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The Stove Adoption Process: Quantification Using Stove Use Monitors (SUMs) in Households Cooking with Fuelwood

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The Stove Adoption Process: Quantification Using Stove Use Monitors (SUMs) in Households Cooking with Fuelwood

by

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Abstract

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The exposure to the toxic products of the incomplete combustion of wood, charcoal, crop residues and dung used as cooking and heating fuels kills 1.6 million people every year. This leading environmental health risk also accounts for about one-third of the global human-caused black carbon emissions. Stove technologies that vent smoke to the outside of a house and have verified improved combustion efficiencies have been identified as a solution to the household air pollution problem. However, a persistent barrier to success has been the lack of systematic and proven ways to ensure that households continue using the stoves in the long-term and reduce their open fire practices.

Over thirty-five years of experience with cookstove dissemination have demonstrated that providing access to the stoves is necessary but not sufficient: people need to accept bringing the stoves into the home (initial acceptance), use them on a the long-term basis (sustained use), incorporate them into their cooking practices, reduce their open-fire use, and importantly, the devices must maintain their performance through time. These seemingly obvious requirements imply that objective metrics need to be developed for these system parameters and ways found to optimize them. The optimization requires better understanding of the cooking technology-behavior interface and an integrative systems perspective to analyze the socio-cultural, economic, ecological and infrastructural factors that regulate the performance of cookstove programs.

This dissertation presents a framework of analysis to characterize stove adoption and it introduces the field methods, signal analysis, metrics and visualization tools to quantify the adoption process using low-cost temperature dataloggers as Stove Use Monitors

(SUMs). The SUMs enable the parameterization of stove usage behavior as a critical stove performance parameter that can be objectively measured, unobtrusively monitored and systematically evaluated together with the reductions in air pollution exposures, fuel consumption and greenhouse gas emissions. Data from two biomass chimney-stove case studies are presented: the Guatemala CRECER-RESPIRE stove trial and the Mexico Patsari Stove Project.

In the first two chapters I review the main approaches to study the stove adoption process. I propose a new framework that redefines the emphasis previously placed solely on the stove technology, extending it to include the whole cooking system, thereby including the dynamic complex interactions between stoves, fuels and household behavior with the greater socioeconomic and ecological contexts. I argue that at the household level the innovation being introduced is not only the stove technology, but a set of modified or new cooking practices. When a new stove is brought into the home, the interactions between the user and the previous cooking fuels and devices are redefined. Each fuel-device combination creates its own niche and is used for the cooking tasks where it best fits the needs of the user ("the adoption niche"). This adoption process commonly leads to the combined use (or "stacking") of new and traditional stoves and fuels and to the redistribution of the cooking tasks that are performed with each device. Drawing from field data and well-documented experiences at the two study sites I find that at the population level the adoption process has three stages: initial adoption, sustained use, and disadoption. Further, I find that the process can be characterized by the following critical parameters: level of acceptance, level of initial use, level of sustained use, time for stabilization, and magnitude of the seasonal fluctuations.

In the third chapter I introduce the concept of Stove Use Monitors (SUMs), devices that objectively quantify stove use through direct measurements of physical or chemical parameters on stoves, cookware or food. Using Thermochron iButton temperature dataloggers as SUMs I recorded the initial adoption and sustained use by 82 households in the Guatemala CRECER stove trial. During the 32 months of the study, I recorded stove temperature signals from a total of 31,112 stove-days, with a 10% data loss rate. I present the protocols for sensor placement, data collection and data management specific to these sensors. I implemented a peak detection algorithm based on the instantaneous derivatives and the statistical long-term behavior of the stove and the ambient temperature signals to count the number of daily meals and determine daily usage. The fraction of days in use from all stoves and days monitored in a period (the "percent stove-days") and other key quantitative metrics are defined and their population-averaged behavior and statistical variability are modeled. Using robust Poisson regression models I detected small (3-12%) but statistically significant seasonal variations in the population level of use, while the age of the stove and household size at baseline did not produce

statistically significant variations. Usage was highest during the warm-dry period from February to April, with 92% stove-days (95% CI: 87%, 97%) and 2.56 daily meals (95% CI: 2.40, 2.74); and it was lower during the warm-rainy season of May to November and the cold-dry season of November to February. The high levels of sustained use found reflect optimal conditions for stove adoption in the CRECER trial. The narrow confidence intervals highlight the precision and accuracy of the SUMs to detect the small seasonal fluctuations. Modeling the variability with a random effects model I find an intraclass correlation coefficient of 76%, confirming the stability of daily use behavior within households, whereas the main sources of variance are found between homes.

In the fourth chapter I study the critical role of behavior in the adoption process and in the delivery of benefits from cookstoves. I focus on the patterns of stove stacking found in the RESPIRE and CRECER studies. Using graphic representations for hierarchical clustering analysis ("heat maps"), I identify groups of households that had similar combined stove-fire use behavioral patterns ("stove stacking clusters"). Despite the high levels of stove use measured with the SUMs, fifty-percent of the households reported continued use of an open fire. The preparation of animal feed was the task most commonly performed with the fire (46% of the households) followed by the boiling of corn kernels to prepare tortillas (*nixtamal*, 25%), space heating (13%), boiling water (11%) and preparing food for the family (11%). The stratification of the SUMs-measured stove use was strongly driven by the preferences of the households for using the stove or the fire for specific tasks. Clusters that performed a larger number of tasks with the fire had lower stove usage. This explains why the between-household differences in the SUMs-measured stove use in the regression models could not be accounted for by the fixed characteristics of the households.

Chapter five presents an integrated discussion and the concluding remarks of the dissertation. I conclude that when the energy end-uses of the open fires extend beyond cooking, cookstoves become imperfect substitutes for all fire tasks. Therefore, in addition to monitoring cookstove use it is crucial to include the residual use of traditional fires in the assessment of the impacts brought by the sustained use of new a cookstove. I describe current research efforts in the development of monitoring tools for stove adoption and discuss the need for open source platforms to scale up stove use monitoring and to merge fuel consumption, air pollution and emissions data with stove use parameters. The Stove Use Monitors can herald a new era of research to elucidate the behavioral determinants of stove usage and cookfire prevalence, which had not been possible previously at larger scales due to a lack of objective measurements. It is equally critical to develop analytical frameworks and quantitative monitoring tools to identify the distinct behaviors affecting each of the stages of the stove adoption process and to understand the role of other behaviors that influence the exposure to household air pollutants, such as the time-activity and time-location patterns of the household members, kitchen ventilation, fuel preparation, stove operation and stove maintenance practices.

To my parents, my brother and my friend Abel.

Contents

Acknowledgments

In the Summer of 2003, the image of three indigenous women wearing oxygen masks fully intrigued me, as I glanced at a television screen. I stopped and sat to listen more attentively to one of the Mexican women who looked just like my grandmother. Sitting next to a group of physicians, she spoke with a breathy voice about her life and daily cooking routine in her hometown. As I listened to the physicians speak about chronic obstructive pulmonary disease, the realization that the women had become ill from cooking for their families in fires shocked me, fueling a journey into cookstove research that years later would lead to this dissertation.

I am thankful to my Dissertation Committee for guiding me in this journey. In particular, I am grateful to Prof. Joan L. Walker for her support and continuous encouragement. I have been very fortunate to learn about household air pollution from Prof. Kirk R. Smith, who at all times encouraged my research interests, supported my projects and taught me through his example to always innovate. I am also thankful to Prof. Alan Hubbard for his statistical advice and for introducing me to social epidemiology and to causal inference. I am grateful to all the faculty of the Civil Systems Program for fostering broad perspectives and integrative approaches to environmental engineering problems. In particular I thank the support of Prof. Steven Glaser who trusted my decisions and helped me reach my goals – for the knowledge and smiles we shared during my Master's work on sensor development, I am very grateful. I acknowledge the support of the thank the University of California Berkeley for a wonderful graduate experience.

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Ilse Ruiz Mercado

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Berkeley, CA

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Chapter 1

Introduction

1 Introduction

1.1 Improved cookstoves and the adoption problem

1.1.1 Improved cookstoves

Currently, forty percent of the world's population relies on solid fuels (wood, dung, charcoal and other biomass fuels) for cooking and heating (International Energy Agency 2010). Most of these people cook on open fires, which burn poorly thus leading to low fuel efficiency and high pollution emissions. The current patterns of use cause significant negative impacts of several types, including human morbidity and mortality (Smith 2004), outdoor air pollution (Chafe 2011), climate change (Wilkinson et al. 2009), and deforestation. Social impacts are also associated with such use, particularly excess time, risk, and strain of fuel harvesting for women and children.

The implementation of stoves that effectively vent smoke to the outside and/or have verified improved combustion efficiencies is potentially among the most cost-effective energy interventions to simultaneously reduce the health burden of household air pollution, achieve significant reductions in greenhouse gas emissions and meet goals of reduced poverty, social welfare and increased environmental sustainability. The so-called "improved biomass cookstoves" (ICS) have long been identified as a promising option to reduce the negative impacts of cooking with traditional open fires. Interventions for disseminating ICS date back to the 1970s and until the new millennium were mainly designed for increasing fuel efficiency, often because of a perceived link between deforestation and household energy (Eckholm 1977; Arnold et al. 2003). More recently, efforts to improve health by reducing the air pollution and safety impacts of traditional solid fuel use have come to the fore, as well as possibilities to mitigate climate change impacts of stoves (Smith and Haigler 2008; Johnson et al. 2009).

Although the term "improved" is non-specific as to technology and performance and often applied loosely by promoters to quite different devices in different periods and regions, we will continue to use it here for simplicity. More and more, however, major improvement is understood to require large increases in combustion efficiency as well as increased fuel efficiency over traditional stoves, thus leading to the more specific term "advanced combustion biomass stoves" (Venkataraman et al. 2010). At the same time, increased field evidence has shown that households combine new and traditional stoves to satisfy their fire needs (Masera et al. 2000); and, that substantial reductions in personal exposures require the abatement or relocation of the residual traditional cookfires in addition to the adoption of advanced combustion devices. These findings are influencing the definition of the broader term "cooking system." (Masera et al. 2005) This in turn has led to integrated approaches to extend the dissemination of cookstoves to the promotion of "healthy and sustainable cooking practices".

1.1.2 Multiple benefits

On one hand, it might seem that the existence of a range of potential benefits from improvements in the cooking settings would be an advantage in competing for resources, but it also acts as a deterrent in that no single sector "owns" the issue and household energy interventions usually do not look as cost-effective and low-risk as other potential interventions in any one of the sectors, in spite of the breadth of benefits across sectors and implied spreading of risk.

The issue of multiple benefits carries over into the choice of metrics to evaluate improved stove programs. The best metric to evaluate a program for health protection is not the same as that for avoiding deforestation, for example. This is because the optimal target households and stove performance parameters vary according to the goal. It is, for instance, quite possible to have a program optimized for one goal and not achieve anything at all or very little for others. Improving fuel efficiency to decrease deforestation, for example, does little by itself for air pollution, indoor or out. On the other hand, lowering exposures with chimneys may do nothing for outdoor air, climate, or deforestation. Indeed, without commensurate increases in combustion efficiency it may increase impacts in these other sectors.

In spite of the different implications of these partly overlapping sets of metrics, all these goals strongly depend on two fundamental basic performance parameters that are often forgotten or glossed over in discussions of improved stove programs: the initial acceptance and the sustained use of the stoves. For instance, today's protocols for carbon projects in the official and voluntary markets allow an unrealistic default value for stove use (100% if the stove is still in place in workable condition) and thus actually discourage efforts to measure and/or optimize it (Climate Care 2010; UNFCCC 2011; UNFCCC 2011).

1.1.3 The adoption problem

No stove program can achieve its goals unless people adopt and then use the stoves in the long term, a seemingly obvious statement that implies that metrics need to be developed for these parameters and ways found to optimize them. Unfortunately, however, doing so has been relatively rare in past stove programs. The largest and most successful one in history, the Chinese National Improved Stove Program (NISP), which introduced 180 million stoves from 1983 to the mid-90s, however, can owe part of its success to monitoring stove acceptance and initial use but did not attempt to monitor sustained use (Smith et al. 1993; Sinton et al. 2004).

The development of frameworks to characterize adoption has been slow considering that over thirty-five years of experience with cookstove dissemination has demonstrated that a main barrier for success is the lack of systematic ways to maintain usage. This is partially because scientific research, field monitoring and evaluation have been hampered by the lack of tools to quantify stove use in ways that are systematic, objective, unobtrusive and that can affordably operate at large scale in widely dispersed populations to provide with data to inform the models.

1.2 Research objectives

The specific aims of this dissertation are two:

1. Develop an analytical framework to characterize the stove adoption process: identify its elements, boundaries, the critical parameters that can quantify its dynamics and define quantitative metrics to evaluate adoption performance.
2. Develop the field methods to use temperature sensors as Stove Use Monitors (SUMs) in biomass chimney stoves to measure the stove adoption process: develop an algorithm for signal interpretation, and model the obtained quantitative metrics to identify and understand the sources of variability in stove use.

1.3 The case studies

This dissertation presents data from two well-documented research sites:

1.3.1 The RESPIRE and CRECER Studies

The Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) was a randomized intervention trial carried out in Guatemala to elucidate if biomass smoke (the treatment variable) caused acute lower respiratory infections (the outcome) during the first 18 months of life. The study population encompassed 23 communities in the rural highland area of San Marcos, Guatemala. The region has three weather seasons, locally described as dry-cold, dry-warm and rainy-warm (further described in chapter 2). The RESPIRE trial spanned from 2002 to 2004 and followed 532 mothers and 515 children participants. After a two-year gap, the Chronic Respiratory Effects of Early Childhood Exposure to Respirable Particulate Matter (CRECER) Project started in 2006. It followed longitudinally, for a 5-year period, 388 households that participated in RESPIRE and that had already received a chimney stove (from both intervention arms). It also recruited 169 new participants originally using a traditional cookfire and receiving the stove 18 months later. The purpose of CRECER is to follow the children who participated in RESPIRE to determine the chronic effects of inhaled PM during the critical time window of infant lung development on respiratory health. The studies are a collaborative effort between the UC Berkeley School of Public health, the Universidad del Valle de Guatemala and the Guatemalan Ministry of Health. Both studies introduced the locally made “Plancha” stove design.

