were hung in the cooking area of a home within 1 m of the stove and 1 m above the ground away from any windows or ventilation. FUEL holders used in the FUEL system shown in Figure

3.5c were manufactured in the local villages using rice jute sacks and nylon rope. Prior to installation, household participants were asked to specify their preferred location for the FUEL system to ensure ease of use. The FUEL systems were then installed by hanging the sensors on preexisting support beams.

Once installed, all sensors were deployed with the launcher initiating monitoring. Sensor data were checked and collected during mid-monitoring check-ins using the launcher to ensure that all sensors were working properly. If a sensor was found to be not functioning, the field staff first attempted to relaunch the sensor; if this was unproductive, the sensor was replaced when possible. Due to limited resources, all sensors were removed from households in between monitoring periods for use in other households, then replaced and relaunched during the following monitoring period.

(a) **(b)** **(c)**

Figure 3.5: Household sensor deployment. (a) EXACT, monitoring stove use; (b) HAPEx, monitoring household air pollution; (c) FUEL, monitoring fuel consumption.

3.2.4 Data Analysis

3.2.4.1 EXACT

Consistently identifying cooking events using stove temperature data can be challenging and is an ongoing research question in the cookstove sector (Ruiz-Mercado et al., 2012; Wilson, Williams, & Pillarisetti, 2020). The EXACT sensors contain internal software that identify cooking events when a temperature threshold is reached. This is then reported as a binary usage metric (1 for cooking and 0 for non-cooking) so that field staff can see in real time if a stove has been used. Once complete data were retrieved, cooking event identification was performed using a the "fire-finder" method (Wilson et al., 2020). The main steps involved in cooking event identifications are;

1. Assume no data points are cooking.
2. Assume all points above a temperature threshold are cooking.
3. Assume points with long run of negative (or null) slope are not cooking.
4. Assume points with very positive slope are cooking.
5. Assume points with very negative slope are not cooking.
6. Merge cooking events that are separated by non-cooking periods shorter than minimum inter-event threshold.
7. Delete cooking events that shorter than minimum event cooking time threshold.

The previously obtained stove usage metrics were adjusted to match the cooking events identified using the method above. Stove usage metrics were then used in all cross-sensor analysis for ease of cooking event association.

3.2.4.2 HAPEx

The HAPEx sensors produce a unitless measure of PM concentration in a given space using light scattering technology. Obtaining the concentration ($\mu g\,m^{-3}$) of a specific aerosol (i.e. $PM_{2.5}$) requires a gravimetric system be co-located with the HAPEx sensor to determine the particulate scattering coefficient. Due to limited resources and challenges of filter handling, no gravimetric systems were used during data collection. Subsequently, all PM data presented in this study will be presented as Concentration Units (CU). Although this limits our ability to report on a stoves ability to meet WHO recommendation based on absolute household $PM_{2.5}$ levels, it does allow for comparison of the magnitude of HAP before and after the introduction of the RPN stove and correlation with cooking events and fuel usage.

3.2.4.3 FUEL

Household fuel consumption is based on decreases in weight (greater than a minimum threshold value) logged by the FUEL system. The FUEL system will also log any bumps or unintentional tugs which must be accounted and adjusted for to ensure accurate calculations (Ventrella, MacCarty, & Lefebvre, 2020). Figure 3.6 shows an example of FUEL system data with a highlighted spike that can be assumed to be the result of the system being unintentionally bumped or pulled. Adjusting these inaccurate data were accomplished by comparing surrounding data points. If there was a sudden weight increase that immediately returned to the previous value or fell below it, the value would be adjusted to the previous value (Example: $y_1 = 10$ kg, $y_2 = 15$ kg, $y_3 = 8$ kg; y_2 adjusted $= 10$ kg). Alternatively, if the weight increase was proceeded with a decrease that did not return to the original value but remained constant the value was adjusted to match the subsequent values (Example: $y_1 = 10$ kg, $y_2 = 20$ kg, $y_{3\text{-}10} = 15$ kg; y_2 adjusted = 15 kg). This process was mirrored to adjust sudden negative changes in weight.

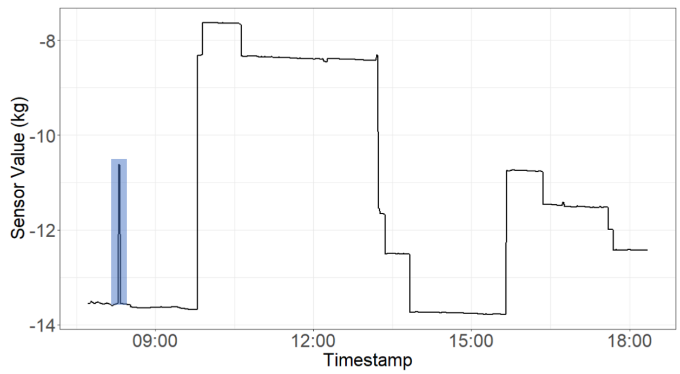


Figure 3.6: Fuel data with a highlighted fuel change indicative of the sensor being knocked or tugged highlighted.

One concern regarding the use of the FUEL system as a method of monitoring household fuel use, is the degree to which households comply with the FUEL system usage instructions. FUEL system compliance includes two different aspects; 1) whether the fuel removed from the system was used in a monitored stove (this will be discussed in section 3.3.4.2); and 2) whether fuel was used in a monitored stove that was not first measured by the FUEL system. Although the amount of unmeasured fuel use can not be reported, household compliance can be investigated by identifying cooking events for which no weight changes occurred.

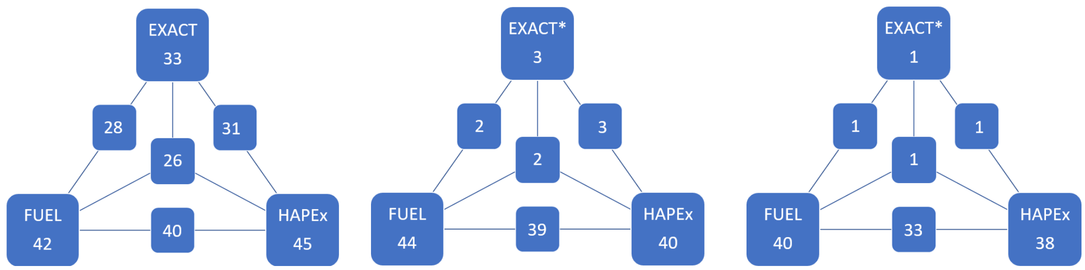
Household fuel usage was adjusted for moisture in two methods and compared; 1) moisture was attributed to fuel changes based on their temporal proximity to a particular moisture reading and 2) all household moisture readings for a monitoring period were averaged and applied evenly to all household fuel changes.

3.3 Results & Discussion

To address whether the implementation of the sensor suite and data collection can be reliably conducted with limited prior experience, data loss/corruption and its impact on sample size will be discussed. The remainder of this section will explore individual as well as cross-sensor data analysis and validation methods.

3.3.1 Sample Sizes

Figure 3.7 is a visual representation of the resulting number of households for which there are usable data (i.e. a minimum of 10 full days of consecutive sensor data) in each monitoring period as well as the number of households with complete data (i.e. usable data for both monitoring periods).



(a) **(b)** **(c)**

Figure 3.7: A visual representation of the number of complete household sensor data (represented by the boxed numbers) available given each combination of sensor type. (a) Sensor data available for monitoring period conducted before the introduction of the RPN stove. (b) Sensor data available for monitoring period conducted after the introduction of the RPN Stove. (c) Sensor data available for monitoring period conducted before and after the introduction of the RPN stove. *EXACT data including complete data for both traditional and RPN stoves.

The extensive loss in EXACT temperature data seen in the monitoring period conducted after the introduction of the RPN stove was caused by two main factors. 1) The RPN stove's chimneys are made of a shiny metallic material; because the EXACT sensors use infrared technology this limits the sensors ability to detect temperature changes when pointed at a reflective surface. The monitoring of the RPN stoves were conducted by adhering the EXACT sensors to the chimneys and no instructions were provided to scuff or blacken out the portion it was pointed at. This resulted in minimal usable EXACT data for the RPN stove. 2) During remote RPN field staff training, it was not made clear enough that all stoves that may be used in a household must be monitored in order to obtain a comprehensive understanding of the household environment. This resulted in many traditional stoves not being monitored after the introduction of the RPN stove.

Other events that resulted in data loss included households moving sensors, participants leaving their residence for an extended duration during the monitoring period, and errors in sensor launching.

3.3.2 Household Air Pollution

Figure 3.8 illustrates the percent change in median household daily average PM after the introduction of the RPN stove within each district. While some households in the Taplejung district experienced increases in median daily average PM, approximately 70% of the households (n=17, median -45.7%) experienced some kind of reduction while all of the households in the Panchthar district (n=19, median = -64.5%) experienced a reduction. These results are further explored in Figure 3.9 which shows the distribution of daily average PM in each district before and after the introduction of the RPN stove.