1.3.2 The Patsari® Stove Project

The Patsari Stove Project has disseminated more than 50,000 Patsari stoves through Mexico to reduce the negative health and environmental effects from biomass cooking and to improve the quality of life of the rural families. The project started in 2003 in the highlands of the state of Michoacan, by the Mexican NGO Interdisciplinary Group on Appropriate rural Technology (GIRA) in partnership with the Center for Ecosystems Research (CIECO) of the National Autonomous University of Mexico as part of a multi-institutional and long-term program to promote cleaner and more sustainable patterns of energy use based on the concept of the "multiple fuel cooking" (Masera et al. 2000; Masera et al. 2005; Diaz 2011). The "Patsari", which in the local Purhepecha language means the one that "cares for" (for one's health, environment, economy, etc.) is a stove design with field-verified improved combustion, fuel efficiency (Bailis et al. 2007; Berrueta et al. 2008) and reduced greenhouse gas emissions (Johnson et al. 2008; Johnson et al. 2009; Johnson et al. 2010) compared to those of the traditional open fires. Its use significantly reduces the levels of personal exposure to and kitchen concentrations of air pollutants (Masera et al. 2007; Zuk et al. 2007; Armendariz-Arnez et al. 2008; Armendariz-Arnez et al. 2010; Riojas-Rodriguez et al. 2011), and it is associated with significantly reduction in symptoms and with significant reduction in the decline of lung function, when compared with the use of the open fire (Romieu et al. 2009). The Patsari is the stove whose adoption process is the most thoroughly documented in the scientific literature (Troncoso et al. 2007; Pine et al. 2011; Zamora 2011). In particular, this dissertation discusses the study of sustained stove use carried out in 2009 by Zamora (Zamora 2011). The study analyzed the socio-ecological impacts that sustained use of the Patsari stove had in 137 households from 7 communities in the Cuitzeo and Purhepecha regions of the Mexican state of Michoacan. Using surveys and recall questionnaires, the study documented the intensity and diversity of Patsari stove use compared to the continued use of the traditional cooking devices. In particular the study documented the changes over time in the patterns of fuelwood use, kitchen appearance and household dynamics that took place after the introduction of the Patsari.

1.4 Dissertation outline

This dissertation presents a framework of analysis to characterize stove adoption and introduces the field methods, signal analysis, metrics and visualization tools to quantify the adoption process using low-cost temperature dataloggers as Stove Use Monitors (SUMs). The dissertation is organized into five chapters:

The current chapter provides the background to understand the impacts of household air pollution from the incomplete combustion of biomass fuels. It defines the stove adoption problem and introduces the study sites: the RESPIRE-CRECER Guatemala study and the Mexico Patsari Stove Project.

Chapter 2 discusses the key role of sustained stove use in the delivery of benefits from stove programs. It reviews current approaches to study adoption and presents a new framework to characterize the stages and critical parameters of the stove adoption process, drawing from field evidence at the two well-documented sites.

Chapter 3 introduces the concept of Stove Use Monitors. It presents the field protocols, signal analysis algorithms, sensor performance evaluation and study design considerations for using temperature dataloggers as SUMs. Key quantitative metrics of stove use to evaluate adoption performance are defined in this chapter. It presents the results, statistical analysis and comparison of stove activity indicators of a 2.6-year monitoring study using temperature dataloggers as SUMs in the chimney stoves of 82 households in rural Guatemala.

Chapter 4 discusses the central role of individual, household and community behavior to the actual field performance of the cookstoves. It focusses on the coupled nature of sustained stove use with cookfire prevalence, and its relevance to the reductions in exposure to household air pollution. It introduces the use of graphic tools for hierarchal clustering to aid in the identification of cooking tasks that can account for the differences in the level of sustained use between homes.

Chapter 5 summarizes the research findings of the dissertation, presents an integrated discussion and outlines the main avenues for future research of stove use monitoring and of the behavioral dimensions of cookstove dissemination.

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Chapter 2

Adoption and sustained use of biomass cooking stoves

2 Adoption and sustained use of biomass cooking stoves

Summary

Sustained use of the so called improved cookstoves is a critical parameter in the adoption process that must be monitored just like the rest of the stove's technical requirements to evaluate stove performance and verify the sustainability of their benefits. No stove program can achieve its goals unless people initially accept the stoves and continue using them on a long-term basis. This chapter reviews current approaches to study adoption and presents a new framework to characterize the stages and critical parameters of the stove adoption process, drawing from field evidence at the two well-documented sites in Guatemala and Mexico. When a new stove is brought into a household, commonly, a stacking of stoves and fuels takes place with each device being used for the cooking tasks where it fits best. As with other household interventions, the innovation being disseminated is actually a set of practices, in the case of stoves cooking practices that go beyond the stove technology and include changes in household behavior. Therefore, to better understand the adoption process and assess the impacts of introducing a new stove, it is necessary to examine the relative advantages of each device in terms of each of the main cooking tasks and available fuels. An emerging generation of sensor-based tools is making possible continuous and objective monitoring of the stove adoption process (from acceptance to sustained use -or disadoption), and has enabled its scalability. Such monitoring is also needed for transparent verification in carbon projects and for improved dissemination by strategically targeting the users with the highest adoption potential and the substitution of the cooking tasks with the highest indoor air pollution or greenhouse gas contributions.

Most of the material in this chapter was published in the Energy Policy Journal with coauthors Omar Masera, Hilda Zamora and Kirk R. Smith (Ruiz-Mercado et al. 2011).

2.1 Introduction

Improved cookstoves are starting to recapture the attention of governments, development organizations and donors. By some estimates (Gifford 2010), there are currently more than 160 cookstove programs running in the world, ranging in size, scope, type of stove, approach to technology design and dissemination and financial mechanisms. So far, however, the attention has concentrated in developing new stove designs, improving large-scale manufacturing processes, marketing techniques and financial incentives for stove dissemination. Relatively few efforts have been devoted to understand how stoves are actually adopted and how to sustain their long-term use (Agarwal 1983; Pandey and Yadama 1992; Hessen et al. 2001; Simon 2010) regardless of the dissemination program objectives. Even when low adoption rates have recurrently been identified as a cause of failure in previous interventions, there seems to be little systematic information available about the dynamics of the adoption process and the factors that have been most important for the successful adoption of cookstoves in practice.

Anecdotal information would indicate that initially households respond to fuel savings (when fuel is very scarce or monetized), speed of cooking, convenience, compatibility with local cooking practices, and status of modernity, but relatively less so to health and air pollution-related issues. There is evidence that the main factors affecting the adoption of stoves can be different at the household and community levels (Pine et al. 2011; Zamora 2011). While some household characteristics such as occupation, income or educational level can be significant for the initial acceptance of the stoves (Troncoso et al. 2007), other factors, such as the compatibility of the stove with local cooking practices, seem more important for sustained use (Zamora 2011). Part of the reason for the slow development of frameworks of stove adoption, however, is that until recently there had not been an objective, inexpensive, and unobtrusive means of monitoring actual stove use to test and inform the models.

Correctly addressing the so-called “adoption” issue is central to the success of ICS dissemination strategies. In short, providing access to improved stoves is a necessary but not sufficient condition to achieve any of the goals of ICS programs because the delivery of their benefits accrues from the initial acceptance and continuous use of the stoves disseminated.

2.2 Adoption of new fuel-devices: conceptual and theoretical backgrounds

2.2.1 Fuel switching / energy ladder

Different conceptual models have been used to describe the adoption of stoves and fuels and the impacts of new cooking energy technologies in developing countries. The crudest model is the so-called “fuel switching” approach (Hosier and Dowd 1987). According to it, traditional devices are entirely replaced by modern alternatives as soon as income and access constraints for modern fuels are removed. Households are usually seen as relying on only one cooking fuel/device. The main impacts – for example in terms of fuel or energy savings – of this switching are usually estimated with the energy efficiency ratio, comparing the energy efficiencies of the traditional and the new devices and the energy content of the fuels. The energy efficiency ratio approach assumes that useful energy is constant across households using different fuels. Hence, household energy consumption is only a function of the end-use device efficiencies. Masera et al. (Masera et al. 2000) gives a more complete description of the model. The implicit premise of this interpretation is that households effectively consider some fuels and devices to be better than others for all cooking tasks, thus resulting in a complete substitution of the traditional devices. This is the framework currently implied in the new wave of ICS that focuses on laboratory efficiency measures (e.g. the water boling test) to estimate the likely savings of the stoves deployed in the field. It is also implicit in the current Clean Development Mechanism (UNFCCC 2011; UNFCCC 2011) methodology for estimating carbon offsets from ICS programs.

A more elaborate version of the fuel switching (or preference-ladder approach) comes from the studies about inter-fuel substitution in urban households (Barnes 1992). In contrast with the fuel switching approach, this model, accounts for the observed fact that fuels are many times "imperfect substitutes" (Dowd 1989). An interesting result of these analyses is to show that usually fuel savings are not directly proportional to the comparative efficiency of cookstoves (Fitzgerald 1990).

2.2.2 Stacking of fuels and devices

While there has been a general trend to replace traditional devices by modern stoves and fuels, particularly in urban areas of the more "wealthy" developing countries, researchers now acknowledge that the process was greatly simplified. Seldom, the substitution of fuels and devices is complete and energy savings are much less than those expected from the efficiency ratios. Increasingly, the presence of multiple fuels and devices is being documented as the "norm" in developing country households, even on a long-term basis, although there are wide variations around the world (Masera et al. 2000; Heltberg 2004; Heltberg 2005; Hiemstra-van der Horst and Hovorka 2008; Joon et al. 2009). We argue that, in order to study stove adoption, it is necessary to redefine the emphasis previously placed solely on the stove technology and to expand it to the whole cooking system, this is an essential outcome resulting from the dynamic interaction between users, stoves, fuels and the larger socioeconomic and ecological contexts. Rather than relying on a simplistic fuel switching approach, the analysis also needs to incorporate the possibility of partial substitution among multiple fuels and devices. This aspect is further discussed in chapter 4.

2.3 A new framework to understand adoption and sustained use

2.3.1 Scope

Acknowledging that adoption is a complex problem, we concentrate the analysis in a subset of issues, having to do with the characteristics of the process (how it occurs), and the time dynamics (when it occurs and how it evolves through time). This chapter does not address the causal factors associated with the adoption process, which are studied in chapters 3 and 4.

This chapter directly addresses the behavioral component of the adoption process and its measurable outcomes: the act of using the stove over time and the patterns of use. In this chapter we do not quantify nor do we try to explain the decision-making processes (Wilson and Dowlatabadi 2007) or other cognitive steps in the adoption process that take place before the stove is first used (willingness to pay, intent or agreement to use it or install it). Furthermore, in this chapter we do not discuss directly nor do we try to explain the causal factors of the adoption process or other impending aspects of such process, such as institutional factors, and the role of change agents (Troncoso et al. ; Simon 2010).

The analysis draws mostly from field data and experience at two well-documented study sites in Guatemala (Smith et al. 2010; Smith et al. 2011) and Mexico (Masera et al. 2005; Masera et al. 2007), where extensive monitoring studies have been conducted.

2.3.2 The cooking system

A more comprehensive model to understand the modernization of household cooking technologies can be developed using the literature on diffusion of innovations originally formulated by Rogers (Rogers 2003) but which can benefit from the theoretical contributions from other authors (Pareek and Chattopa.Sn 1966; Agarwal 1983; Shih and Venkatesh 2004; Dearing 2009). We propose a new framework where the adoption of a new cooking device is seen as a dynamic "complex process and a stage in a larger process" (Pareek and Chattopa.Sn 1966) of technology absorption (Murphy 2001), cultural adaptation and "appropriation" of the technology (Overdijk 2006).

We propose that the introduction of new fuels/devices takes place in a dynamic system with strong interactions between the user, the technology, the fuels and the larger socioeconomic and ecological contexts. Since the main goal of a stove user is to prepare cooked food rather than the consumption of fuel per se or the utilization of the cooking device in itself, we argue that at the household level the innovation being introduced is not only the cookstove-device, but the set of modified (or new) cooking practices that result from incorporating the new stove technology and/or fuels into the existing household system.

Here we define "cooking practices" as the processes (or recipes) that the user follows to transform the food using a particular device-fuel combination to accomplish a given cooking task like fried rice, handmade tortillas, ugali, etc. Both the practices and the definition of the tasks themselves are dynamic in nature and their changes have different time scales. Under this framework, when a new stove technology is brought into the household, the initial conditions of the system are redefined and each fuel-stove combination finds a new equilibrium state in the cooking practices were it performs best as perceived by the user (the "adoption niche"). The process is regulated to different extents by tradition, resource availability, migration patterns, and perceived costs, and it often leads to the stacking of fuels and devices rather than to complete switching (Figure 2.1). The modified cooking practices can have different impacts in terms of fuel consumption, exposure to indoor smoke, pollutant emissions, cooking time, time spent in the kitchen or stove operation.

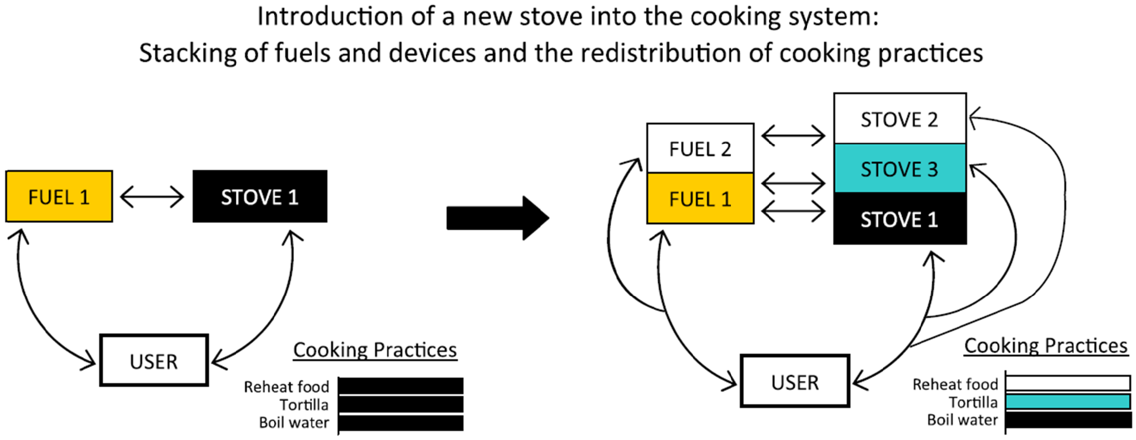

Figure 2.1 New interactions between stoves, users and fuels are created when a new stove is brought into the existing cooking system. Very often users prefer to "stack" cooking devices rather than to completely abandon the traditional stoves. Each stove-fuel combination creates its own "adoption niche" and is used for the cooking tasks where it best fills the needs of the user. In the example, the acquisition of two stoves by a household transforms the original cooking system of one stove-fuel into a new system of three stoves and two fuels (right). The new stoves finds a niche in the cooking tasks of making tortillas and reheating food, while the old one is still used to boil water.

The new devices are incorporated into the target population according to a learning curve with specific timing and saturation levels that depend on the characteristics of the users, those of the technology(Rogers 2003), and on the degree to which the users are able to incorporate and combine them with the existing practices (Pareek and Chattopa.Sn 1966). The process of interest in the case of cookstoves goes beyond the acceptance and initial use originally studied by Rogers and has to do with sustained use, since it is stove use over time that really drives all the expected benefits from the innovation. The examination of this process also requires looking at other factors and at the dynamics of post-adoption usage (Prins et al. 2009). Finally, the extent and depth of use of the new devices require going beyond "cooking" as a single activity, but rather examining the relative advantages of each device in terms of the main cooking tasks. The implications of the stacking process –in terms of energy, health or climate- will heavily depend on which particular tasks are substituted by the new technology over time.

2.3.3 Adoption as a dynamic learning process

At the household-level, the adoption process that we describe starts at the "initial acceptance" of the stove, which we define as its agreed purchase, reception as a gift, construction or installation, i.e., when the stove is brought into the home.

An important consequence of including the dynamic interactions between fuels, stoves and users is that the adoption of a new cookstove should not be seen as an on/off static state that ends with the initial acceptance of the stove or its mere first uses. It is through sustained long-term use that the decision to adopt the device is translated into action. It is in fact the timing, variety and consistency of use (Pareek and Chattopa.Sn 1966; Shih and Venkatesh 2004) that defines the magnitude of adoption. For clarity, from this point forward, the term "adoption" is reserved to refer to a process or part therein. We minimize its use as a verb, because when saying that a household "adopted a stove" it is ambiguous to what stage and to what level of usage one is referring to. Instead, to denote users that have entered the adoption process we explicitly name the stage of interest or the stage when the act of using the stove is occurring. We avoid the term "adopter" for the same reason. The only exception is when citing the work of others that have used the terms in their analyses (like Rogers, Pareek and Chattopadhay or Pine et al.).

At the population level, we describe the adoption process of one stove in terms of three stages: 1) initial adoption (or learning-adjustment), 2) sustained use (or stabilization), and 3) disadoption. We identified six critical parameters that seem to characterize this process:

1. The level of initial acceptance (A_0).
   Number of households that initially accepted (as defined above) the stoves, or fraction of the population that accepted them from the total stoves that were disseminated or deployed.

2. Learning or adjustment period (ΔL)
   Time between initial acceptance until sustained use is reached, or the time that it takes the population to learn how to use the stoves, incorporate them into their practices and reach a stable level of use.

3. The level of initial use (U0)
   Level of use measured during the stage of initial use: any point after initial acceptance and until sustained used is reached.

4. Level of sustained use (U_{sust})
   Level of use after the learning period or the fraction of the population that initially accepted the stoves and that undertake sustained use.

5. Maximum level of use (U_{max})
   Highest level of use shown during the adoption process.

6. Use variability (ΔU_{sust})
   Size of the fluctuations around the mean U_{sust} due to seasonal and regional patterns that affect the level of use.

The process is schematically shown in Figure 2.2. Figure 2.2 assumes that all individual households had access to the stove starting on the same day. When this is not the case, the start times of all households should be synchronized in the analysis to assess the population U_0 and ΔL. This adjustment is more important when ΔL lasts only some days and it seems less so for the visualization of sustained use, where the influence of seasonal variations are better appreciated. The figure shows the level of initial acceptance A_0 only as an upper bound value, not as a value of the stove usage curve to clearly distinguish between the several stoves that can be accepted by the households but not used a single time afterwards. The levels of usage can be quantified in absolute terms (number of stoves used) or percentages. In the following sections, we document these stages and parameters drawing field evidence from the case studies in Mexico and Guatemala.

The stove adoption process at the population level:
stages and critical parameters

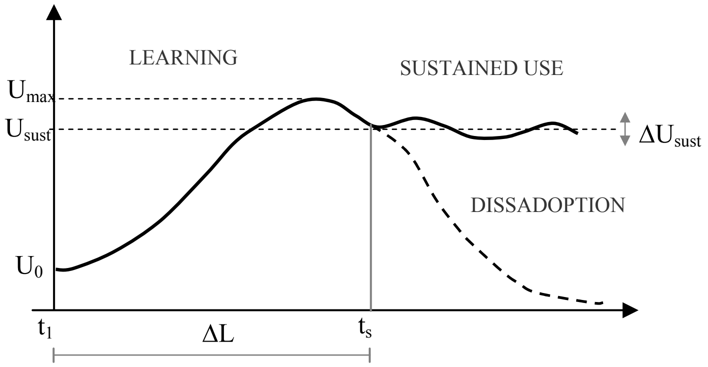

Figure 2.2 The adoption process of cookstoves at the population level may be characterized by the following parameters: a) the initial acceptance (A_0) by a fraction of the families that were offered the new stove, b) the "learning" time (ΔL) after acceptance for the population to incorporate the device into the existing cooking practices, c) the level of initial use (U_0) during the initial adoption stage, d) U_{max} – the maximum level of use observed; e) a stable level of sustained use (U_{sust}) after initial adoption; and e) ΔU_{sat} the size of the fluctuations around the mean U_{sust}. The figure assumes that access to the stoves began on the same day for all households in the population.

2.3.4 Critical times: time for saturation

In the process described by the diffusion of innovations theory, the adoption curve in a population has an S-shape curve given by the cumulative percent of individual adopters through time. Pine et al. (Pine et al. 2011) found somewhat similar S-shaped curves when studying the evolution of the number of stoves in use in the Patsari chimney-stove trial in rural Mexico. The stove adoption study followed a sample of 112 homes from 5 communities from the day of stove construction for up to 10 months. At each monthly visit, a binary indicator of use was assigned to each cooking device in the home based on the reported use and on visual inspection of physical traces of use. The analyzed sample excluded those users that reported never using the stove, i.e., the percent of initial acceptance was not quantified. In this population, the level of initial use (U_0) of 40% was found in the first month, and a maximum level of 70% (U_{max}) was reached at month 4, after which a gradual decline over months 5-7 stabilized at 50% (U_{sust}) after the eight month of use (see Figure 2.3).

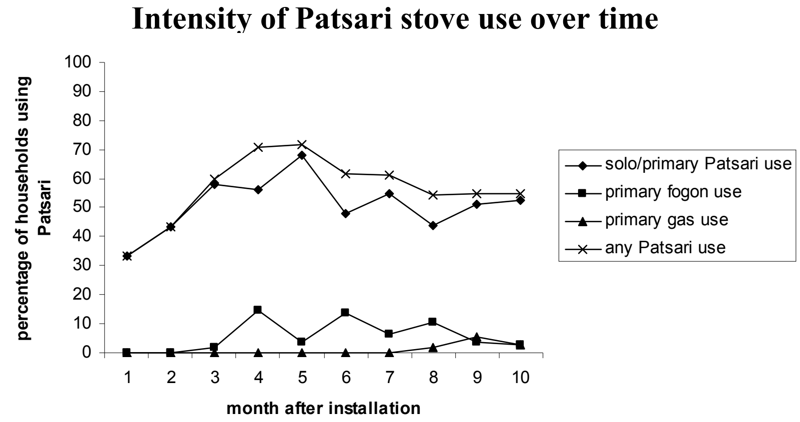

Figure 2.3 Process of stove adoption in a stove trial in 112 rural Mexican households (Pine et al., 2010). Users of Patsari stoves showed a learning period of 4 months and a level of sustained use of 50%. Although most users declared the Patsari as their primary stove, many also combined its use with the open fire or a gas stove. Data were obtained from monthly questionnaires.

The observed dynamics highlight that monitoring at different times over a period of several months may be needed to correctly assess sustained use levels: cross sectional evaluations limited to the first days or weeks after initial use are likely to yield misleading results. In section 3 of this chapter we discuss the difficulties of performing such ongoing monitoring, and outline a set of new tools to reduce the resource burden of such measurement of stove use. In chapter 3 we detail some field and analysis methods.

In a larger randomly selected sample of 259 homes of the same study population the authors found that in fact the adoption curve was the cumulative result of distinct groups of individuals that started to use the Patsari stove at different times. Using a multinomial logistic regression with month of use as an outcome, they found that the community was the strongest significant effect that account for the differences between the groups who started using the stove at month 1 (early adopters) compared to those that did at months 2 or 3 (late adopters). They also identified other significant attributes that coincided with those described by Roger's theory, like educational level and type of occupation.

2.3.5 Saturation levels

As early as 1966, Pareek and Chattopadhyay formulated adoption metrics that highlighted the distinction between the total number of improved practices that are communicated to an individual and the maximum number that he or she, given the existing practices, is willing or able to incorporate.

This distinction is particularly relevant to multi-device and multi-practice adoption processes like cookstoves, where previous and new cooking devices and practices are likely to coexist to some extent. The use of multiple fuel/devices to meet the cooking budget could be: a) a pre-existing condition, b) a consequence when a single stove design cannot fulfill the range of cooking settings and all the cultural elements provided by cookfires, or c) the result of new cooking practices created by the interaction of previous and new stoves.

The sensor-based measurements of stove use in the CRECER Guatemala stove study (Ruiz-Mercado et al. Under review; Ruiz-Mercado et al. Under review) provided experimental evidence of the levels of sustained use and new insights into the dynamics of the stove adoption process. Here, we briefly summarize the results of the study, which are the core of chapter 3. Using small temperature dataloggers as stove use monitors (SUMs) the stove surface temperature was recorded in a group of 82 homes for over 2.6 years, measuring in alternate months. Cooking events were identified in the signals using an algorithm, and a count of the number of meals per day and the days of use in the monitoring periods were obtained. It was found that although the population saturation level (U_{sust}) remained more or less constant at 92% stove-days[1] (see Figure 2.4), the set of specific stoves not used was different every day. This is, despite the fact that all households used the chimney stove in a sustained basis, at any given day there seems to be a 10% of this population that cook elsewhere, do not cook at all or use the open fire. A small (3-12 percent points) but statistically significant seasonal fluctuation (ΔU_{sust}) was found.

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[1] Percent stove-days: the fraction of use from all stoves and days monitored in a time period.

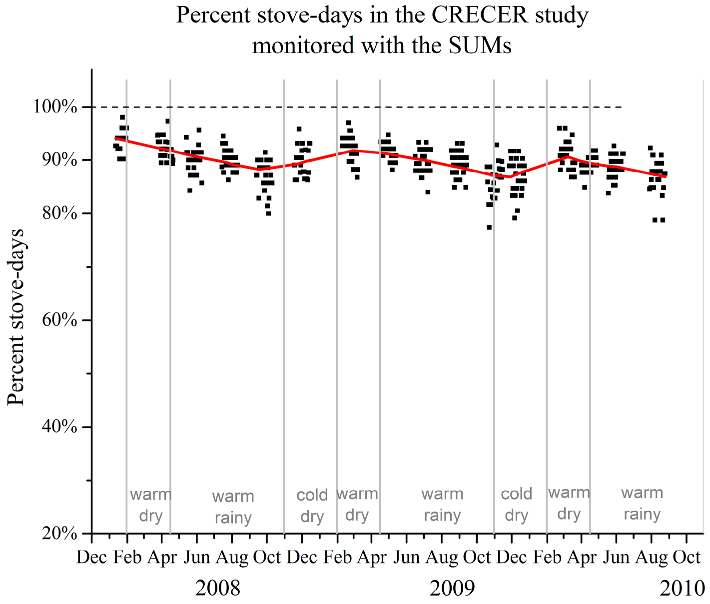

Figure 2.4 Use of chimney stoves (Planchas) measured with temperature-based SUMs in the Guatemala CRECER study for a population of 82 households (Ruiz-Mercado et al. Under review; Ruiz-Mercado et al. Under review). Each point shows the percent of stoves actually used among the total number of stoves monitored, which are all in households of long-term users. The 92% level of use indicates that at any given day 8% of the homes cook with another device, do not cook at all, or cook elsewhere.

The trend of daily meals displayed a similar pattern, fluctuating around 2.5 daily meals. At a household level, this means that long-term users might not cook with the improved stove (and presumably use the traditional cookfire) or with any stove at all in some days or seasons. It also implies that some households, despite their sustained usage, cook only one or two (out of three main meals observed in this population) with the improved stove. At the population level, this translates into a saturation level that is below 100% for the new stove, even if all users have initially accepted it and undertaken its sustained use.

Understanding the denominator of stove use to take into account the use of multiple devices or non-cooking periods helps set more realistic goals of adoption and to determine when the assumptions of 100% daily use and complete substitution are reasonable ones. The choice of a denominator in assessing the percent meal-days for an improved stove alone is less obvious and requires measurements of use from all existing cooking devices in the household. For further discussion of this point see chapters 3 and 4.

2.3.6 The redistribution of cooking tasks brought by multiple fuel-devices

As stated earlier, evidence from Africa, Asia and Latin America increasingly suggests that when new cooking devices are incorporated, it is seldom that the old ones are completely phased out; in many cases old and new devices coexist on a long-term basis. Figure 2.5 illustrates this process in the case of 4 villages in Mexico's Highlands, which have been grouped in two population categories: "Purhepecha" (indigenous) and "Mestizo" (non-indigenous) according to the dominant ethnic group. "Purhepecha" families conserve their own language and follow deep-rooted traditions. In terms of their cooking behavior this is reflected in the dominant use of ceramic pots to cook traditional dishes, the overall arrangements of the kitchen, and a lesser penetration of liquefied petroleum gas (LPG) stoves or other cooking devices. "Mestizo" families are more open to changes in their cooking practices, cooking devices and diets. The access to LPG and the penetration of LPG stoves is larger in this group. The graph summarizes the results from a long-term follow up study of sustained use in Patsari stove users (Zamora 2011). It is clear from the diagram that the process of adoption from the traditional three-stone fire (TSF) and LPG stove to Patsari stove and to microwave (MW) in a small group of households has many avenues and generally leads to increasing the portfolio of options. Even in the less indigenous villages, still more than 50% of households continue using the TSF in conjunction with other devices. For example, about half of mixed TSF-LPG in the Mestizo villages chose to add the Patsaris to their portfolio of options (TSF-LPG-Patsari in the Figure 2.5) rather than getting rid of the TSF.

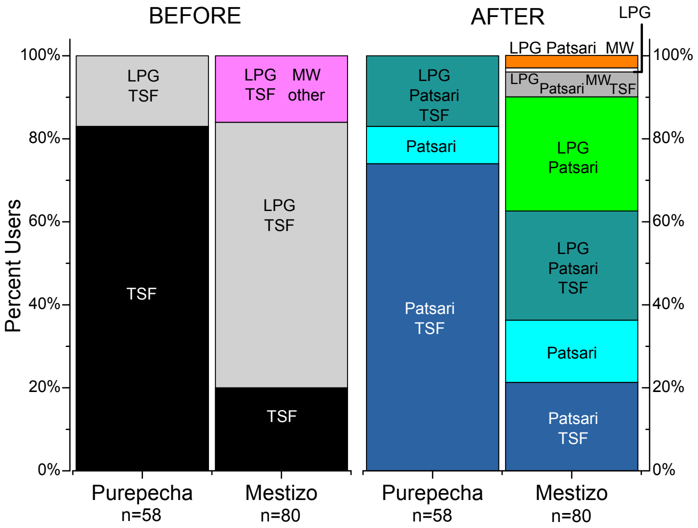

Figure 2.5 Stacking of fuels and devices in the case of Mexico's highlands (Zamora 2011). Even in the non-indigenous population (Mestizo), 50% of the households continue using the three-stone fire (TSF) with gas (LPG) stove and even microwave (MW). In the more indigenous group (Purhepecha) after the adoption of the Patsari stove only 10% of the households abandoned the TSF completely, while the remaining 90% now "stack" the TSF with Patsaris, LPG stoves and MW. The sample sizes are shown below each column.