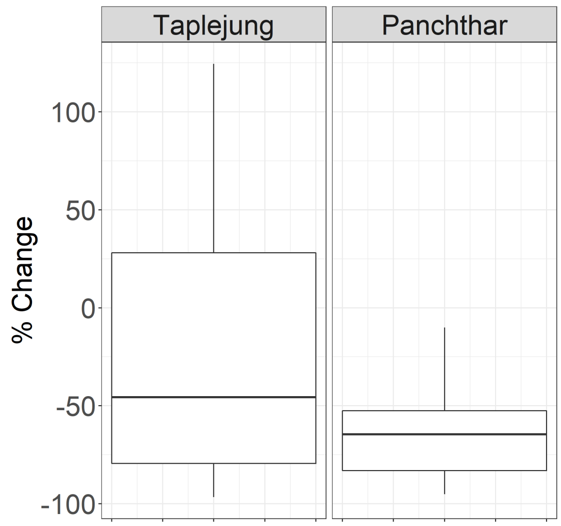


Figure 3.8: Percent change in household median daily average PM in each household. Taplejung (n = 17, med = -45.7%); Panchthar (n = 19, median = -64.5%); Total (n = 36, median = -61.2%)

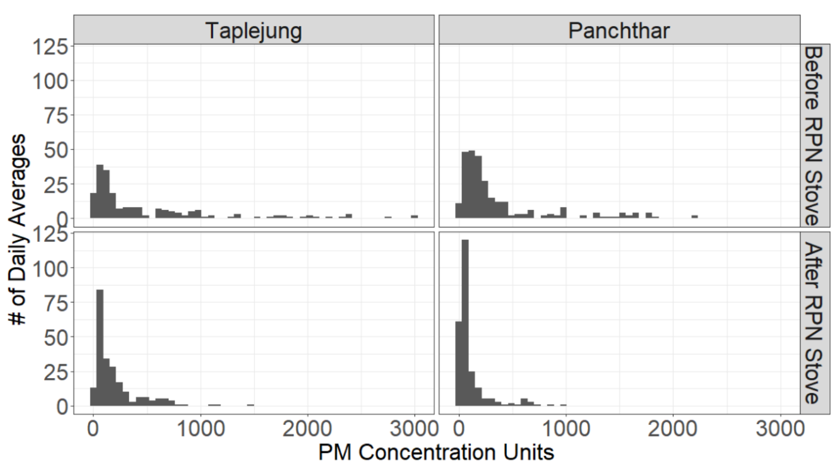


Figure 3.9: The distribution of average daily PM measured in each district before and after the introduction of the RPN stove.

3.3.3 Stove Usage

Limited data on stove usage was retrieved after the introduction of the RPN stove, however the baseline monitoring of households has the potential to shed insight on household context and cooking patterns. Figure 3.10 shows the difference in average daily cooking time in households from each district. Households in the Taplejung district reported a much larger number of people of fed each day. This is reflected in the data as Taplejung households spent more time on average cooking but much less time cooking per person fed.

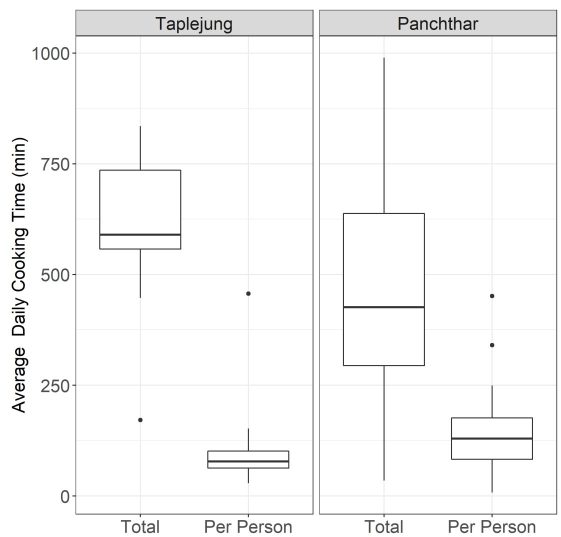
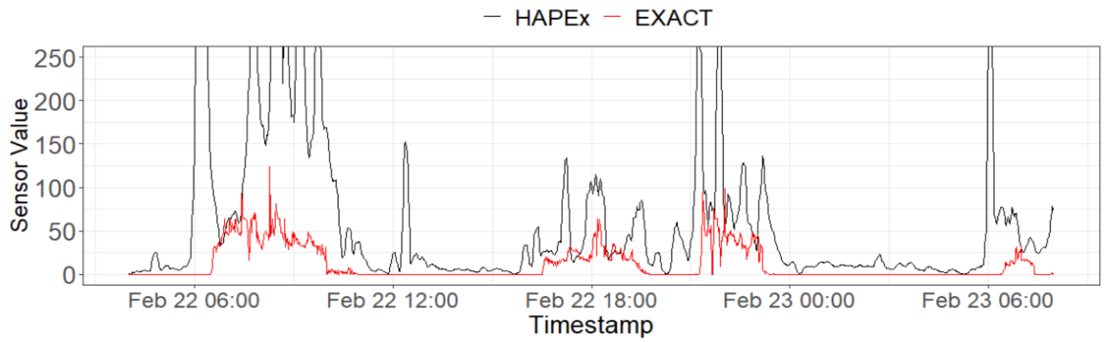


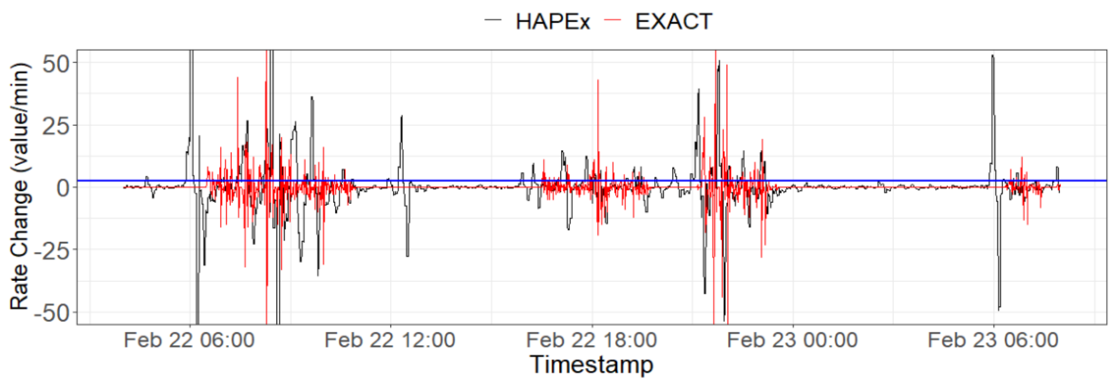
Figure 3.10: The average daily cooking time and the average daily cooking time per person fed in each household before the introduction of the RPN Stove.

3.3.3.1 Stove Usage and Household PM Data

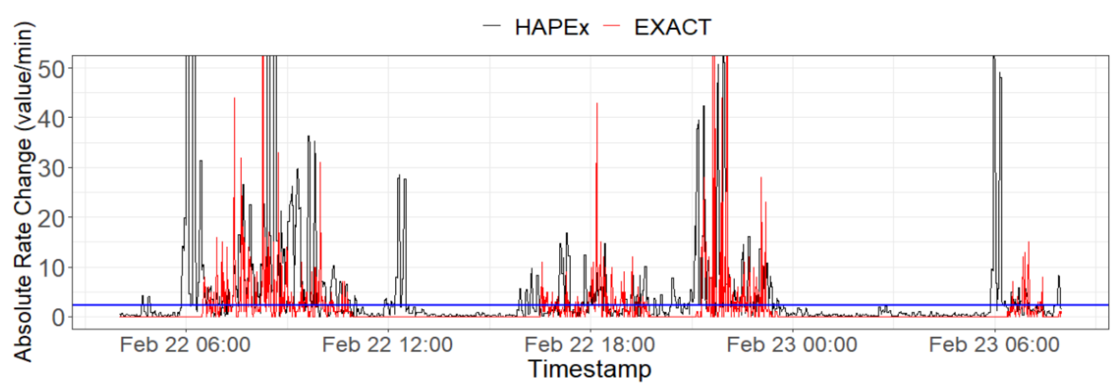
One of the challenges of stove temperature sensors is accurately identifying the beginning and end of a discrete cooking event. Data from households in both districts showed a clear agreement between cooking events and PM measurements. Figure 3.11a illustrates how the sensor data from the HAPEx and EXACT sensors mirror one another while Figure 3.11b and Figure 3.11c show the rate of change and absolute rate of change respectively for the same data further illustrating their agreement.



(a)



(b)



(c)

Figure 3.11: HAPEx and EXACT sensor agreement. (a) Direct sensor values; (b) Rate of change in sensor values; (c) Absolute rate change in sensor values. Household median PM rate of change (2.0 CU/min) indicated with the blue horizontal lines. *Note: Household 2 before the introduction of RPN stove.

The absolute rate of change in household PM reliably increases with the increase in stove temperature due to naturally rapid fluctuation in PM concentration inherent to biomass combustion. However, the magnitude of that change differs depending on the stove and fuel in use as well as the household ventilation and cooking practices (Sharma & Jain, 2019). Due to HAPEx sensors logging continuously, including overnight, there will naturally be more PM data logged during non-cooking periods than during times when stoves are being used. Considering that household PM concentration is constantly fluctuating, values below the median rate of change in PM within a household should be representative of a non cooking period. The blue lines in Figure 3.11b and Figure 3.11c represent the household median rate of change in PM, illustrating that the absolute rate of change in PM data occurring outside of a cooking event rarely exceeds this value.