To better understand the process of multiple-device use it is necessary to think beyond cooking as a single activity and to examine cooking tasks in more detail. When doing so, as illustrated by Figure 2.6 for the case of the Mexican Highlands, we see that in most cases each device has marked preferences for specific cooking tasks. In other words, the device adoption niche has to do with the compatibility and comparative effectiveness with regards to the different tasks.

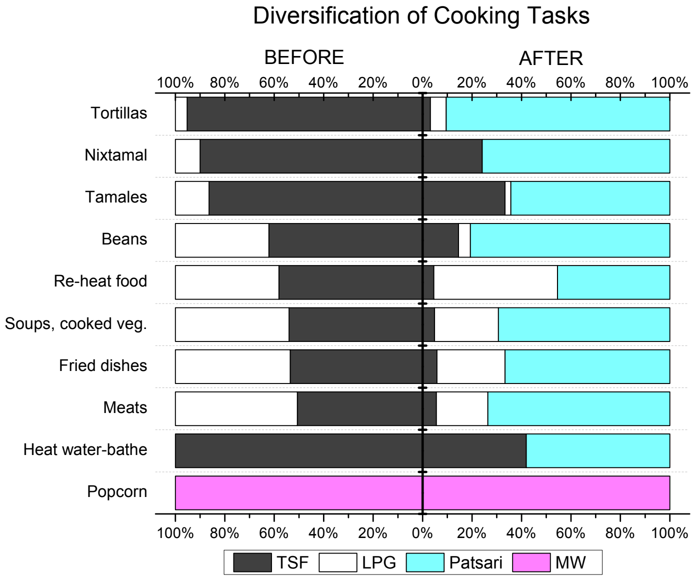

Figure 2.6 Distribution of the main cooking tasks by device before (left) and after (right) the introduction of the Patsari stove in a Mestizo population in Mexico's highlands (Zamora 2011). All families have access to gas (LPG) stove, Patsari, three-stone fire (TSF) and small percentage also have a microwave (MW). While the Patsari stove is widely used to perform cooking tasks like tortilla making (top), an increased fraction of the population now use LPG stove to re-heat cooked food (middle). Although a fraction of the households now use the Patsari to heat water for bathing, the use of TSF for that task is still large.

This process was documented by Pareek and Chattopadhyay (Pareek and Chattopa.Sn 1966) in the context of the adoption of innovations in agricultural systems. They realized that rather than an on/off adoption process, farmers were very selective and adopted the different innovation at different rates and extent for the different agricultural practices. The same phenomenon was documented for the mechanization of agriculture systems in Mexico (Masera 1990).

In the case illustrated, we see that Patsari stoves are effective at substituting for TSF in making tortillas. However, TSF continue to be used quite extensively for heating water for bathing and for other traditional cooking tasks such as making tamales and *nixtamal*[2]. A similar process is observed in the Guatemala CRECER study as discussed in chapter 4. Liquefied petroleum gas (LPG) stoves, on the other hand score better for tasks that require fast heating of food, such as preparing coffee in the morning, or to warm food already prepared. Interestingly, the addition of microwaves opens a new cooking task (making popcorn) specific to this device.

2.3.7 The importance of cooking tasks in weighing the impacts of new fuel-stoves

Examining the initial acceptance and sustained use of stoves by focusing on the individual cooking tasks is also critical because the impacts of introducing a new stove may be different depending on the particular tasks that the fuel-device replaces or complements. In the case of rural Mexican households it has been found (Masera et al. 2005; Masera et al. 2007; Cynthia et al. 2008) that if one is interested in reducing fuel consumption or indoor air pollution (IAP) associated to open fires for example, then the task of tortilla making should be tackled as it accounts for a large share of human exposure to IAP and of fuel consumption. Tortilla making in a typical home is one of the most intense cooking tasks that account for 40% of total wood use. It is a major contributor to the 24-hr population averages of personal exposure to IAP, since the preparation of this traditional task causes 2-4 hours of exposure per day in close proximity to the cooking device. Consequently, to be effective in terms of reduction of health impacts, the new stove needs to clearly outperform the traditional device for this particular task. Figure 2.7 illustrates the ranges of kitchen concentrations of particulate matter (PM 2.5) and carbon monoxide (CO) for a typical Mexican rural household, where it can be seen that different cooking tasks are indeed associated with distinct “signatures” of IAP. Similarly, GHG levels may vary a lot with the different cooking activities, and therefore cookstoves should be designed to be effective at replacing the most GHG-intensive tasks.

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[2] *Nixtamal*: maize kernels cooked with an alkaline additive for the preparation of masa to make tortillas. This traditional cooking practice requires boiling the corn in large pots with water and lime, steeping, washing and subsequent grinding of the corn kernels with stones.

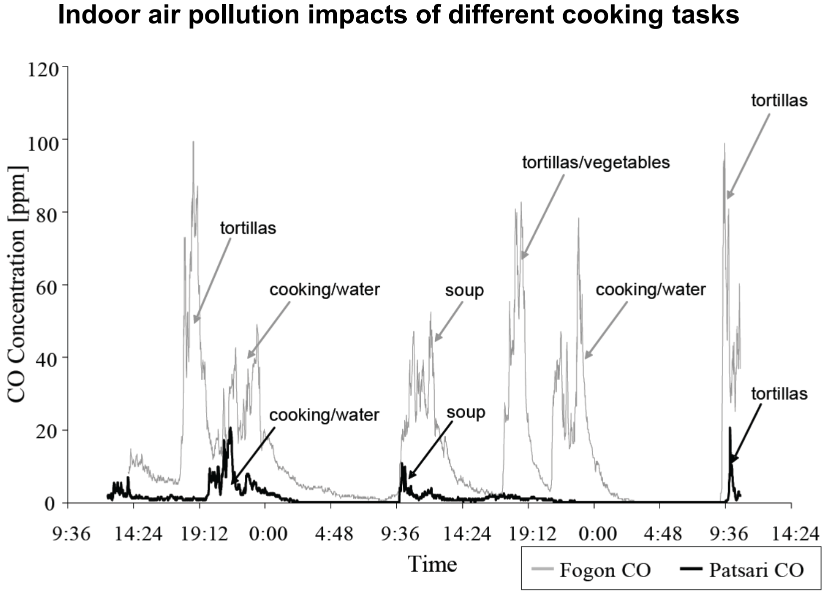

Figure 2.7 Different cooking tasks can exhibit distinct "signatures," contributing differently to the levels of indoor air pollution. In the case of Mexico, the task of tortilla making accounts for most of the carbon monoxide (CO) and particulate matter emitted indoors by traditional open fires. Due to the high intensity of this activity and close proximity of users to the fire when making tortillas, this task is a major contributor to personal exposure derived from stove emissions. This figure (from Masera et al., 2007 (Masera et al. 2007)) also shows the reductions in open fire CO (thin line) brought by the introduction of the Patsari stove (thick line) in specific cooking tasks.

2.4 Monitoring adoption and sustained use

2.4.1 The need for adoption performance parameters

All the benefits from improved cookstoves depend on their long-term sustained use. Thus, verifying that the adoption performance parameters of the cooking system are met is equally important to monitoring the fulfillment of any other technical specification. A complete assessment of stove performance will require that the measures of fuel efficiency and emissions currently performed for individual stoves are complemented with individual and population-level adoption performance parameters and that these parameters are derived from objective measures of stove use.

The dynamic nature of the adoption process requires these measurements to be taken at different times, and if possible, on all the devices present in the household. Characterizing this process also needed to obtain statistically representative samples since the population-level parameters of the adoption curve are determined by the averaged individual delays until first use, levels of saturation and gaps in use.

As a starting point, we propose the monitoring of the following adoption performance parameters (defined in section 2.3.3) to characterize the process and to develop strategies for its optimization:

1. Level of acceptance (A_0)
2. Level of initial use (U_0)
3. Saturation level (U_{sat})
4. Time for stabilization (ΔL)
5. Variations of use (ΔU_{sat})
6. Main cooking tasks for each stove type, with the purpose of characterizing the adoption niche of the new and existing stoves.

In the following section we outline the new set of tools currently available for improving the quantitative metrics of stove use and how they can be used for obtaining the adoption performance parameters. In chapter 3 we incorporate these parameters into adoption metrics.

2.4.2 Cost-effective monitoring and improved dissemination

2.4.2.1 New tools: Stove Use Monitors (SUMs)

One of the most important barriers to the monitoring of stove adoption has been the lack of tools and methods to quantify the dynamics of the cooking system in ways that are objective, unobtrusive, scalable and affordable. The traditional methods of observation, household surveys, questionnaires, diaries, phone interviews, etc., provide valuable insights to understand specific aspects of the household dynamics and to inform the selection of the covariates and temporal scales likely to affect the system. However, these methods are extremely resource-intensive to be performed continuously or at large scale and they can be subject to biases, as they often rely on the householder's recollection or on their desire to respond as they think they should (Barnes 2010).

A new generation of monitoring tools has emerged, leveraged by the availability of unobtrusive, rugged and low-cost sensors combined with IT-technologies for data collection, transmission and management, as well as with the pervasiveness of cell phones and personal computers.

Sensor-based measurements of stove use have enabled the objective quantification of the adoption performance parameters described above and of other parameters of use. The measurement of temperature as a primary parameter to track stove activity seems an obvious choice[3] and it has been implemented in biomass stoves by Ruiz-Mercado et al. (Ruiz-Mercado et al. 2008; Ruiz-Mercado et al. Under review; Ruiz-Mercado et al. Under review) with the Stove Use Monitors (SUMs) presented in chapter 3 and by Grupp et al. (Grupp et al. 2009) in the Synoptic Use Meter (SUM) for solar cookers. Both research groups used commercial temperature sensor/dataloggers to record daily details of cooking device use. The Synoptic Use Meter measured the number of cooking cycles (the relevant unit of stove use in solar stoves) and its duration. The amount of food cooked in each cycle was estimated from the thermal parameters of the system and further the savings in fuel and reductions in greenhouse gases with respect to the baseline cooking intensity were obtained.

The Stove Use Monitors (SUMs) implemented by Ruiz-Mercado et al. have been used to measure the frequency of cooking events and provide systematic documentation of the stove use patterns (Figure 2.8). The data from individual SUMs are analyzed to identify daily use/no use and to count the number of meals per day. The counts of meals and days used for each household yield individual household adoption curves that were aggregated to derive the population parameters U_0, U_{sat}, ΔL and ΔU_{sat}. When the characteristic temperature signals or "signatures" of the main cooking tasks are obtained and their frequency is measured, the adoption niche of each cooking device can be quantified from SUMs-based data in terms of the redistribution of cooking tasks.

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[3] However, the concept of sensor-based SUMs is not limited to temperature measurements. Different stove designs can benefit from the integration of measurements of other physical parameters like heat flux, light or motion to monitor portable stoves, or electrical current to monitor fan activity in the case of semi-gasifier stoves.

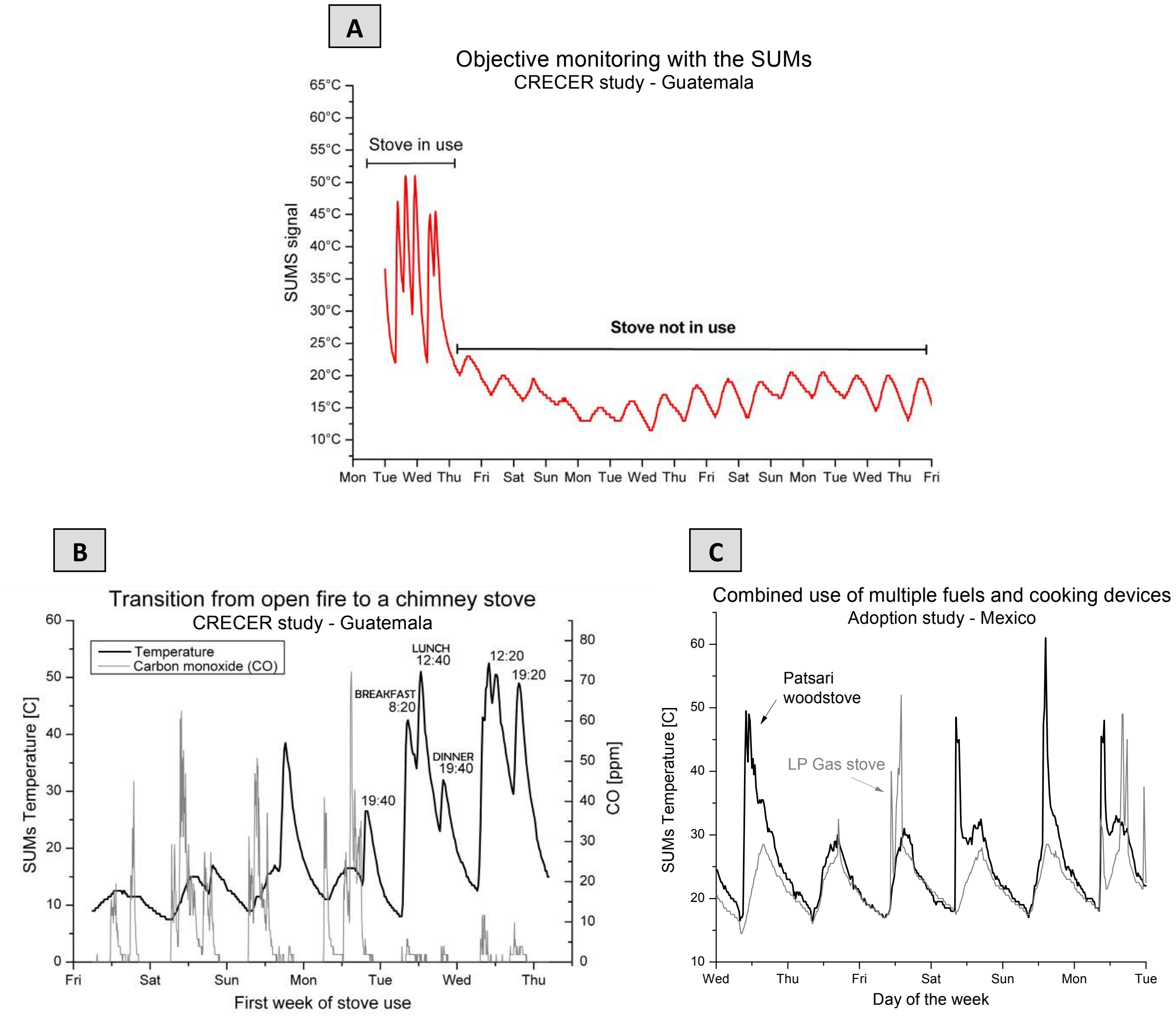

Figure 2.8 Measuring stove use with the SUMs. (A) Validation of stove use (up): Stove use monitors (SUMs) data provides unique evidence of how this newly introduced chimney stove was only used during the first 2 days of monitoring as differentiated by the distinct stove and ambient temperature signals. (B) Dynamics of the learning stage (down left): The adoption process of a new chimney stove as seen by the SUMs daily patterns in thick line (left-axis) and kitchen carbon monoxide (CO) concentrations (right-axis). On Sunday and Monday the family gradually began using their stove as shown by the increased peaks of temperature compared to Friday, but still there was significant CO presumably form their traditional stove. By Wednesday, they seem to only use the chimney stove, which resulted in much lower CO levels in the kitchen during cooking (figure from Ruiz-Mercado et al., 2008 (Ruiz-Mercado et al. 2008)). (C) Simultaneous use of multiple fuels and devices (down right): SUMs measurements in all devices present in the household document how a Patsari woodstove (thick line) and a LP gas stove (thin line) are used in combination on Monday and alternated on Friday and Saturday, as each device is used for different cooking tasks.