By determining the median rate of change in household PM it is possible to determine the start of a cooking event, identify cooking duration, and flag rises in PM that occur outside of stove temperature identified cooking events. Similar to the “fire finder” method used to identify cooking events, Figure 3.12 illustrates the results of the following method used for verifying cooking duration and any extraneous heightened PM concentration events.

1. Assume no data points occurred during cooking.
2. Assume all PM data points with an absolute rate change greater than the median household PM rate change to have occurred during cooking.
3. Merge all assumed cooking events that are separated by non-cooking periods shorter than minimum inter-event threshold.
4. Delete all cooking events shorter than minimum event cooking time threshold.

5. For each cooking event identified, flag any event with no corresponding stove temperature rise during the duration of the event.

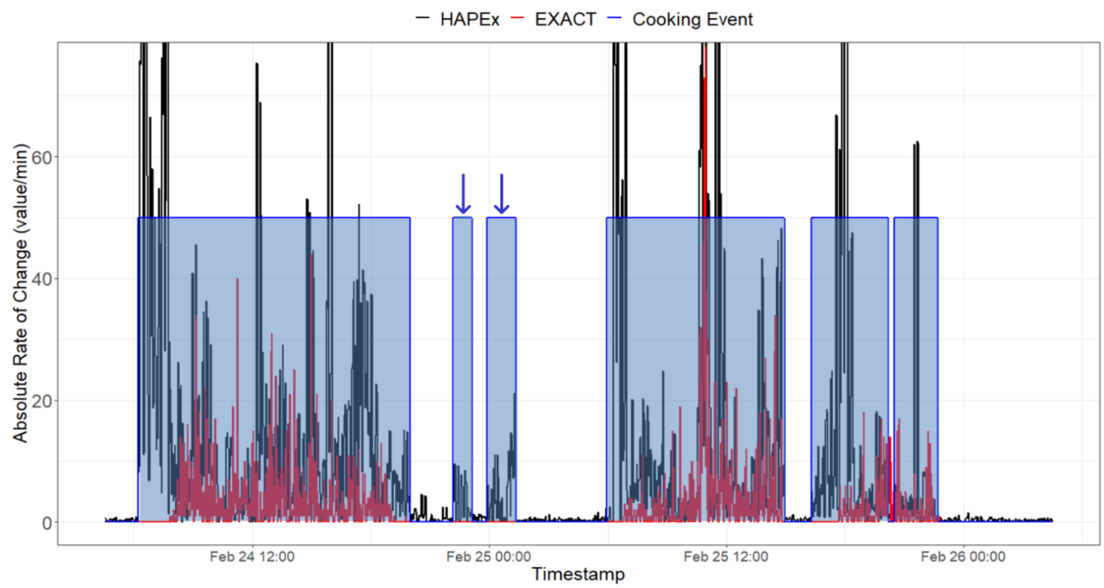


Figure 3.12: Cooking duration verification using absolute PM data rate change. Highlighted blue squares indicate identified cooking events, with blue arrows indicating flagged extraneous heightened PM concentration events. *Note: Household 2 before the introduction of RPN stove.

3.3.4 Fuel Usage

One of the most important impact metrics of projects is the change in fuel consumption after introduction of the new stove. Figure 3.13 illustrates the percent change in household fuel consumption after the introduction of the RPN stove if all weight changes (post data cleaning) that occurred during the monitoring periods are assumed to be reflective of actual household fuel consumption. Households in the Taplejung (n = 15) district that experienced fuel reduction experienced larger reductions in both total fuel consumption (median = -44.6%) and fuel consumption per person fed (median = -69.8%) when compared to households in the Panchthar district (n = 2, median Total = -15.2%, median Per Person = -3.22%).

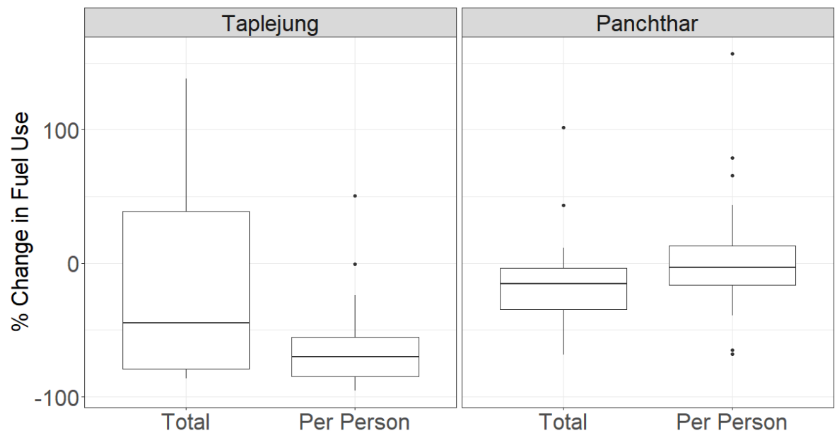


Figure 3.13: Percent change in total and per person fuel consumption in households after the introduction of the RPN stove. These values were adjusted for fuel moisture content by taking the average of all moisture readings within a household during a particular monitoring period. Taplejung (n=15): median (Total = -44.6%, Per Person = -69.8%); Panchthar (n=22): median (Total = -15.2%, Per Person = -3.22%); Both (n= 37): median (Total = -16.5%, Per Person = -16.1%)

3.3.4.1 Impact of Moisture Content

While the measurement of moisture content and the adjustment of fuel weight to account for it may provide more accurate measures of the magnitude of energy consumption, it shows a limited influence when determining the percent change of total fuel consumption. Figure 3.14 shows a maximum difference in calculated percent change in measured fuel consumption occurring when moisture content is applied to the fuel changes based on their temporal relationship to moisture readings (Adj 1) as apposed to even distribution of average household fuel moisture content to all fuel changes (Adj 2). The effects of these adjustments ranged from 2.7% to 4.9%.

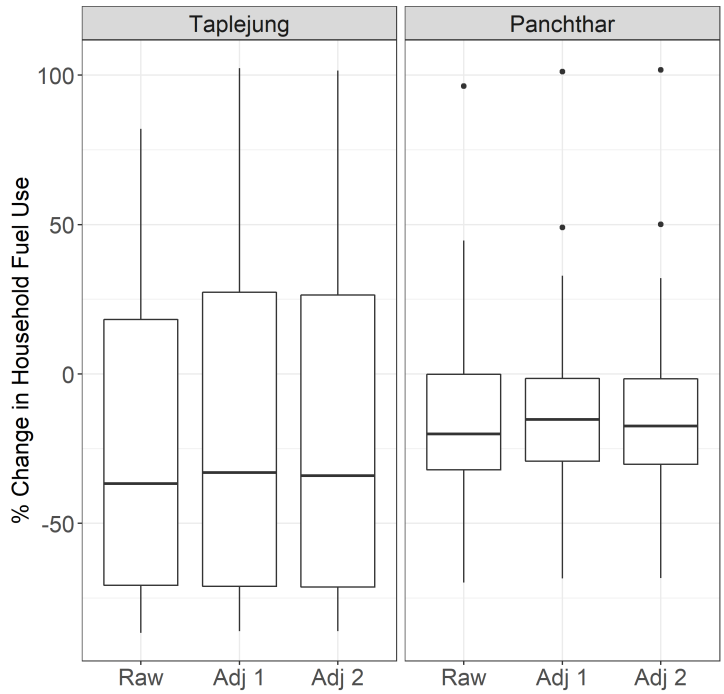


Figure 3.14: The difference in the percent change of total household fuel consumption for Taplejung(n = 16, Raw Med = -36.7%, Adj 1 Med = -33.0%, Adj 2 Med = -34.0%) and Panchthar (n = 23, Raw Med = -20.1%, Adj 1 Med = -15.2%, Adj 2 Med = -17.5%)) households with and without fuel adjusted for moisture content. Raw indicated the change in fuel consumption if moisture content is not accounted for; Adj 1 indicated the change in fuel consumption when the moisture readings collected at each household visit are assigned to fuel consumption based on moisture reading it was closest to in time; Adj 2 indicates the change in fuel consumption when all moisture readings for a household are averaged over the monitoring period and applied evenly to all fuel consumption.

3.3.4.2 FUEL system Compliance

One question about the use of the fuel sensor is whether users are using it as directed as far as 1) burning the fuel from the holder in the monitored stove only, and 2) always placing the fuel in the holder before burning it in the monitored stove. With cross-sensor analysis, there are two methods to check for both of these scenarios: correlation with temperature data, and correlation with PM data.

Verifying that fuel from the holder is being burned in the monitored stove only can be accomplished through association with identified cooking events using EXACT temperature data. Any lack of correlation using this method could be due to stove stacking, improper FUEL system usage (such as removing fuel before intended use), or improper EXACT sensor placement (resulting in cooking events missing or appearing shorter than they actually were).

Alternatively, verifying that fuel from the holder is being burned in the household can be accomplished through correlation with rises in PM emissions as measured by HAPEx sensors. As described in section 3.3.3.1, a household's PM median rate of change can be assumed to represent a non-cooking period. Following a similar method to temperature identification, a fuel change can be verified if the rate of change in PM is greater than the median within 30 minutes of the fuel change.

Looking at all identified fuel changes (n = 1785) in households (n = 26) prior to the introduction of the RPN stove with complete EXACT and HAPEx data, the temperature verification method was able to verify 72.8% of all fuel changes (77.0% of total fuel measured) where as the PM verification method was able to verify 96.9% of all fuel changes (97.3% of total fuel measured). Figure 3.15 shows how this affected the total percentage of measured household fuel use in each of the two districts that were able to be verified using each method.

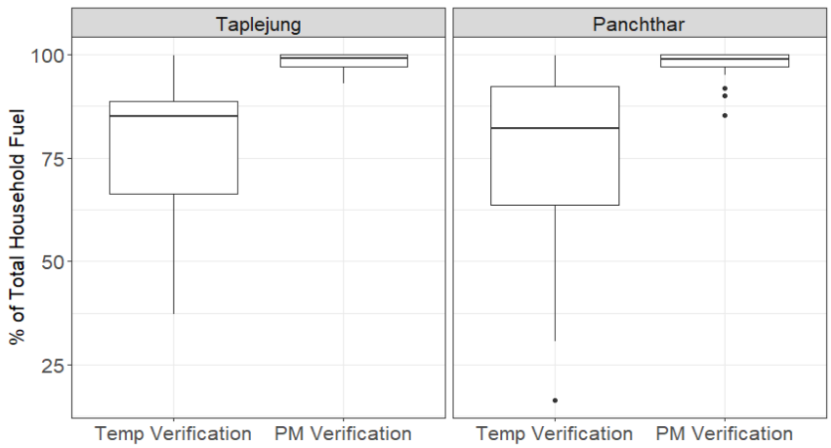


Figure 3.15: Percent of total household fuel (kg) that could be verified using the temperature and PM verification methods. Taplejung (n = 10, Temp Verification median = 85.0%, PM Verification median = 99.1%); Panchthar (n = 16, Temp Verification median = 82.2%, PM Verification median = 98.9%); *Note: includes data only collected prior to the introduction of the RPN stove in household with complete EXACT and HAPEx data.

As it is impossible to quantify what was never measured, it is not possible to verify that only fuel placed in the FUEL holder was used in household cooking events. However, it is possible to quantify FUEL system compliance by identifying cooking event occurrence without the occurrence of FUEL system weight changes. Using household PM data the initiation of cooking events were identified as described in section 3.3.3.1. Fuel changes were then associated to cooking events if they occurred during or within 30 minutes prior to the initiation of a cooking event. For consistency fuel changes were only associated with single cooking events (i.e. if a large fuel change occurred and was followed by multiple cooking events with no other fuel changes the fuel was attributed to only the first event). Using this method, Figure 3.16 shows the percentage of FUEL system compliance in terms of total cooking time with fuel association in households from both districts. A median FUEL system compliance of 78.4% was observed for all households while households in the Taplejung district experienced slightly higher compliance rates with a median of 80.4% when compared to households in the Panchthar district (median = 68.6%). These results reflect similar findings to those reported by Ventrella & MacCarty (2019) that indicated correct household FUEL system usage for 85% of monitoring days.

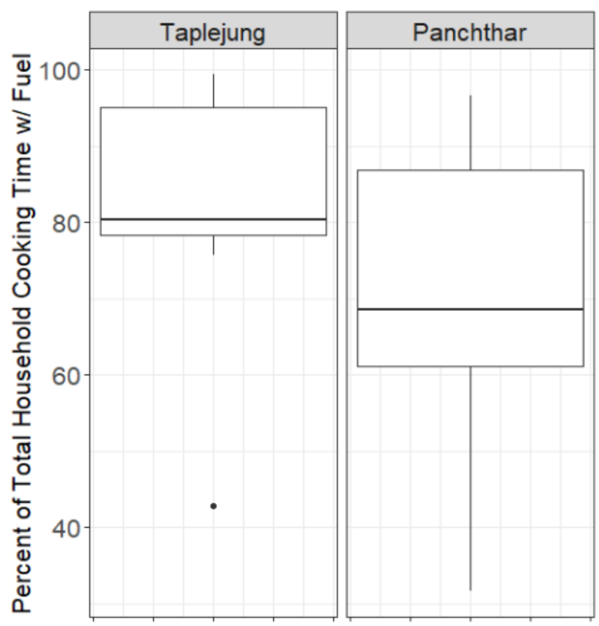


Figure 3.16: Percentage of total household cooking time with fuel association before the introduction of the RPN stove. Taplejung (n=10): median = 80.4%; Panchthar (n=16): median = 68.6%; Total (n= 26): median = 78.4%.

A low percentage of total household cooking time with fuel association indicates that measured household fuel consumption may not represent actual household fuel consumption or that the household may simply be using the FUEL system incorrectly. Figure 3.17 shows a households with low FUEL system compliance (42.8%) and a household with high FUEL system compliance (96.4%) in terms of total percentage of household cooking time with fuel association. Although the low compliance household does show two long periods of non-compliance (i.e multiple cooking events with no fuel association), cooking events with high fuel associations are regularly followed by cooking events with no fuel association. When instructed on FUEL system usage, households are told to never place fuel back in the FUEL system once it is removed. This shows that households are likely following those instructions but may be removing more than is necessary for a given cooking event. It is possible that adding clarification within the FUEL instructions that stresses the importance of taking out only what is necessary for a cooking event may justify these issues. By setting a desired household compliance level, households with compliance levels that fall below the threshold can be investigated as shown in Figure 3.17 and subsequently removed from analysis used for reporting if it is determined that the FUEL system was not used properly.

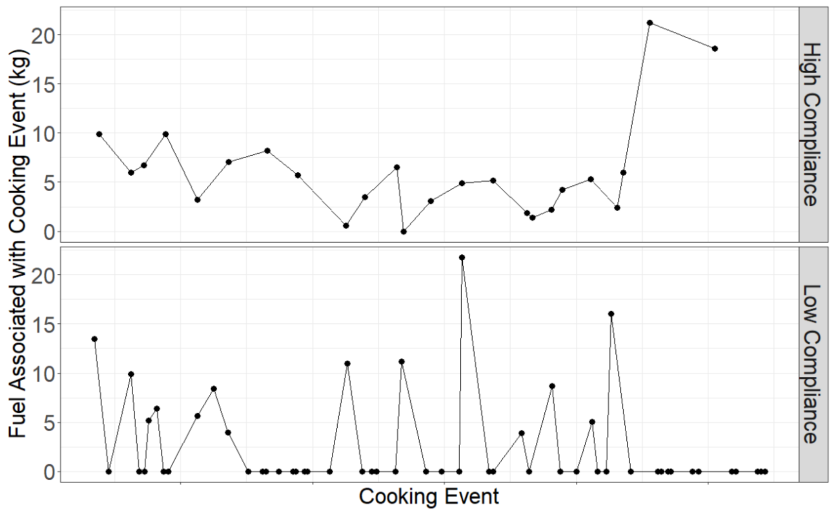


Figure 3.17: Fuel (kg) associated with each cooking event (represented by the points) in a household with a low and high percentage of total cooking time with fuel associated. The high compliance household (Taplejung, household 6) had fuel associated with 96.4% of its total cooking time. The lowest compliance household (Taplejung, household 4) had fuel associated with 42.8% of its total cooking time.

3.3.5 Feasibility of Remote Training for Local Capacity Building

The feedback provided by the RPN field staff responsible for sensor deployment and data collection indicated that they felt as if the remote training materials provided were sufficient and that all necessary information was included. However, it was indicated that occasional launcher and sensor malfunctions prolonged time spent in the field and increased the difficulty of sensor deployment and data collection. Although lack of explicit instructions on installation of the EXACT sensors on chimneys and miscommunication regarding continued monitoring of traditional stoves resulted in extensive loss of stove temperature data, there were few other errors in sensor deployment or data collection. Given the novel nature of this monitoring method and the difficulties associated with the remote training of partners, the limited numbers of errors suggests the feasibility of this system for capacity development.

3.4 Conclusions

The households monitored in this study experienced a median reduction of 61.2% (n = 38) in their daily average PM levels following the introduction of the RPN stove with households in the Taplejung district (n = 17, median = 45.7%) experiencing lower median reductions than those in the Panchthar district (n = 19, median = 64.5%). The overall median fuel reduction for both total and per person measurements was approximately 16% following the introduction of the RPN stove. However, households in the Taplejung district (n = 15) experienced greater median reduction in both total and per person fuel consumption (total median = 44.6%, per person median = 69.8%) than households in the Panchthar district (n = 22, total median = 15.2%, per person median = 3.22%).

The large differences in stove impact on both daily average PM levels and total fuel consumption between districts is likely due to household context. Households in the Taplejung district rely primarily on hosting guests and tourists heading to worship at the Pathibhara temple for their income generation. This results in cooking for longer durations of time for much larger numbers of people on a daily basis. Alternatively households in the Panchthar district represent more traditional household settings predominantly relying on livestock herding for income generation and often only preparing food for those who live in the household. These differences in context explain why households in Taplejung experienced greater fuel savings (likely through economy of scale) where as households in Panchthar experienced greater reductions in household air pollution (HAP) (likely due to spending less time overall cooking, limiting the potential production of PM). Validation of these results should be pursued through the study of the RPN stove in households of different context, throughout different seasons, and for longer duration to ensure that these results represent real world stove outcomes.