2.5 Conclusions

The adoption process of improved cookstoves is complex and relatively few efforts have directly addressed it. We documented how the dynamic interactions of the user with the new and existing fuels and stoves leads to the stacking of fuel-devices and the redistribution of cooking tasks rather than to immediate complete substitution. Identification of the main cooking tasks performed with each stove-fuel combination is important to optimize the adoption process of improved cookstoves and to correctly weigh their impacts. These phenomena highlight the need for considering adoption and sustained use, together with the rest of the technical requirements, as critical parameters that can affect the performance of the improved stoves. Systematic, cost-effective, objective and scalable monitoring of use is now possible with the new generation of sensor-based and IT-based stove use monitors.

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Chapter 3

Quantifying adoption and sustained use with Stove Use Monitors (SUMs)

3 Quantifying adoption and sustained use with Stove Use Monitors (SUMs)

Summary

Objective monitoring of use of improved cookstoves, which is essential to verify the sustainability of their benefits, requires affordable and scalable instruments as well as validated metrics of adoption and usage. We introduce the concept of Stove Use Monitors (SUMs) and present a 32-month study using temperature dataloggers as SUMs for the chimney stoves of 82 households in rural Guatemala. We recorded a total of 31,112 stoves-days and observed a 10% data loss rate. We implemented a peak selection algorithm based on the instantaneous derivative and the statistical long-term behavior of the temperature signals to count cooking events and determine daily use. At this study site, a single temperature threshold from the annual distribution of daily ambient temperatures was sufficient to accurately identify days of stove use with 0.97 sensitivity and 0.95 specificity compared to the peak selection algorithm. Using robust Poisson regression models we found the stove age and household size at baseline not to affect use significantly. Usage was highest during the warm-dry season with 92% stove-days (the fraction of days in use from all stoves and days monitored) (95% CI: 87%, 97%) and 2.56 daily meals (95% CI: 2.40, 2.74). With respect to this value, the percent stove-days decreased by 3% ($p<=0.013$) and 4% ($p<0.013$) during the warm-rainy and cold-dry periods respectively, and the daily meals by 5% ($p<0.0001$) and 12% ($p<0.0001$) respectively. Qualitative indicators of use from recall questionnaires were consistent with the SUMs measurements of the 15-day and 3-month periods preceding the questionnaires and there was no significant difference between recall periods, indicating stable sustained use and questionnaire accuracy. These results reflect optimum conditions for sustained stove use in this project, which may not occur in disseminations undertaken elsewhere. Integrating questionnaires and SUMs data we documented the combined use of traditional and improved cooking devices, which highlights the need to monitor the use of traditional open cookfires to assess the impacts of stove implementations. An intraclass correlation coefficient of 76% from a mixed effects model without covariates confirmed that within households daily use behavior is very stable and that the main sources of variance are between homes.

3.1 Introduction

The implementation of stoves that effectively vent smoke to the outside and/or have verified improved combustion efficiencies together with the significant reduction of open cookfire practices are potentially among the most cost-effective energy interventions to simultaneously reduce the health burden of household air pollution, achieve significant reductions in greenhouse gas emissions and meet goals of reduced poverty, social welfare and increased environmental sustainability. As discussed in the previous chapter, this is true, however, only if usage levels and stove performances are maintained through time. Therefore, measuring the levels of use during the initial adoption and sustained use or disadoption of the stoves is as important as monitoring other technical specifications of the cooking devices to ensure the sustainability of the benefits from stove programs.

This chapter presents the field data collection and analysis methods to obtain measures of daily use and meal frequency from stove temperature signals. We analyze the longitudinal patterns of stove use in a group of 82 Guatemalan households participating in a chimney-stove epidemiological study. The data were collected over 32 months (16 monitoring periods in alternating months from 2008-2010) using Thermochron iButton temperature dataloggers as Stove Use Monitors (SUMs). We begin by outlining the protocols for placement, sampling frequency, reference measurements, data collection and data management. We define key quantitative metrics of use for the case of a single stove being used in the household. We then apply the metrics to the SUMs measures and implement two statistical models: the first one to account for the correlation between repeated measures on a subject and to obtain robust estimates of the long-term population-averaged means of the metrics , the effect of some baseline covariates on usage and the level of seasonal variability. With the second model we estimate the intra-household and between-household variances. The parameters from both models are used to perform sample size calculations. The results illustrate that the SUMs can provide detailed individual data and statistically reliable population-level data with smaller sample sizes and improved temporal resolution than the traditional survey methods. We compare the SUMs measures with qualitative indicators of stove use from recall questionnaires and discuss the usefulness of each method and metric to characterize the different aspects of the adoption process. We end the chapter examining the adoption dynamics observed in this stove dissemination performed under optimal conditions to guide the selection of parameters to quantify sustained use and set realistic goals of adoption performance in other implementations.

Through this chapter we reserve the term “adoption” to denote the adoption process, which we previously described in terms of the initial adoption, sustained use and disadoption stages and five characteristic parameters (level of initial acceptance, length of the learning period, level of initial use, level of sustained use, and seasonal variability). All the material in this chapter has been submitted for publication to the Biomass and Bioenergy Journal with coauthors Eduardo Canuz, Joan L. Walker and Kirk R. Smith and is undergoing review (Ruiz-Mercado et al. Under review; Ruiz-Mercado et al. Under review).

3.2 Methods

3.2.1 Study site

The study area encompasses 4 municipalities in the State of San Marcos in the western highlands of Guatemala. The region has temperate climate and mostly rural population. Local experience divides the year into three seasons and previous studies (Bigham 2007) have defined them as: dry-cold (Nov 15 – Feb 2), dry-warm (Feb 15 – Apr 30), and rainy-warm (May 1 – Nov 14). Figure 3.1 shows the daily mean, maximum and minimum temperature and rainfall trends recorded during the 2008-2010 study period with the weather station (CR800, Campbell Scientific Inc.) located at the study headquarters (Latitude: 14.6 N, Longitude: 90.8 W, Altitude: 2686m).

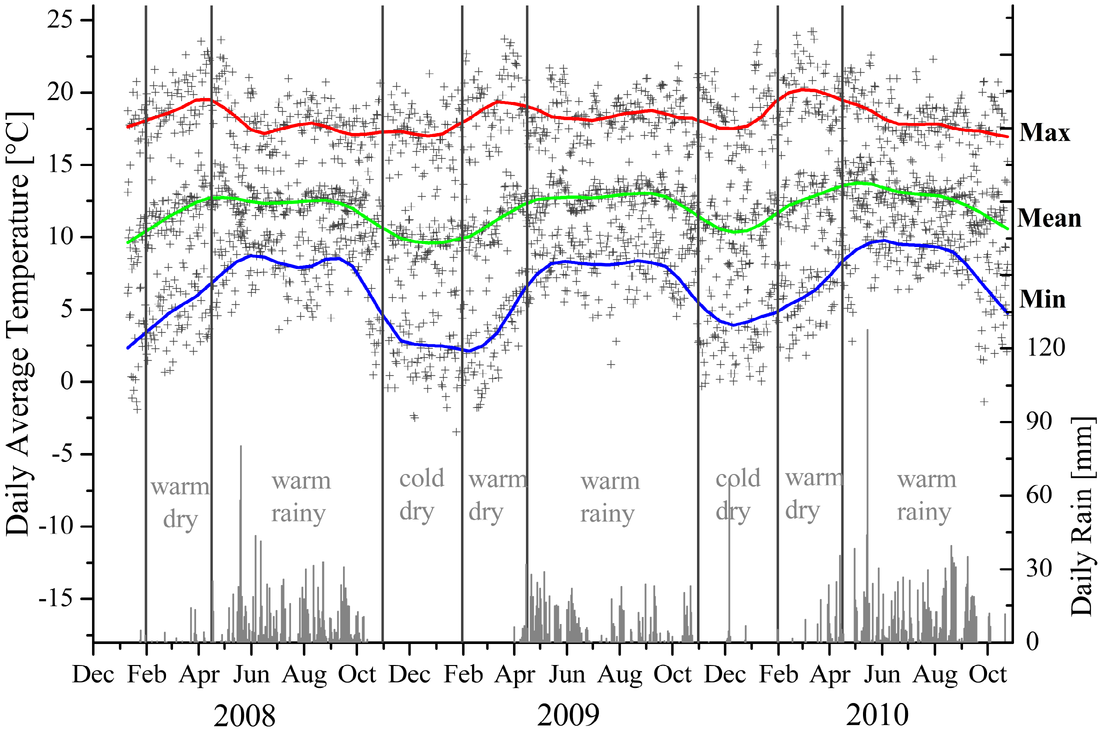

Figure 3.1 Daily mean, minimum, maximum temperatures and rainfall data at the study site in San Lorenzo Guatemala (Latitude: 14.6 N, Longitude: 90.8 W, Altitude: 2686m) during the 2.6 years of the SUMs study. Every year is divided into the three locally accepted seasons.

3.2.2 Study sample

The sample population consisted of a convenience sample of 82 households from 10 communities enrolled in the CRECER epidemiological study (Smith et al. 2010; Smith 2011). Two stove-age groups are present in the sample: one of newer users (65%) who had the stove built in their homes in January 2008, and a second of older users (35%) whose stove was built between November 2002 and December 2004. One-hundred percent of the SUMs-sampled households consider themselves indigenous, i.e., of Native Mayan heritage and used indoor open wood-fired cookfires before the study began. The sample characteristics for each group are displayed in Table 3.1. The size of the households at baseline (March 2006) and end (April 2010) of the CRECER study did not change significantly.

	Both groups	Group 1 newer users	Group 2 older users
Sampled Population			
Households monitored	82 (100%)	53 (65%)	29 (35%)
Mean stove age in years	5.5 (2.1)	3.9 (0.0)	8.2 (0.8)
Mean household size at baseline[a]	7.8 (2.6)	7.6 (2.6)	8.2 (2.7)
Mean household size at exit[b]	8.0 (2.7)	7.5 (2.5)	8.5 (2.3)

Table 3.1 Some baseline characteristics of the households monitored with the SUMs. Data are mean (S.D.) or number (percent).
[a] March 2006.
[b] April 2010.

3.2.2.1 Household characteristics

The characteristics of the SUMS-sampled households were collected as part of the CRECER research protocols at baseline and at the end of the study.
Table 3.2 summarizes for each group the socioeconomic indicators of the households and their characteristics regarding house structure, patters of fuel collection, cooking needs and patterns of stove and fire use. The full version of the questionnaire materials and study protocols can be found elsewhere (Smith 2011).

	Both groups n = 82	Group 1 newer users n = 53	Group 2 older users N = 29
Household Characteristics			
Socioeconomic Indicators			
Homeowners	67 (81%)	41 (77%)	26 (90%)
Landowners	68 (83%)	42 (79%)	26 (90%)
Main income as *jornalero*[a]	53 (65%)	36 (68%)	17 (59%)
Receives remittances from U.S.	7 (9%)	3 (6%)	4 (15%)
TV ownership	24 (30%)	14 (26%)	10 (34%)
Cellular phone ownership	25 (30%)	16 (30%)	9 (31%)
Electricity in main house	54 (66%)	31 (58%)	23 (79%)
Mother completed elementary school	56 (68%)	38 (72%)	18 (62%)
House Structure			
Aluminum roof	59 (72%)	39 (74%)	20 (67%)
Adobe walls	72 (88%)	44 (83%)	28 (97%)
Dirt floor in main house	73 (89%)	47 (89%)	26 (90%)
Number of rooms in house	1.3 (0.6)	1.2 (0.6)	1.3 (0.6)
Fuel patterns			
Wood exclusively collected	14 (17%)	5 (1%)	9 (31%)
Collection time per month in hours	8.0 (3.7)	9.6 (4.3)	7.1 (3.2)
Wood exclusively purchased	23 (28%)	14 (26%)	9 (31%)
Cost per month in Quetzales[b]	185 (104)	198 (120)	164 (76)
Wood collected and purchased	45 (55%)	34 (64%)	11 (38%)
Collection time per month in hours	6.2 (3.9)	6.8 (4.0)	4.2 (3.1)
Cost per month in Quetzales	117 (70)	114 (75)	126 (55)
Wood & crop residues used for cooking[c]	42 (51%)	28 (53%)	14 (48%)
Wood and charcoal used for cooking	1 (1%)	1 (2%)	0
Wood and gas (LPG) for cooking[d]	0	0	0
Cooking and Woodfire Practices			
Age in years mother started cooking	12.1 (2.2)	12.2 (2.0)	12.1 (2.5)
Hours spent cooking every day	3.6 (1.2)	3.7 (1.2)	3.3 (1.2)
Open cookfire is in elevated platform	21 (26%)	20 (38%)	1 (3%)
Uses woodfired *chuj*[e]	82 (100%)	53 (65%)	29 (35%)
Chuj use frequency, days per week	1.7 (0.5)	1.7 (0.5)	1.7 (0.6)

Table 3.2 Household characteristics of the SUMs-sampled households. There were no statistically significant differences between groups.

[a] Working someone else's land; [b] Currency of Guatemala. At the time of writing 1 USD = 7.8 Guatemalan Quetzal (GTQ); [c] Includes households that exclusively use wood for cooking and those combining wood with crop residues (corn stalks, lima beans, cabbage scraps, corn cobs); [d] At the end of the study only one household combined fuelwood and LPG for cooking; [e] Traditional steam bath. In the San Marcos region the *chuj* consists of a small unvented adobe structure about five cubic meters in volume where a woodfire is built to heat rocks that produce steam when water is poured over them.

3.2.3 Chimney-stove and cookfire configurations

The chimney stoves (Figure 3.2(D) in the next section) have a brick, mud and cement body, and were built with standardized dimensions by the same local manufacturer using the "Plancha" stove design (Boy et al. 2000; Granderson et al. 2009; Ruiz-Mercado et al. Under review). Although locally known by this name, not being centrally manufactured, design and construction details may be different in other regions. The stoves built have a brick, mud and cement body with firebricks in the combustion chamber (Boy et al. 2000; Granderson et al. 2009), wood is fed through a front door and inclined planes in the chamber direct hot gases to the pots and then to a flue with damper for venting outside the kitchen. The cooking surface is a removable steel plate (*plancha*) with 3 pot-holes, with decreasing diameters from front to back. Concentric rings accommodate different pot sizes that are placed directly over the fire. The surface around the steel plate is tiled, providing a working space for kitchen tasks. All stoves in both groups were built by the same local manufacturer with standardized materials and dimensions and all materials and stoves built were checked for quality control by research project staff. The stoves of the new users were built over a 1-month period, and all of the households in this group were asked to begin using the stoves on a specific date, after the last stove built had cured (about 30 days after construction). The households were visited and reminded that they begin use on the proposed date. Shortly after the scheduled start, the study personnel organized workshops in every community (for newer and older users) where local fieldworkers demonstrated how to light the stove, cooked local dishes and reviewed use and maintenance practices.

The indoor cookfires consisted of a few rocks (usually 2-3) arranged to lift the pots above the open cookfire (Figure 3.2(A)). The rocks were usually placed on the ground and in some households a knee-height platform is built to rise the fire from the ground.

3.2.4 Stove Use Monitors (SUMs)

3.2.4.1 Temperature datalogger characteristics

We used the Thermochron iButtons 1921G (Maxim Integrated Products, Sunnyvale, CA) as SUMs. The Thermochron iButtons enclose a silicon temperature sensor, an eeprom memory, a clock/calendar, signal processing circuitry and a battery in a stainless steel can that is water resistant, tamper proof and about the size of a coin cell battery (1.6 cm in diameter) (Figure 3.2(B)). Depending on the operating conditions the sensor battery can last for a number of years, after which the whole unit must be replaced. They have been widely used to track skin and core body temperature in humans (Areas et al. 2006; Lichtenbelt et al. 2006; van Marken Lichtenbelt et al. 2006; Rutkove et al. 2007; Sarabia et al. 2008; Rutrove et al. 2009; Nardin et al. 2010; Smith et al. 2010; Zornoza-Moreno et al. 2011) and animals (Davidson et al. 2003; Robert and Thompson 2003; Lea et al. 2008; Lovegrove and Genin 2008; Lima and Wethey 2009; Lovegrove 2009; Willis et al. 2009; Coleman and Downs 2010; Hilmer et al. 2010; El Ouezzani et al. 2011; Glander et al.

2011), for monitoring bird nest activity (Hartman and Oring 2006; Schneider and McWilllams 2007; Moore et al. 2010), animal foraging patterns (Kanda et al. 2005), thermogenesis patterns in plants (Suinyuy et al. 2010), meat conditions during transportation (Dadgar et al. 2010; Liu et al. 2010), compliance with oral devices (Inoko et al. 2009), permafrost monitoring (Ramos et al. 2009), and for hydrology studies (Hubbart et al. 2005; Johnson et al. 2005; Abis and Mara 2006; Massuel et al. 2009).

Communication with the sensors to program them or download data is by momentary contact with a special probe using the 1-wire protocol (at 15.4 or 125 kbps) and can be easily done in the field with a PDA, smartphone or laptop computer. We used 1921G model, which costs about $20 at the time of writing, operates between -40 °C and 85 °C and can record up to 2048 temperature and date-time readings with ±1 °C accuracy. Tutorials on the use of these sensors can be found elsewhere (Hubbart et al. 2005). There are other devices available commercially that have similar capabilities.

3.2.4.2 SUMs placement and sampling frequency

We used two locally made holders for the SUMs: perforated metal sheets to attach the sensors to the stove body (Figure 3.2(B)) and metal brackets nailed into the dirt floor and facing the center of the open cookfire (Figure 3.2(C)). In the chimney stoves, the SUMs were attached to the back surface at the chimney base to capture conducted heat and were set to record every 20 minutes. The brackets were nailed 20-30 cm away from the open cookfire (Figure 3.2(A)) and the SUMs set at a 10-minute sampling rate to capture thermal radiation.

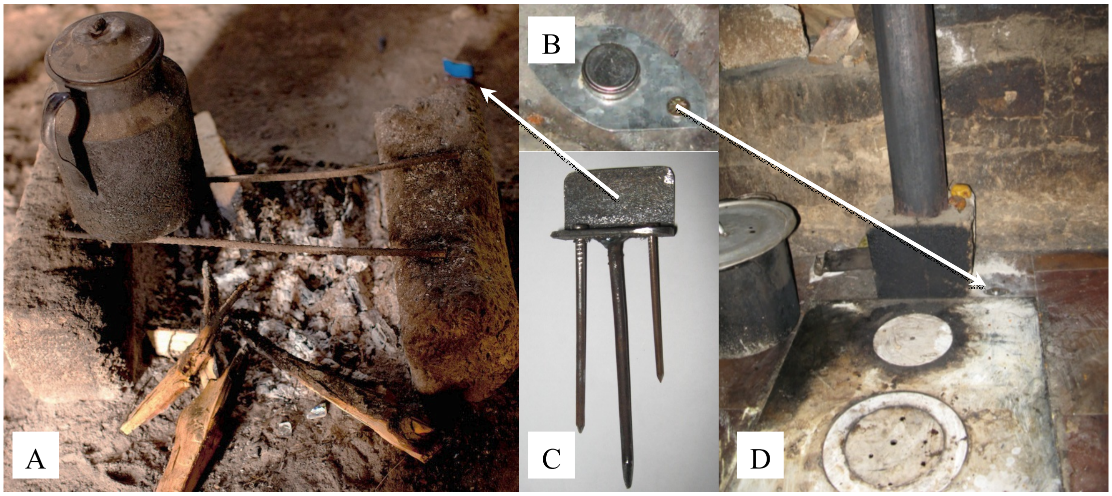

Figure 3.2 To record stove activity in the chimney stoves (D) we attached the Stove Use Monitors (SUMs) to the stove body with metal sheet holders (B). To monitor the open cookfires we attached the SUMs to metal brackets (C) nailed into the dirt floor facing the center of the fire and 20-30 cm away from it (A).

These settings were determined with a two-stage protocol to first ensure the iButtons operated below 85 °C and to then determine the sampling rate and location that would provide enough data resolution to track usage at the meal level without interfering with the householder's activities.

In the first stage of the protocol we used temperature-indicator labels at multiple points in the surface of the stoves and at different distances from the center of the open cookfires. With the labels we monitored the temperature dynamics during the maximum fuel feeding intensity that could be accomplished by a household cook or local fieldworker. The labels are made of liquid crystal or other temperature sensitive materials that reversibly (RLC-50, Omega) or irreversibly (and TL-S, Omega) change color at specific temperature thresholds. High-temperature thermocouples or other temperature indicators like crayons and lacquers can also be used at this stage. Those label locations in the stove and fire that did not exceed the monitor manufacturer's limit of 85 °C were selected for the next stage. In the second stage we recorded temperature in the selected stove locations during regular cooking cycles in actual homes during 1-2 days. We sampled at 30-second resolution with a multi-channel thermocouple datalogger (TC-8, Picco Technologies) to determine the appropriate sampling frequency and we also measured with the iButtons and the labels.

The final selection of stove and fire locations consisted of those where the first derivatives of their temperature signals provided distinct identification of the stove/fire cooking episodes. The choice of sampling frequency is a tradeoff between: (1) the temporal resolution required to measure stove use at the desired level of detail (day, meal, cooking task) given the thermal inertia at the stove location and the nature of the cooking cycles; and, (2) the frequency of visits that can be afforded given the maximum storage capacity of the devices. For example, to capture the details or duration of the cooking cycles in a portable stove used for cooking small food volumes, a faster sampling than the one used for the high-mass chimney stove in this project might be needed. Another consideration for placement and sampling frequency is that the batteries of most temperature dataloggers exhibit longer lifetimes at lower sampling frequencies and lower operating temperatures. Figure 3.3 depicts an example of the temperature signals recorded from the chimney stoves and open cookfires.

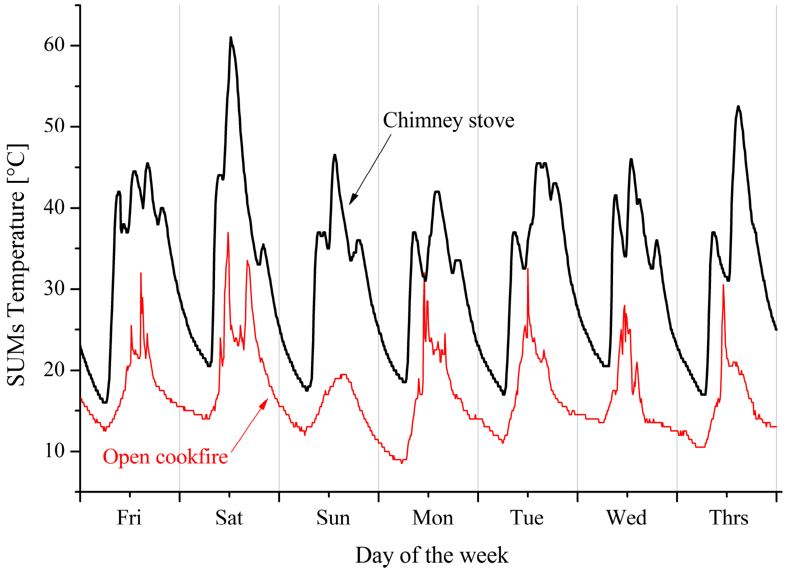

Figure 3.3 Temperature signals recorded with the dataloggers used as Stove Use Monitors (SUMs in the surface of a chimney stove (20-min sampling rate, thick line) and nearby an open cookfire (10-min sampling rate, thin line). The chimney stove traces illustrate the peaks due to the main cooking events through the day. On Sunday, the open cookfire is not lit and the ambient temperature fluctuation is registered.

3.2.4.3 Data collection and management

Data downloading and programming of the sensors were done in the field with Palm IIIc and Palm m105 PDAs (Palm Inc., Sunnyvale, CA) and data transferred to a PC in a comma-separated format using the ThermoChron System software and probes (Scanning Devices Inc., Lexington, MA). The SUMs were programmed to start in a delayed mode and collected after the sampling period ended. Figure 3.4 shows a PDA downloading data from a SUM installed in a stove.

Figure 3.4 Small temperature dataloggers were used as Stove Use Monitors (SUMs). The SUMs, attached to the chimney-stove body, were programmed bi-monthly in the field and the data were downloaded using PDAs.

For quality assurance and data management a field form was filled out for each sensor at each household visit. Field forms and stove use questionnaires were double-entered and a clean database was generated with SAS/STAT version 9 (SAS Institute Inc., Cary, NC) to ensure matching of the household, sensor and file names. The field forms are included in the appendix.

3.2.4.4 Reference measurements

At the end of each monitoring year we brought all monitors to the project headquarters and performed water bath comparative measurements to detect those with anomalous readings. We performed 3 annual reference measurements of all the devices deployed: one in the field (data not shown) and two in the lab. For the lab measurements, the monitors were placed together with a new iButton in a re-sealable plastic bag inside a small container with water at 70-75 °C. The setup was allowed to reach thermal equilibrium with the surroundings at about 25 °C, as measured with a reference mercury thermometer. The sampling frequency was set to 1 minute during the comparative procedures.

The manufacturer reports no known physical mechanism for the monitors to go out of calibration (Maxim Integrated Products) and separate assessments of their performance (Hubbart et al. 2005) have found their accuracy to be within manufacturer's specifications. Nevertheless, we retired some iButtons that significantly drifted down from the reference in the water bath. Figure 3.5(B) (lower graph) summarizes one of the comparative experiments and illustrates the behavior of the anomalous monitors, which is not apparent during the baseline period. Rather than a drift in calibration, these two monitors stopped recording temperature for 20-30 minutes. The Thermochron iButton model that we used does not record the absolute time of the samples taken. The samples are sequentially saved in a memory location and the sample time is derived from the start time, sample rate and sample number. Thus, after the "sleeping" period of the anomalous monitors they resumed recording and the first reading was stored in the next available memory location, which was assigned the time stamp that followed the last temperature recorded. The temperature decay experienced by the monitors at time 10:20 in Figure 3.5(A) (upper graph) was registered at an earlier time (9:50 and 10:00) by these two monitors. When the anomalous monitors are excluded from the analysis, the deviations (with respect to the reference iButton) in the temperature and rate of change of the group were within the range of variability expected from the experimental setup.

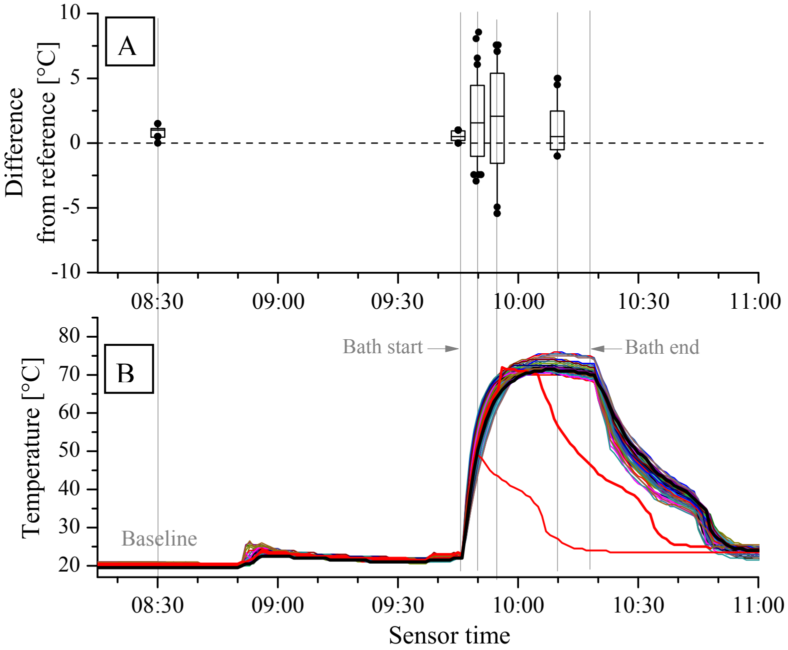

Figure 3.5 Annual comparative temperature measurement performed in all deployed monitors. The temperature dataloggers were placed for 30 minutes in a water bath. The lines in the lower graph (B) depict the temperature traces of the group of 82 monitors. The two anomalous monitors that drifted down from the reference are seen with temperature traces that decay earlier than the group. The two sensors were retired. The upper boxplots (A) show the absolute temperature deviation of the group without the anomalous monitors from the reference monitor measured at the times signaled with the vertical lines. In the boxplots the centerlines are median, the boxes enclose one standard deviation and the back dots are outliers (values outside the 5th and 95th percentiles).

3.2.4.5 *Algorithm for analysis of stove temperature measurements*

We implemented an algorithm to determine daily use and quantify the frequency of stove activity through the day based on the instantaneous derivative and long-term behavior of the stove and ambient temperature signals. The flow diagram of the algorithm is shown in Figure 3.6. This dissertation focuses on the analysis of the chimney-stove data (the results of the open-cookfire signals are presented elsewhere). Only 30,122 stove-days were used to feed the algorithm. The data from the first monitoring period when households were learning to use the stoves were excluded.