Based on both the RPN field staff feedback as well as the quality and quantity of resulting study data, further development of the sensor suite training material is needed before it can be reliably implemented by individuals with limited prior experience. However, as is common in sensor-based stove monitoring, the temperature sensors were the main source of data loss and corruption. It is anticipated that further stove studies involving the sensor suite and continual development of the training material will produce a robust and reliable tool capable of building local capacity for household stove monitoring projects.

Through cross-sensor analysis household PM data was used to verify cooking duration and flag rises in PM concentration without the increase in stove temperature. Furthermore, measured household fuel consumption using the FUEL system was verified using both household PM and stove temperature data with FUEL system compliance quantified with stove temperature data. This research shows that the presence of multiple sensors in a household provides the potential for extended insight on multiple key stove performance metrics while also providing a means for single sensor measurement verification.

3.4.1 Limitations

The monitoring of stove usage within their context of use will inevitably involve potential error and missing data. In this study, our ability to report on stove usage was limited by incorrect or missing sensor placement due to miscommunications and/or confusion within the newly-developed remote training environment. The lack of a gravimetric system co-located with the HAPEx sensors allowed only for reporting relative changes in household PM concentrations rather than absolute magnitude of in specific aerosols such as $PM_{2.5}$. Although we are able to report on the changes in total fuel consumption measured, it is possible that fuel was used in study participants households that was not captured by the system.

3.5 Acknowledgements

We would like to thank RPN staff for their partnership and diligent work to make this study successful under unprecedented circumstances. Specifically, Sonam Tashi Lama, Haris Rai, and Ang Phuri Sherpa for the considerable time and effort during the study development and implementation. We would also like to thank the National Science Foundation grant #1662485 and the Richard and Gretchen Evans Family Fellowship for their financial support.

3.6 Conflict of Interest

One or more authors of this paper declare a conflict of interest because they are involved with the manufacture and sale of the integrated suite of sensors described herein.

Chapter 4: Conclusion

This work has resulted in the testing of a novel integrated sensor suite developed to provide a more holistic understanding of household level stove performance. To collect and interpret sensor data and illustrate the sensor suites capacity, training, data processing, analysis, and visualization methods were developed and implemented. Chapter 2 of this thesis provided initial performance metrics regarding HAP and fuel usage of the RPN stoves in a report developed for the expressed purposed of communicating stove household impact regarding fuel savings and household air pollution to project stakeholders. Chapter 3 provided a more in depth analysis of the data and presented novel methods of cross-sensor to allow for single sensor verification and the development of insights on household stove performance despite data loss and/or corruption. This chapter also explored the feasibility of using this integrated sensor suite as a tool capable of building local capacity for stove monitoring projects. Attached as an appendix are the materials developed for the remote training of our RPN field partners in the deployment of sensors and collection of data.

Cross-sensor analysis methods used in in this study proved to be useful in the validation of single sensor readings which will allow for increased accuracy in reporting of stove performance metrics. This allowed for a more holistic and comprehensive view of a household then previously capable with single sensor stove monitoring. While absolute concentrations of household particulate matter (PM) could not be reported, the data captured regarding general PM concentrations allowed for verification of cooking event duration, flagging of elevated PM concentrations outside of identified cooking events, and verification of household fuel usage. Stove usage data was also used to both verify fuel usage and quantify household FUEL system compliance.

The data collected for this study found that the introduction of the RPN stove into rural mountainous households in the Taplejung and Panchthar district resulted in an overall reduction in both household air pollution (HAP) and fuel consumption. The data also showed that household context (i.e household income generation, stove type, cooking patterns, and household structure) likely plays a significant role in the magnitude of the stoves impact.

The data collected during this study illustrates the potential of the sensor suites as an accessible tool capable of building local capacity in stove monitoring projects. Working to develop this capacity shows promise in reducing the time, cost, and technical training required in the attainment of real-world stove performance metrics. Furthermore, ensuring the accessibility of this tool would allow for more transparency in the clean cooking sector and support opportunities for result-based financing making it possible to provide more high performing stoves to those who need them most.

During this research a data analysis platform was also developed. This platform is being designed to allow sensor suite implementers to upload data from monitoring campaigns aiding in data management, visualization, and analysis. The methods developed for the data analysis in this study will be integrated into this platform to increase the accessibility of this sensor suite tool. Furthermore, it is expected that this database will eventually allow for the ease of comparison of stove performance between stove types and regions.

Though not explored directly within this work, the FUEL system is capable of monitoring many different fuel types, including liquid fuels, with the use of a compressive scale. Future work will include developing robust methods for analysis of data produced using the compressive scale, completing integration of all data processing and analysis methods into the data analysis platform currently under development, and conducting further studies involving the sensor suite and its deployment in different cultural and geographic regions to allow for its validation in varying contexts.

References

Abdelnour, S., & Pemberton-Pigott, C. (2018). For cook and climate: Certify cookstoves in their contexts of use. *Energy Research & Social Science*, *44*, 196-198. Retrieved from https://www.sciencedirect.com/science/article/pii/S2214629618301853 doi: https://doi.org/10.1016/j.erss.2018.05.014

Bailis, R., Drigo, R., Ghilardi, A., & Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*, 266-272. doi: https://doi.org/10.1038/nclimate2491

Bailis, R., Smith, K. R., & Edwards, R. (2007). *Kitchen performance test (kpt).*

Barnes, B. R. (2010). The hawthorne effect in community trials in developing countries. *International journal of social research methodology*, *13*(4), 357–370.

Chowdhury, Z., Edwards, R. D., Johnson, M., Naumoff Shields, K., Allen, T., Canuz, E., & Smith, K. R. (2007). An inexpensive light-scattering particle monitor: field validation. *J. Environ. Monit.*, *9*, 1099-1106. Retrieved from http://dx.doi.org/10.1039/B709329M doi: 10.1039/B709329M

Climate Solutions Consulting. (2018). *Household Air Pollution Exposure HAPEx Sensor v4 User Manual.* Retrieved from https://climate-solutions.net/images/HAPEx_v4_User_Manual_9_2_2018.pdf

Harrell, S., Beltramo, T., Blalock, G., Kyayesimira, J., Levine, D. I., & Simons, A. M. (2016). What is a "meal"? comparative methods of auditing carbon offset compliance for fuel-efficient cookstoves. *Ecological Economics*, *128*, 8-16. Retrieved from https://www.sciencedirect.com/science/article/pii/S0921800916303470 doi: https://doi.org/10.1016/j.ecolecon.2016.03.014

IEA. (2012). World energy outlook 2012. *IEA, Paris*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2012

Manoj Kumar, Sachin Kumar, & Tyagi, S. (2013). Design, development and technological advancement in the biomass cookstoves: A review. *Renewable and Sustainable Energy Reviews*, *26*, 265-285. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032113003134 doi: https://doi.org/10.1016/j.rser.2013.05.010

Pratiti, R., Vadala, D., Kalynych, Z., & Sud, P. (2020). Health effects of household air pollution related to biomass cook stoves in resource limited countries and its mitigation by improved cookstoves. *Environmental Research*, *186*, 109574. Retrieved from https://www.sciencedirect.com/science/article/pii/S0013935120304679 doi: https://doi.org/10.1016/j.envres.2020.109574

Rehfuess, E. (2006). *Fuel for life: household energy and health.* Retrieved from https://www.who.int/airpollution/publications/fuelforlife.pdf

Rhodes, E. L., Dreibelbis, R., Klasen, E., Naithani, N., Baliddawa, J., Menya, D., ... Checkley, W. (2014). Behavioral attitudes and preferences in cooking practices with traditional open-fire stoves in peru, nepal, and kenya: Implications for improved cookstove interventions. *International Journal of Environmental Research and Public Health*, *11*(10), 10310–10326. Retrieved from https://www.mdpi.com/1660-4601/11/10/10310 doi: 10.3390/ijerph111010310

Ruiz-Mercado, I., Canuz, E., & Smith, K. R. (2012). Temperature dataloggers as stove use monitors (sums): Field methods and signal analysis. *Biomass and Bioenergy*, *47*, 459-468. Retrieved from https://www.sciencedirect.com/science/article/pii/S096195341200342X doi: https://doi.org/10.1016/j.biombioe.2012.09.003

Sharma, D., & Jain, S. (2019). Impact of intervention of biomass cookstove technologies and kitchen characteristics on indoor air quality and human exposure in rural settings of india. *Environment International*, *123*, 240-255. Retrieved from https://www.sciencedirect.com/science/article/pii/S0160412018324772 doi: https://doi.org/10.1016/j.envint.2018.11.059

Stanaway, J. D., Afshin, A., Gakidou, E., Lim, S. S., Abate, D., Abate, K. H., ... Murray, C. J. L. (2018). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017 : a systematic analysis for the Global Burden of Disease Study 2017. *LANCET*, *392*(10159), 1923–1994. Retrieved from http://dx.doi.org/10.1016/s0140-6736(18)32225-6

Thomas, E. A. (2017). Beyond broken pumps and promises: Rethinking intent and impact in environmental health. *Energy Research & Social Science*, *25*, 33-36. Retrieved from https://www.sciencedirect.com/science/article/pii/S2214629616303012 doi: https://doi.org/10.1016/j.erss.2016.12.006

Thomas, E. A., Tellez-Sanchez, S., Wick, C., Kirby, M., Zambrano, L., Abadie Rosa, G., ... Nagel, C. (2016). Behavioral reactivity associated with electronic monitoring of environmental health interventions—a cluster randomized trial with water filters and cookstoves. *Environmental Science & Technology*, *50*(7), 3773-3780. Retrieved from https://doi.org/10.1021/acs.est.6b00161 (PMID: 26986617) doi: 10.1021/acs.est.6b00161

Ventrella, J., & MacCarty, N. (2019). Monitoring impacts of clean cookstoves and fuels with the fuel use electronic logger (fuel): Results of pilot testing. *Energy for Sustainable Development*, *52*, 82-95. Retrieved from https://www.sciencedirect.com/science/article/pii/S0973082619300547 doi: https://doi.org/10.1016/j.esd.2019.06.004

Ventrella, J., MacCarty, N., & Lefebvre, O. (2020). Techno-economic comparison of the fuel sensor and kitchen performance test to quantify household fuel consumption with multiple cookstoves and fuels. *Development Engineering*, *5*, 100047. Retrieved from https://www.sciencedirect.com/science/article/pii/S2352728520300014 doi: https://doi.org/10.1016/j.deveng.2020.100047

Ventrella, J., Zhang, S., & MacCarty, N. (2020). An international, multi-site, longitudinal case study of the design of a sensor-based system for monitoring impacts of clean energy technologies. *Design Studies*, *66*, 82-113. Retrieved from https://www.sciencedirect.com/science/article/pii/S0142694X19300821 doi: https://doi.org/10.1016/j.destud.2019.11.006

WHO. (2018). *Household air pollution and health.* Retrieved from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Wilson, D., Coyle, J., Kirk, A., Rosa, J., Abbas, O., Adam, M. I., & Gadgil, A. J. (2016). Measuring and increasing adoption rates of cookstoves in a humanitarian crisis. *Environmental Science & Technology*, *50*(15), 8393-8399. Retrieved from https://doi.org/10.1021/acs.est.6b02899 (PMID: 27435285) doi: 10.1021/acs.est.6b02899

Wilson, D., Williams, K., & Pillarisetti, A. (2020). An integrated sensor data logging, survey, and analytics platform for field research and its application in hapin, a multi-center household energy intervention trial. *Sustainability*, *12*(5). Retrieved from https://www.mdpi.com/2071-1050/12/5/1805 doi: 10.3390/su12051805

APPENDICES

Appendix A: Training Material

Project Sensors and Enumerator Training

Contents

1 Introduction

This document is meant to serve as a reference document for each stage of the project. In this document you will find information on what to do and consider at each stage. Please be sure that you understand all of the material in this document before you begin the project. All reference documents, tools, and videos can be found on the provided microSD.

If you have any questions feel free to contact Dr. Nordica MacCarty.

1.1 Before Going to a Household

Before any household is visited for this project it is imperative that all enumerators are properly trained in privacy and gaining consent, a clear an executable plan is in place for how the FUEL sensors will be installed in the households, and that the sensors are prepared properly and everyone working with them understands how they function.

Each household will be equipped with sensors that monitor stove use, fuel use, and air quality. These sensors will be launch and the data they collect will retrieved using a launcher. Each household will also be given a GPS logger to take with them on fuel gathering trips and each enumerator will need to know how to use a moisture meter to record the average moister content of the fuel that a household is using.

It is very important that an effective system for keeping track of households is developed. A numbering system that connects each household to a number, name, and location will be critical to ensure that all longitudinal data can be correlated.

1.2 Pilot Period

Before the official study begins it is important that a subset of household (5-10) should be monitored with these sensors for a few days to ensure that all methods are understood and appropriate. This would ultimately serve as an opportunity for all enumerators to get a better understanding of how all of the sensors are meant to operate with one another, determine if any adjustments need to be made to the procedures, and get any and all questions they may have about the process of deploying the sensors and downloading the monitoring data out of the way.

2 Training Enumerators

It is critical to ensure that all enumerators are trained in privacy and gaining consent. This is a requirement in the review and publication process for ethical treatment of human subjects. Training should include the following:

2.1 Informed Consent

Subjects in the study must participate **willingly**. Informed Consent is a voluntary agreement to participate in research. The goal of the informed consent process is to provide sufficient information so that a participant can make an informed decision about whether or not to enroll in a study or to continue participation. Informed consent is essential before enrolling a participant and ongoing once enrolled. Obtaining consent involves informing the subject about his or her,

1. Rights
2. The purpose of the study
3. The procedures to be undergone
4. The potential risks and benefits of participation

Before beginning the study please ensure that all enumerators understand each of the following points about informed consent and what each means in regards to their conversations with potential participants.

- The informed consent process must be a dialogue of the study's purpose, duration, experimental procedures, alternatives, risks, and benefits.
- The informed consent process should ultimately assure that the subject understands and really "gets" what they are signing up for.
- Information must be presented to enable persons to voluntarily decide whether or not to participate as a research subject and they must verbally agree to consent if they choose.
- The process of consenting is ongoing and must be made clear to the subject that it is his or her right to "withdraw" or "optout" of the study or procedure at any time, not just at the initial signing of paperwork.
- Vulnerable populations (i.e. prisoners, children, pregnant women, etc.) must receive extra protections.
- The legal rights of subjects may not be waived and subjects may not be asked to release or appear to release the investigator, the sponsor, the institution or its agents from liability for negligence.
- The location where the consent is being discussed, the subject's physical, emotional and psychological capability must be taken into con-

sideration when consenting a human subject.

- Any compensation that is provided to the participant must be reasonable and appropriate such that the person does not feel coerced or otherwise financially motivated to participate in research they may not be comfortable with.

2.2 Privacy and Confidentiality

Privacy and Confidentiality

During the informed consent process, if applicable, subjects must be informed of the precautions that will be taken to protect the confidentiality and privacy of participants. Confidentiality and privacy are important aspects of ethical research because a participant ought to have control over whether it becomes public knowledge that they participated in a research study, as well as over the information that they provided while participating in the research. In this context, confidentiality can be thought of as keeping the identity of the participant away from public view, while privacy can be understood as keeping the participant's information away from public view. Confidentiality often comes down to one or more ways of de-identifying participants, and privacy often comes down to one or more ways of securing information. Confidentiality may be maintained by:

- Giving participants pseudonyms or using initials rather than full names.
- Not writing down any identifying information in the first place, even if the researcher knows participant names.
- Arranging to interact with participants in such a way that the researcher never knows the participants' names in the first place; this is sometimes known as anonymity.
- Removing certain demographic information from research.
- Using a consent process where a participant consents without their name being captured either on paper or on a recording.
- Privacy can be maintained by:
  - Not leaving questionnaires, interview transcripts, or field notes with participant identifications sitting out where others might see them but rather locking them up

- Using electronic data security measures to lower the odds that, even if one's laptop is stolen, information on it will be easily readable; this might include password protection, encryption, or other measures

2.3 Certification of Collaborator

Before an individual engages with any households participating in the study it is important that they receive verbally administered training on how to gain consent and protect participants privacy. Once they have received the training they must sign a certificate of collaboration acknowledging that they have received and understand the training. Upon completion, this document should be immediately sent to Nordica MacCarty.

Within the Training Documents there is a folder Labeled ”IRB Human Subjects”. This folder contains the following three documents,

1. Brief consent and privacy training : Training material to verbally administer to all enumerators and data collectors.
2. Certification of Collaborator[1] : Must be signed by all enumerators as well as anyone else involved in collecting data.
3. Verbal Consent Guide[2] : A guide on what specifically to say to gain consent from study participants.

3 Sensors

3.1 The Launcher

These videos will introduce you to the basic functionality of the launcher, how to launch sensors using the launcher, and finally how to retrieve data from the sensors using the launcher. When assigning a name to a sensor in the launcher it is important that the name does not exceed a length of 8 characters. Any names exceeding 8 characters will be truncated in the data files.

1. Intro Launcher
2. Launcher START

[1] 7257_MacCarty_certification_of_collaborator_10.9.20
[2] 7257_MacCarty_VerbalConsentGuide_Combined_10.9.20

3. Launcher DOWNLOAD

Figure 1: Launcher

3.2 FUEL Sensor

It is important to have a plan in place for how the FUEL sensors will be installed **BEFORE** they are taken to a household. To best understand what kind of materials you will need and what you should consider please watch the following videos. For additional information on how to operate the FUEL sensors please review the **FUEL User Manual**[3].

Note: When launching the FUEL sensor in the field be sure to zero the sensor before any fuel is placed on it NOT after.

[3]FUEL_User_Manual_11_23_2020.pdf can be found in the FUEL folder in the Training Documents

Figure 2: FUEL Sensor: Tensile Version

Figure 3: FUEL Sensor: Compressive Version

3.2.1 Video 1: FUEL Overview and How it Works/ Resumen de FUEL y Como Se Funciona

This video covers the purpose of FUEL, how it can be used with single or multiple stoves and fuels, and what the data will show.

English: FUEL Overview
Español: Resumen de FUEL

3.2.2 Video 2: Installing FUEL/ La Instalación de FUEL

This video shows how and where to hang the sensor, including the variety of structures that the sensor can be hung from and vessels that can be used.

English: Installing FUEL
Español: La Instalación de FUEL

3.2.3 Video 3: Training Participants to Use FUEL/ Capacitación de Participantes para Usar FUEL

This video covers how to train cooks and others in the households to use FUEL by storing their fuel supply in the holder and ensuring that only fuel that has been in the holder is consumed in the stove.