First, we detected the signal peaks using the data analysis and graphing software Origin 8.1 (OriginLab, Northampton, MA), and the rest of the analysis was done using SAS/STAT version 9. Positive peaks were filtered from those due to the diurnal indoor kitchen temperatures, noise or outside heating events using threshold slope values (S_0+ and S_0-) on the onset and decay of the peaks. The threshold slopes (dashed box in Figure 3.6) were obtained a posteriori, from the days that the sampled homes did not use the stove according to an initial threshold temperature (T_0). The instantaneous derivatives of these reference non-use days were obtained and the 1st and 99th percentiles of the derivatives distribution were selected as S_{0-} and S_{0+} respectively.

Positive peaks were defined as "fueling events" only if the positive slopes of the onset and the negative slopes of the decay exceeded S_{0+} and S_{0-} respectively. We defined the fueling events as the minimum unit of stove use and adjacent events found within a fixed-time window were then clustered in a single "cooking event". The time length of the clustering window was determined from the average duration of meals obtained from the recall questionnaires and from the temporal distribution of all the stove events registered in all days and households. We consider these cooking events to be reasonable approximations of a "meal" in this particular stove and population. Lastly, the temperature distribution of the days with zero fuel events was studied to determine the best final threshold temperature values (T_f) for the "binary indicator of daily use" (δ).

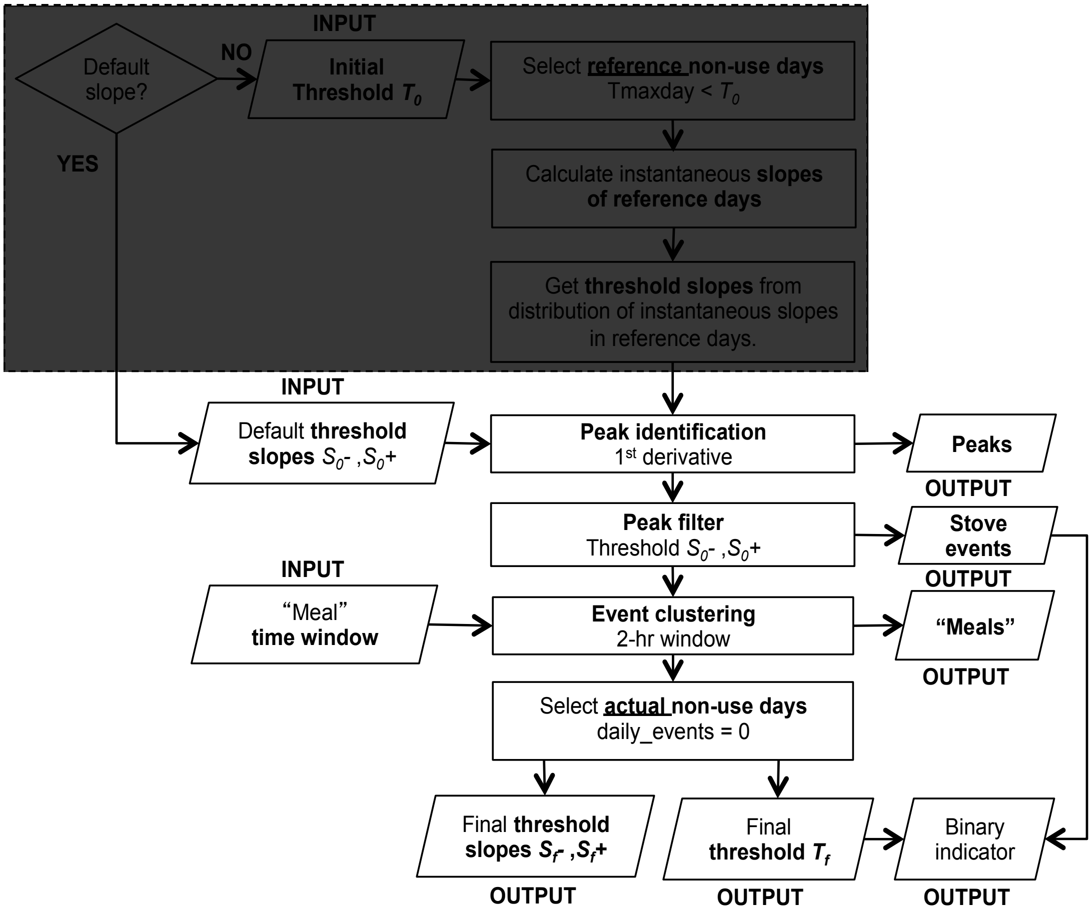

Figure 3.6 Flow diagram of the stove temperature signals analysis.

3.2.5 Other measures of stove activity

3.2.5.1 Recall questionnaires of stove and cookfire activity

Quarterly questionnaires about stove and fire use were performed in both groups after the construction of their chimney stoves as part of the CRECER research protocols (Smith 2011). The recall questions were answered by the main cook and included: frequency of chimney stove and open-cookfire use, the amount of time spent preparing each meal and the number of hours the fire is lit at each meal time. The responses to the questions about frequency of stove and fire use were matched with their SUMs-measured usage from the periods of the 15 days preceding the questionnaire. The distribution of hours of stove activity was used to define the average duration of a meal in the population. All the questionnaires can be found in the RESPIRE-CRECER websites (Smith 2011; Smith 2011).

Table 3.3 summarizes the distribution of the data collected with the SUMs and the recall questionnaires in the 82 homes during the period of SUMs monitoring. The first monitoring period (from January-February 2008) followed an initial sample of 50 homes (30 newer users and 20 older users) during the stage of initial adoption, after construction of the stoves of the new users. Thirty two more homes (20 newer users and 10 older users) were added to the sample in February 2008 and the subsequent 15 monitoring periods followed the sustained use of the chimney stoves in the resulting total of 82 households.

	Both groups	Group 1 newer users	Group 2 older users
Data Collection			
1. Initial Adoption – SUMs Measurements (1 period)			
Stoves[a] monitored (percent)	50 (100%)	30 (60%)	20 (40%)
2. Sustained Use – SUMs Measurements (15 periods)			
Stoves monitored (percent)	82 (100%)	53	29
Stoves per period (S.D.)	72.4 (2.7)	45.9 (2.3)	26.5 (2.8)
Mean monitoring periods per stove (range)		13.7 (1-15)	12.9 (10-15)
Total stoves and days measured	30,122	19,058	11,064
3. Sustained Use – Recall Questionnaires (15 periods)			
Questionnaires with SUMs[b] during 15-day recall	192	131	61
Questionnaires with SUMs during 3-month recall	168	109	59

Table 3.3 Stove use measurements collected with Stove Use Monitors (SUMs) during initial adoption (1) and sustained use (2), and with recall questionnaires during sustained use (3).
[a]At each house only one chimney stove was monitored.
[b]The recall questionnaires were matched with SUMs measures of the 3-month and 15-day periods that preceded the questionnaire date.

3.2.5.2 *Indoor kitchen carbon monoxide concentrations*

Minute-by-minute CO concentrations were recorded with the Hobo Electrochemical Carbon Monoxide Logger (Onset Corp., Cape Cod, MA) in 11 households (4 newer users and 7 older users) during the period of initial use of the group of newer users. The electrochemical sensors were calibrated against CO span gas before deployment, and were placed in the study kitchen walls following the standardized protocols described elsewhere (Northcross et al. 2010; Smith et al. 2010).

3.2.6 Metrics of stove use

In this section we formulate individual and population level metrics to quantify stove usage. We focus here in the case of only one chimney stove being measured at every household and therefore we indexed the stoves rather than homes to allow later inclusion of multiple cooking devices per household.

Let δ_{ti} be the binary indicator of daily use for the i-th stove on day t (equal to 1 if the stove is used that day, zero if not) and T_i the total number of days that the stove was monitored. Let m_{ti} be the number of meals that the stove was used.

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

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

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

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

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

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

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

Similarly, for a single day, we quantified the number of stoves used (or the percent out of all I stoves) and the number of meals on a day (or the average daily meals across I stoves).

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

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

$$\mathit{stove\text{-}days} = \sum_{t,i} \delta_{t,i} = \sum_i X_i = U \tag{5}$$

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

$$\%\ \mathit{stove\text{-}days} = \frac{\sum_{t,i} \delta_{t,i}}{\sum_i T_i} = \frac{\sum_i X_i}{\sum_i T_i} = \frac{U}{T} \tag{6}$$

For example, 3 out of 10 monitored stoves used each during the 10 days of the monitoring period yield the same stove-days (30) than 1 out of 10 monitored stoves used during a period of 30 days. However the first case accounts for 30% stove-days and the second one for 10% stove-days.

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

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

$$average\ daily\ meals = \frac{\sum_{t,i} m_{t,i}}{\sum_i T_i} = \frac{\sum_i Y_i}{\sum_i T_i} = \frac{M}{T} \tag{7}$$

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

$$meals\ per\ stove - day = \frac{\sum_{t,i} m_{t,i}}{\sum_{t,i} \delta_{t,i}} = \frac{\sum_i Y_i}{\sum_i X_i} = \frac{M}{U} \tag{8}$$

Other potential group-level metrics are discussed in section 3.4.2.

3.2.7 Statistical models

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

To estimate the population-averaged percent stove-days and daily meals and assess the effects of stove age difference, household size at baseline and season we used Poison regression models (Diggle et al. 1994; Rabe-Hesketh 2005) implemented in STATA (Stata-Corp LP, College Station, Texas). Robust standard errors were estimated to account for the correlation between repeated measures on each stove and Poisson distributions for the counts of stove-days and meals were assumed. In the multivariate analyses only the effect of season was significant. The final models had the form:

$$\ln(\mu_{use}) = ln\left(E\left(X_{ij}|W_{ij}\right)\right) = \beta_1 + \beta_2(cold)_j + \beta_3(rainy)_j + \beta_4(stoveage)_i + \beta_5(hhsize)_i \tag{9}$$

$$\ln(\mu_{meal}) = ln\left(E\left(Y_{ij}|W_{ij}\right)\right) = \gamma_1 + \gamma_2(cold)_j + \gamma_3(rainy)_j + \gamma_4(stoveage)_i + \gamma_5(hhsize)_i \tag{10}$$

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

To assess the stability of daily usage within households and the level of homogeneity in stove activity between homes we apportioned the between and within household variances (σ_b^2 and σ_w^2) using linear mixed models (Diggle et al. 1994) in the data without covariates. We used the variance stabilizing (assuming Poisson distribution) square root transformation of the actual counts. The models, implemented in STATA, had the form:

$$E\left(sqrt\left(X_{ij}\right)\right) = \beta_0 + (\alpha\_use)_i + (e\_use)_{ij} \tag{11}$$

$$E\left(sqrt\left(Y_{ij}\right)\right) = \beta_0 + (\alpha\_meal)_i + (e\_meal)_{ij} \tag{12}$$

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

We used the intraclass correlations from the models $\rho = \sigma_b^2 / (\sigma_b^2 + \sigma_w^2)$ and the standard deviation of the observed means at each monitoring period to obtain in STATA sample size estimations from one-sample comparisons of means to hypothesized values for set levels of significance and power. The predicted random effects estimates for each household (considered the best linear unbiased predictors) are the stove use values assigned to each home in chapter 4.

3.3 Results

3.3.1 Analysis of chimney stove temperature measurements

The temperature of the stoves that are not in use is expected to closely follow the indoor kitchen temperature, which in turn will be a function of the interaction of ambient temperature with the kitchen structural characteristics and the potential presence of another stove or cookfire (the only heating sources used in the region). This is illustrated in Figure 3.7. The figure shows the bimodal distributions of daily maximum (red histogram, Figure 3.7(A)) and of daily mean (red histogram, Figure 3.7(B)) stove temperatures of the 30,122 stove-days analyzed. In both graphs, the first mode defines the surface temperature values when the stoves are not in use. In Figure 3.7(A) this mode overlaps with the distribution of the daily maximum ambient temperatures observed during the same sampled days (blue). The ambient temperatures were recorded with the project weather station located at the research site (CR800, Campbell Scientific Inc., Logan, UT). The second mode defines the range of temperatures when the stoves are being used. Its dispersion reflects the variability between households and within days in the temperature used for cooking, as well as the ambient temperature differences by day and by location. The daily minimum and range of stove temperatures have similar bimodal distributions (data not shown).

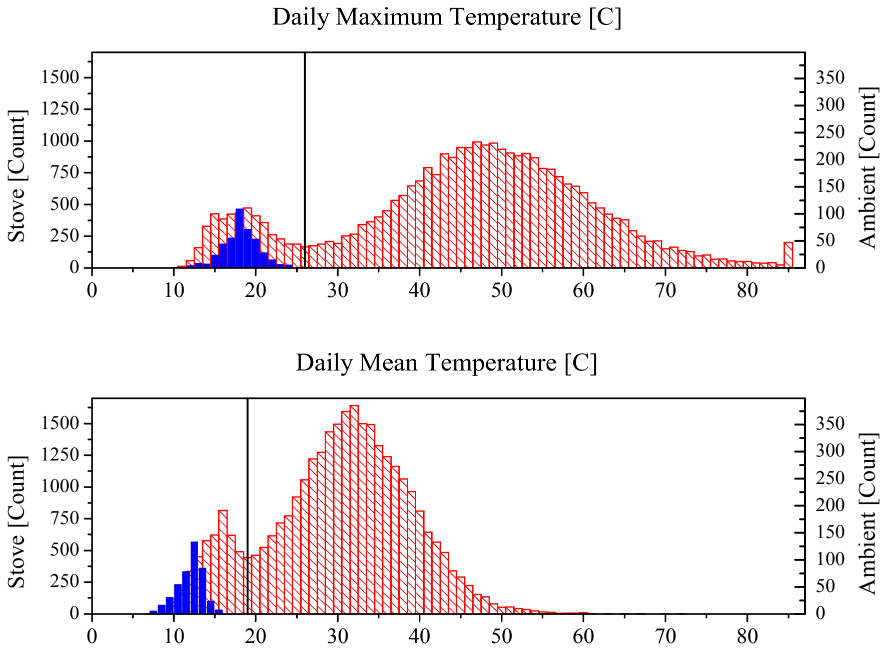

Figure 3.7 Count distribution of stove temperatures (red) and ambient temperatures (blue) for all monitored days and households. The daily maximum distributions are shown in the upper graph (A) and the lower graph (B) shows the daily average temperatures (30,122 stove-days monitored). The vertical lines are minimum temperature values in the range between modes, which are the cutoffs used as initial thresholds.

The minimum value between modes (T_0=26 °C from the maximum temperatures and T_0=19 °C from the daily averages) were used as the initial cutoffs. The days with daily maximum and daily average stove temperature equal or smaller than the cutoffs were selected as reference non-use days. For each of the two sets of reference days we obtained the instantaneous derivatives of their signals (see Table 3.4). These non-use stove derivatives reflect the response of the stove thermal mass to the ambient temperature cycle and to other heating sources in the kitchen. It is possible that they also include some misclassified in-use days from those stoves operated at atypically low temperatures. The 99th and 1st percentiles of the distributions were used as S_0- and S_0+ respectively.