English: FUEL Training
Español: Capacitación de FUEL

3.3 HAPEx and EXACT

This video provides a quick overview of these sensors and how they can be accessed using the Launcher. HAPEx EXACT features

3.3.1 HAPEx

The HAPEx sensor is a air quality sensor (specifically $PM_{2.5}$) that can either be mounted in a home or worn by a study participant. Before the HAPEx is used it should be zeroed. This video (HAPEx Zero) will explain this process. For additional information on how to operate the HAPEx sensors please review the
HAPEx User Manual[4].

[4]HAPEx_v4_User_Manual_1_10_2019.pdf can be found in the HAPEx folder in the Training Documents

Figure 4: HAPEx Sensor

3.3.2 EXACT

The EXACT is a temperature sensor that should be mounted on each stove that will be used in a household. The mounting of these sensors may look different depending on both the household and the stove. However a consistent placement between households in a study is key to collecting consistent data. Please make sure that there is a plan in place on how to properly install the EXACT sensors on the stoves before the study begins. Below are a few potential options for mounting the EXACT sensor. If you have additional questions about how to best mount the sensor please contact Olivier Lefebvre (olivier@climate-solutions.net).

For more details on how to operate the sensor please review the **Exact User Manual**[5].

[5] EXACT_User_Manual_v4_1_9_2019.pdf can be found in the EXACT folder in the Training Documents

Figure 5: EXACT Sensor

Placement

The placement of the EXACT sensor is very important when measuring stove usage. If the sensor is placed too far away the sensor may not be able to accurately identify temperature increases. The sensor can withstand an internal temperature of 85C. Because of their mounting system, that means they can be placed on surface that will be as hot as 300C. Depending on the stove type the placement may vary but the placement of the sensor should be the same for all stoves of the same kind within a study. However, it is important that the sensors not be exposed to direct flame as this could result in the sensors components to over heat and potentially explode.

Metallic Tape

If you are trying to attach the EXACT sensor to a chimney it may be best to use a metallic tape that is rated to at least 100C (Figure 6). Before putting the tape on it is important to clean the area with rubbing alcohol (70% or higher) or IsoPropyl Alcohol and let the alcohol dry. This will ensure that the tape sticks to the chimney.

Figure 6: Metallic tape used to attach the EXACT sensor to a chimney. The tape should be rated to at least 100C.

Stakes

Heavy duty tent stakes (Figure 7) can be used when working with mud and three stone fires by placing them in the ground next to the stove as seen in Figure 8.

Figure 7: Heavy Duty Tent Stakes

Figure 8: Placement examples when using tent stakes with stoves.

U-nails

For metallic stoves, floors that do not allow for stakes, or stoves that are too high off the ground you may be able to use U-nails (Figure 9) to attach the

EXACT directly to the stove (Figure 10). The U-nail should go through the 2 holes in the mount of the sensor.

Figure 9: U-nails

Figure 10: EXACT sensor attached directly to a stove using U-nails.

Epoxy

If you are monitoring a metallic stove and none of the above options are applicable you may need to use an epoxy putty that is provided with the sensors. The epoxy putty provided with the sensor is rated for 250C so it best to place the sensor in a location that will not get hotter than 250C. If you choose to use this method please be aware that the bond created will create a very strong bond which may be very difficult to remove at the end of the study and could possibly result in damage to the stove. To use the epoxy putty please follow the procedure below.

1. Clean the surface of the stove with the alcohol wipe provided

2. Sand the surface with the sand paper to roughen it
3. Clean the surface with another wipe (wait a minute for the alcohol to dry)
4. While the alcohol dries, cut a piece of epoxy putty
5. Knead the putty thoroughly during one minute (use plastic gloves)
6. Place the putty on the sensor mount and press it firmly against the cleaned stove area
7. Cut a piece of the high temperature tape provided and place it on top of the sensor mount and epoxy to reinforce the initial bond.
8. The epoxy has a 5 minutes working time and a 1-hour full cure time.
9. If possible place the sensor will the stove is not too hot.

3.4 GPS Loggers

The GPS loggers (see Figure 11 will be used to collect data on fuel wood collection. These loggers will be taken with participants as they collect their fuel as a way to measure how far people travel, where they go to collect fuel, and how much time they spend collecting fuel. For additional information on how to operate the GPS sensor and how to access the data please review the **DG-500 user manual**[6].

[6]DG-500 QSG ENG V1.3_20170105.pdf can be found in the GPS Logger folder in the Training Documents

Figure 11: DG-500 GPS Logger

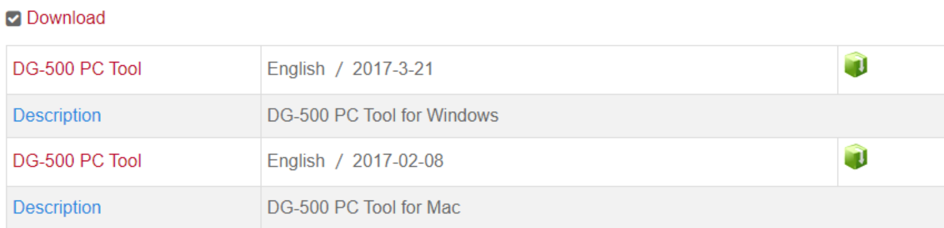
3.4.1 GPS Logger Introduction

GPS Logger

3.4.2 GPS Logger Data Retrieval

In order to download data from the GPS loggers you will first need to gain access to the Global Sat DG-500 Tool. There are two main ways to accomplish this. In the materials sent you there will be a microSD card which we have downloaded all of the documentation on. In the documentation there will be a file for the GPS Logger which contains the setup files for both windows and mac products. Using these you will be able to download and set up the tool on your device. If you would prefer to not download the tool on your device you may also access the tool while the microSD card is plugged into your device (Please note that you will also need to plug the device in so you will need a device with a minimum of 2 USB ports for this option). Alternatively you may navigate to this GloablSat web-page and download the tool from here. To download the tool and navigate to the bottom of the web page where you will find the download section that looks like Figure

12.



Download

DG-500 PC Tool	English / 2017-3-21	
Description	DG-500 PC Tool for Windows	
DG-500 PC Tool	English / 2017-02-08	
Description	DG-500 PC Tool for Mac	

Figure 12: Downloading the GlobalSat Tool

This video (GPS Data Download) will show you how to download the data from the GPS logger. Below are the steps that are covered in the video.

1. Once the tool is downloaded, navigate to the tool and open it.

Figure 13: GlobalSat Tool

2. Once a GPS Logger is plugged into the device the top task bar should resemble the task bar seen in Figure 14. Please do not use the red x icon as this will delete all data on the device. Additionally please do not alter any of the settings.

Figure 14: GlobalSat Tool Task Bar.

3. Select the Green arrow on the task bar. This will pull up a window that shows all files that are currently being stored on the document (Fig-

ure 15). As these sensors will likely be used by multiple households please be sure to only select the files that have dates that correspond to the most recent study period. For example, if I began a study on 11-11-20 I would select the files as seen in Figure 16.

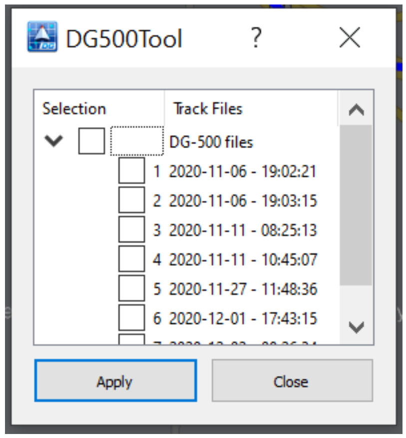


Figure 15: GPS Logger Files

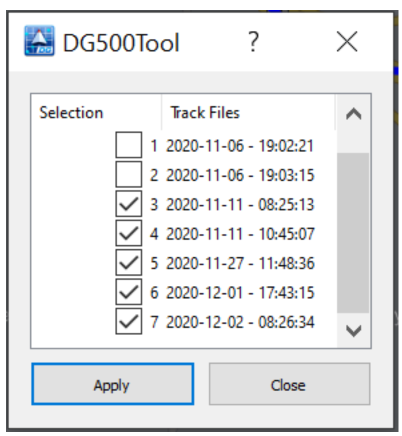


Figure 16: Select files that correspond to most recent study period.

4. The files will now be imported into the GlobalSat Tool and will show up in the left panel of the tool. Be sure that all files are selected (see Figure 17) and select the floppy disk icon next to the looking glass on the task bar.

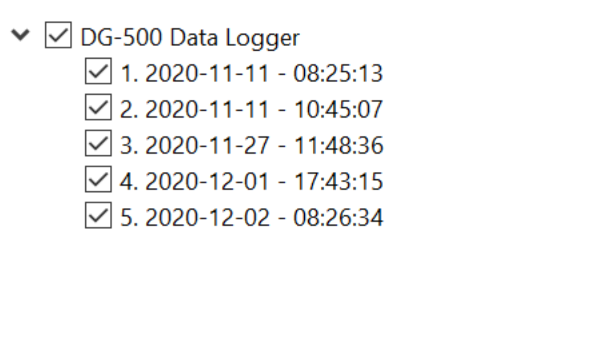


Figure 17: Select ALL of the files that have been imported.

5. This will produce a window that will allow you to choose the name, file type, and location of the file. Please be sure to save the file in an easily accessible location as a .csv file with an appropriate name (Figure 18). To name the file we ask that you include the last three digits found on the back of the GPS logger under the bar code and the household number associated with the data, **Sensor#_H#.csv** (ex. If I was using the sensor shown in Figure 19 and the data was from a household that we had assigned to 12 the name of the file would be 507_H12.csv).

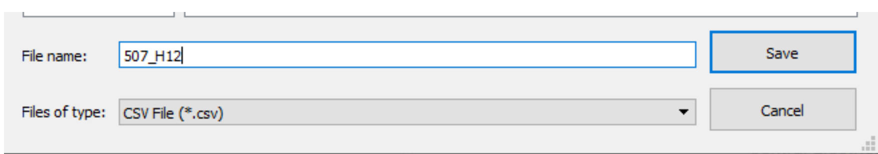


Figure 18: Saving the files with the appropriate name.

Figure 19: Back of Sensor 507.

6. Once this process is completed please be sure to zip all of the files together before sending them to Dr. Nordica MacCarty.

3.5 Moisture Meter

When you go to a household you will need to collect data on the moisture content of the fuel that they are using (*Note: These moisture meters should only ever be used on wood). This video (Moisture Meter) will introduce you to the moisture meter, show you how to properly prepare the meter before going into the field, and how to use it once you are in the field.

Figure 20: MO210 Moisture Meter

When using the Moisture meter there are some steps that should be taken before you take it into the field.

Before Use

1. The moisture meter should have arrived in a package that contained 3 individual lithium batteries, a baggy full of replacement electrode pins, and a small screw driver. If any of these items are not there please contact us and make sure you have them before you need to take the meter into the field.

Figure 21: MO210 Moisture Meter and Supplies

2. The moisture meter will have arrived to you without the batteries already inside. Using the small screw driver remove the back panel of the moisture meter, place the batteries into the device, and replace the back panel. (*Note: The batteries should be placed in with the positive [shiny side] facing outward).

Figure 22: Installing Batteries in Moisture Meter

3. The moisture meter switch should always be kept on wood (as shown in Figure 20) and should never be used while in building mode.

4. The device automatically shuts down when the cap is on. Remove the cap to turn on the device.
5. With the device on it is not time to test that both the device and the batteries are working properly.

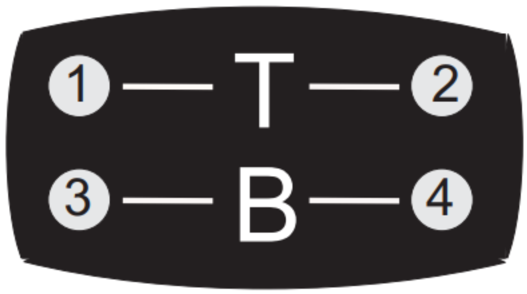


Figure 23: Moisture Meter Testing Diagram

6. To verify that the device is working properly, touch the pins to the testing spots on the cap that are labeled 1 and 2 in Figure 23. The read out should be between 25% and 29%. If the read out does not say this it means the device may need repair. Please contact us if this happens.

Figure 24: Moisture Meter Testing

7. To check the batteries you will repeat the above process with the pins on the testing spots 3 and 4 shown in Figure 23. The readout should

be between 42% and 46%. If this is not the case please replace the batteries and repeat this step.

Figure 25: Moisture Meter Battery Test

8. If at any point the electrode pins begin to show signs of wear or build up please replace them. This can be done by simply unscrewing the old pins and installing new ones.

Using the Moisture Meter in the Field

1. To take a a moisture reading press the electrode pins of the moisture meter into a piece of wood as far as they can go (do not force so hard that it might cause damage). When placing the electrode be sure that you are pressing them in perpendicular to the grains of the wood (see Figure 26). If the pins are placed in the same direction that the grains run the reading will not be accurate.

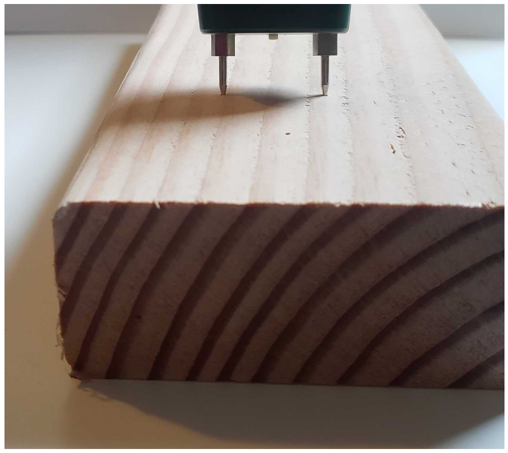


Figure 26: Taking Moisture Readings

2. Repeat this process **3** times with **3** randomly chosen pieces of wood.
3. Record all moisture readings in your household visit checklist.

After Use

Once you have finished using the moisture meter placed be sure to store it with the cap on and the batteries removed to conserve their life span.

For additional information on how to operate the Moisture Meter please review the **Moisture Meter User manual**[7].

4 Study Procedure

Once there is a clear plan in place for sensor placement, all enumerators have been trained on gaining consent, and the pilot period has been completed the study can begin. It is important that a checklist be completed during each visit to a household and the information collected saved for analysis.

[7]MoistureMeter_MO210_UserGuide.pdf can be found in the Moistre Meter folder in the Training Documents

4.1 Initial Visit

In the initial visit to the household the enumerators will be gaining consent, setting up the sensors, explaining to the participants how to properly use the sensors, launching the sensors, and taking fuel wood moisture measurements. Figure 27 shows the checklist that should be completed at each household. It is very important that the assigned household number as well as the GPS ID is recorded along with the fuel moisture content and the anticipated number of people who will be fed during the monitoring (it is ok if this is not the same every day, just ask the participant to give their best estimation). This information should be saved and sent with all the other data.

Initial Home Visit Checklist

HH #:			**GPS ID:**	
	**Gain participant consent for IRB.			
	Set up FUEL system.			
	Train household participant how to use sensors.			
		FUEL		
		HAPEx		
		GPS		
	Install and launch the sensors.			
		FUEL		
		HAPEx		
		EXACT		
	Take all **9** wood fuel moisture readings			
		Piece 1	Piece 2	Piece 3
	1			
	2			
	3			
	Ask participants how many people have been and/or will be fed.			
		Child: 0-14 years		
		Female: over 14 years		
		Male: 15-59 years		
		Male: over 59 years		
	Complete Household Survey			

** Must perform task first

Figure 27: First Home Visit Checklist

4.2 Follow Up Visit

After the participants have had a few days to get to know their sensors it is useful to do a follow up visit. This will allow for the participants to ask any questions and voice concerns if they have them. Figure 28 shows the checklist that should be taken to each household and filled out during the visit. Again it is important to record the household number and the GPS ID to ensure that the correct data is assigned to the appropriate household. Please again record the fuel moisture content as well as asking the participants to give an estimate of the number of people in each category they anticipate to feed (please fill this in even if it has not changed).

Follow-Up Home Visit Checklist

HH #:			**GPS ID:**	
	Download sensor data using the Launcher.			
	Check to see if the participants have been engaging with the sensors.			
		FUEL (via data readout)		
		HAPEx (via data readout)		
		GPS (ask the participant if they have been using the sensor)		
	Take all **9** wood fuel moisture readings			
		Piece 1	Piece 2	Piece 3
	1			
	2			
	3			
	Ask participants how many people have been and/or will be fed.			
		Child: 0-14 years		
		Female: over 14 years		
		Male: 15-59 years		
		Male: over 59 years		
	Ask participants if they have any problems/questions.			

Figure 28: Follow Up Home Visit Checklist

Using the Launcher (3.1) you will be able to look at summary data for the FUEL and HAPEx sensors, please be sure not to stop the sensors (see Launcher DOWNLOAD video). This will tell you whether the participants have been engaging with the sensors. If you notice that there is very little or no data ask the participant if they have been having issues with the sensor. If they have any issues or questions about how best to use the sensor be sure to do your best to answer them and record their issues/questions.

4.3 Final Visit

With the monitoring duration complete it is now time to collect the sensor data and the sensors themselves. Figure 29 shows the checklist that should be taken with and used for this visit. Again be sure to record the household number, the GPS ID, fuel wood moisture content, and how many people on average have been fed each day.

Sensor Retrieval Home Visit Checklist

HH #:			**GPS ID:**	
	Download sensor data using the Launcher.			
		FUEL		
		HAPEx		
		EXACT		
	Stop all sensor logging using the Launcher.			
	Take all **9** wood fuel moisture readings			
		Piece 1	Piece 2	Piece 3
	1			
	2			
	3			
	Ask participants how many people have been and/or will be fed.			
		Child: 0-14 years		
		Female: over 14 years		
		Male: 15-59 years		
		Male: over 59 years		
	Ask participants if they have any problems/questions.			

Figure 29: Final Home Visit Checklist

Using the Launcher (3.1) you will be able access and download the data for the FUEL, HAPEx, and EXACT sensor (see Launcher DOWNLOAD video). Once you see all of the sensors in the household on the screen you may select the ”Stop & Download” button. The sensor reading will turn green once it has downloaded successfully. Once all of the sensor reading have turned green you may turn off the Launcher and collect the sensors.