	Reference non-use days (n=4,491)	Reference non-use days (n=4,419)	Ambient temperature (n=62,081)
Selection Criteria	Tmax <= 26C	Tavg <= 19C	All
Quantile	Instantaneous slope [C min-^{1}]		
Max	0.338	0.613	0.304
99%	**0.038**	**0.050**	0.112
95%	0.025	0.025	0.058
90%	0.013	0.013	0.038
75%	0	0	0.012
50%	0	0	-0.003
25%	-0.013	-0.013	-0.016
10%	-0.013	-0.013	-0.033
5%	-0.013	-0.025	-0.046
1%	**-0.038**	**-0.038**	-0.081
Min	-0.163	-0.400	-2.48

Table 3.4 Reference slopes for chimney stove meal count. Distribution of instantaneous slopes of the stove temperatures during the reference non-use days (first two columns) and of the ambient temperature on those same days (third column).

We identified the positive peaks in the signal with the Origin 8.1 peak identification routine. Then, through iterative tests of several individual signals we found that a triggering slope of S_0+=0.038 °C min^{-1} during the 40 minutes previous to the temperature peak and an exit slope of S_0-=-0.038 °C min^{-1} in the following hour after the peak were sufficient to filter out most fueling events in the temperature signal. The number of daily fueling events in the main dataset was counted and days with one or more events were assigned a binary indicator of use δ=1, and a value δ=0 otherwise.

We observed that the feeding or stirring of fuel during cooking could cause consecutive peaks in the signal during the cooking period of a single meal. Therefore, fueling events separated by less than 2 hours were clustered and counted as single cooking events. The clustering window size was based on the average time length for meal preparation and the average time that the stove fire was lit on each meal, both from the quarterly recall questionnaires answered by the monitored households (Table 3.5).

	Time spent daily preparing meal		Time that fire is lit at every meal	
	Hours	95% C.I.	Hours	95% C.I.
Meal				
Breakfast	1.42	(1.34, 1.50)	2.51	(2.38, 2.63)
Lunch	1.38	(1.30,1.45)	2.07	(1.94, 2.19)
Dinner	1.39	(1.27, 1.50)	2.41	(2.28, 2.55)
Nixtamal[a]	0.53[b]	(0.50, 0.57)	1.14	(1.05, 1.23)
Other[c]	--	--	1.36[d]	(0.98, 1.74)

Table 3.5 Daily hours that the stove fire is lit and that the cooks spend cooking at each mealtime, according to recall questionnaires performed in the SUMs monitored households.
[a] *Nixtamal*: maize kernels cooked with an alkaline additive for the preparation of dough to make tortillas. This traditional cooking practice requires boiling the corn in large pots with water and lime, steeping, washing and subsequent grinding of the corn kernels with stones.
[b] Only 50% of the responses to the quarterly questionnaires reported cooking *nixtamal* on the day prior to the household visit.
[c] The questionnaire did not inquire about the time spent daily preparing other meals.
[d] Only 24% of the responses reported another mealtime, equally split between cooking food for animals and cooking an intermediate meal locally called *refacción*.

The clustering window was also determined by the distribution through the day of all the stove events measured with the SUMs, which showed three well-defined peaks centered at the hours of 09:00, 14:00 and 20:00. This clustering of records has been used in similar research problems (Clasen ; Ram et al. 2010) and seems to work well on this stove type and population as discussed below.

Figure 3.8 illustrates the results of the identification of peaks (squares), filtering to select fueling events (vertical lines) and clustering of events into meals (grey rectangles). Using this algorithm we estimated that the fraction of days in use from all stoves and days monitored (the "percent stove-days") in the 15 monitoring periods had a mean value of 89.4% (95% CI: 87.9, 90.9). The population average of the daily meals was 2.44 meals (95% CI: 2.38, 2.49) and the average of daily cooking events 2.98 (95% CI: 2.91, 3.05)[4].

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[4] Observed confidence intervals, not corrected for the correlation between repeated measures.

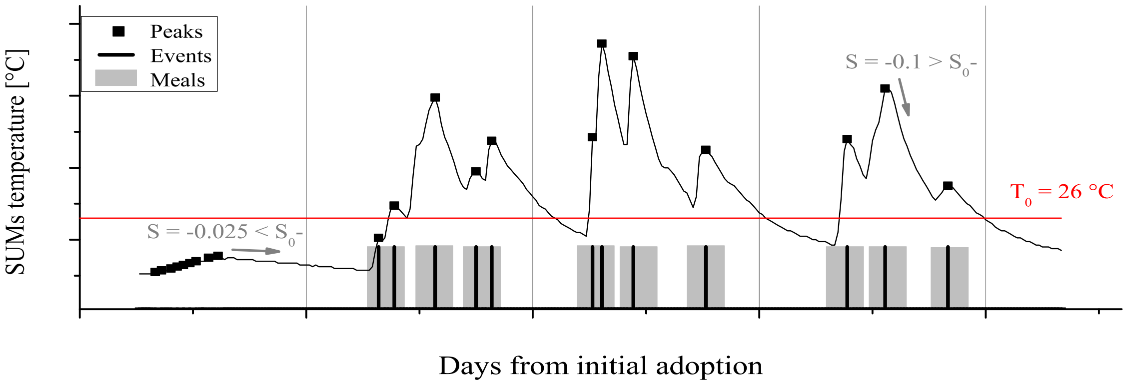

Figure 3.8 Determination of meals from the SUMs temperature signals from a chimney stove. Conditioning on triggering and exit slopes (S_0) the peaks detected are filtered to distinguish stove events (days 12-14) from ambient temperature fluctuations (day 11). Stove events (vertical lines) that are with a 2-hr fixed window are clustered into meals (grey squares). The triggering and exit slopes are obtained from those days when the threshold temperature T_0 was not exceeded, presumably because the stove was not in use.

In our analysis we define “meals” as distinct time-spaced peaks in stove temperature. The precise determination of “meals” from fueling events, however, could be a non-trivial task in other populations since the duration and separation of meals can vary across households and seasons, and the fueling patterns for a given meal course can vary from day to day depending on the food cooked and fuel used. Additional or alternative parameterizations of stove use (and appropriate validations) could be needed for other outcomes of interest like the duration of cooking, the duration of exposure to air pollutants or the amount of fuel consumed.

Going back to Figure 3.7, the coincidence of the right tail of the ambient distribution (blue) with the bi-modal cutoffs suggests that records of past meteorological data for the location of interest could also be used to select T_0 before data collection begins. Indeed, the weather station from the Guatemalan Institute of Meteorology (INSIVUMEH) closest to our study site (50 km south at a similar elevation) reported absolute maximum temperatures around 26 °C during the years of our study (Instituto Nacional de Sismologia).

To assess the accuracy of the count of days in use when a single temperature threshold is applied to all households and season, we compared the days in use that were identified with the peak counting algorithm with those that exceeded the thresholds (regardless of the peak count). The results are presented below in the ROC (receiver operating characteristic) curves (Metz 1978) in Figure 3.9. In the curves, for every temperature threshold parameter (mean, minimum, maximum, range and coefficient of variation) the fraction of “hits” where the single threshold was exceeded and the number of peaks was greater than zero (true positives) are plotted against the fraction of “false alarms” (false positives) for different values of T_0.

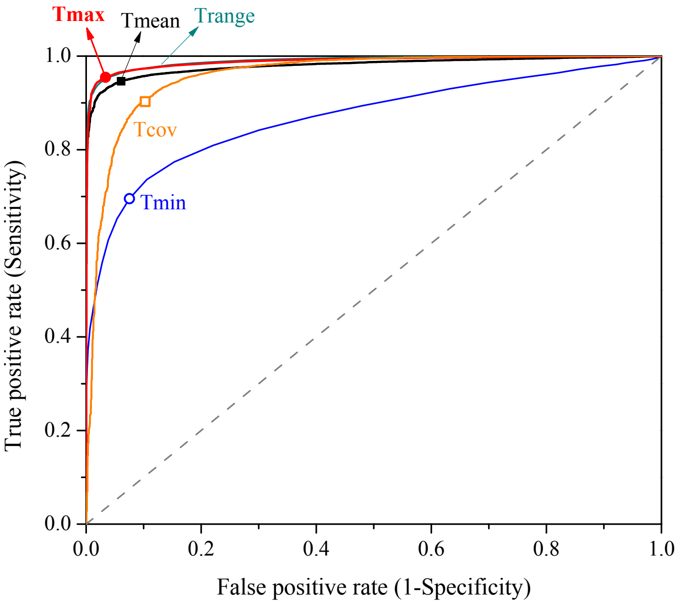

Figure 3.9 ROC curve comparing the specificity and sensitivity to detect daily use of different thresholds, compared to the determination of use by peak detection. Lines passing through the left top corner have higher sensitivity and higher specificity and are preferred. Each line represents the sensitivity-specificity combinations for different threshold values of a temperature distribution. The marked points represent specific thresholds for the daily maximum (T_0=26 ºC), mean (T_0=19 ºC), range (T_0=11 ºC), minimum (T_0=16 ºC) and coefficient of variation (17%) for the 31,112 stove-days monitored.

In Figure 3.9, the daily maximum, range and mean temperatures perform similarly and are better choices than the coefficient of variation and the daily minimum for this site, as measured by the larger area under their ROC curves (greater specificity and greater sensitivity). The accuracies of the threshold values derived from the bimodal distributions are listed below in Table 3.6.

	ROC curve			Performance of specific thresholds		
	Area	95% C.I.		Accuracy[a]	Sensitivity[b]	Specificity[c]
Daily parameter			***T0***			
Range	0.990	(0.989, 0.992)	11 ºC	0.95	0.95	0.96
Maximum	0.989	(0.987, 0.991)	26 ºC	0.96	0.95	0.97
Mean	0.980	(0.977, 0.983)	19 ºC	0.95	0.95	0.93
Coefficient of variation	0.959	(0.956, 0.962)	17%	0.90	0.90	0.90
Minimum	0.869	(0.861, 0.877)	16 ºC	0.72	0.70	0.92

Table 3.6 Performance of specific stove temperature threshold values to identify the daily use diagnosed with the peak algorithm.

[a] Accuracy = Sensitivity × (% use days detected with algorithm) + Specificity × (% non-use days detected with algorithm).

[b] Sensitivity = (number of days detected as in-use by both the algorithm and the T_0) / (number of days detected as in-use by the algorithm).

[c] Specificity = (number of days detected as non-use by both the algorithm and the T_0) / (number of days detected as non-use by the algorithm).

The initial purpose of the threshold temperature T_0 is the selection of reference non-use days. The slopes S_{0-} and S_{0+} that characterize cooking events are determined from those reference non-use days. Alternatively, these slopes might potentially be estimated a priori from simulated cooking cycles in the laboratory or from a heat transfer model of the monitor at the stove surface. Or they could be measured in the field by purposively sampling in "reference kitchens" of actual households where the stove monitored with the SUMs is never lit but is still subject to the diurnal and household temperature changes.

3.3.2 Field performance assessment of the temperature sensors

Over the 2.6 years of data collection, an average of 82 SUMs were deployed every monitoring round (except the first round where 50 were deployed) and a total of 112 sensors had to be replaced, adding up to 192 SUMs used in total during the project. Figure 3.10 shows the number of sensors lost in the project office or in the households; broken, exploded or about to explode from becoming too hot; programmed incorrectly (labeled "operator error"); or found with significant deviations in the annual reference measurements (labeled "calibration").

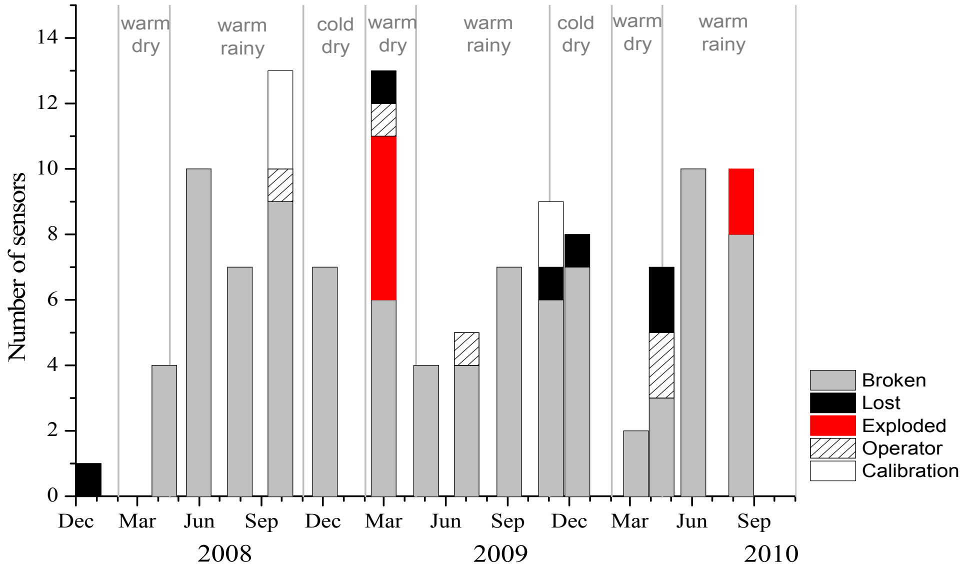

Figure 3.10 Data loss rate of the Thermochron iButtons (1921G) used as SUMs in the CRECER study.

We found that with adequate placement, the overall sensor lifetime of the 1921G models can exceed 1.5 years in stove parts with high thermal mass. This corresponds to the minimum sensor lifetime specified by the manufacturer for a 20-min sampling rate and continuous exposure to 70 °C (Maxim Integrated Products). The latter is likely to be different for sensors placed in metallic surfaces or close to the fire, as they are exposed to higher daily swings and to temperatures closer to the manufacturer's limits. An average data loss rate of 10% per monitoring round was observed through this study (Figure 3.10), including programming, downloading and data managing errors. We consider this to be a low bound estimate for SUMs projects using iButtons, given the optimum infrastructure available to our study and the strict protocols followed. It is worth noting that the sensors are not waterproof, only water resistant. We observed that after the rainy season some monitors were permanently damaged in those houses where water leaked into the kitchens through the roof and chimney openings, dripping over the sensors. The effects of water in the iButtons have been reported elsewhere (Wolaver and Sharp 2007). Sensor breakdown was also more common in those stoves were the daily temperature was closer to the limit specified by the manufacturer. We did not, however, observed a definite seasonal pattern in the loss of sensor data.

3.3.3 Stove adoption performance in the CRECER study

3.3.3.1 Initial adoption

The gradual transition from the traditional open cookfire to the new chimney stove had different timing across households. Figure 3.11 depicts the learning or adjustment period for two different houses, as seen by the SUMs signals (black) and by the drastic reductions in the kitchen levels of carbon monoxide (red). For household #1 it only took four days until they cooked the three main meals with the chimney stove, while household #2 took 12 days. Although the lighting of the stove in household #1 commenced in the second day (as seen by the rate of temperature changes), the number of cooking events (the number of peaks) increased gradually. This was a common pattern in the study population. After a few days, nearly all households entered a stable period of sustained use. The spikes in the CO signal observed in day 8 for household #1 and day 14 for household #2 during sustained stove use could be due to the simultaneous use of a cookfire in the kitchens or to the way the stoves were operated.

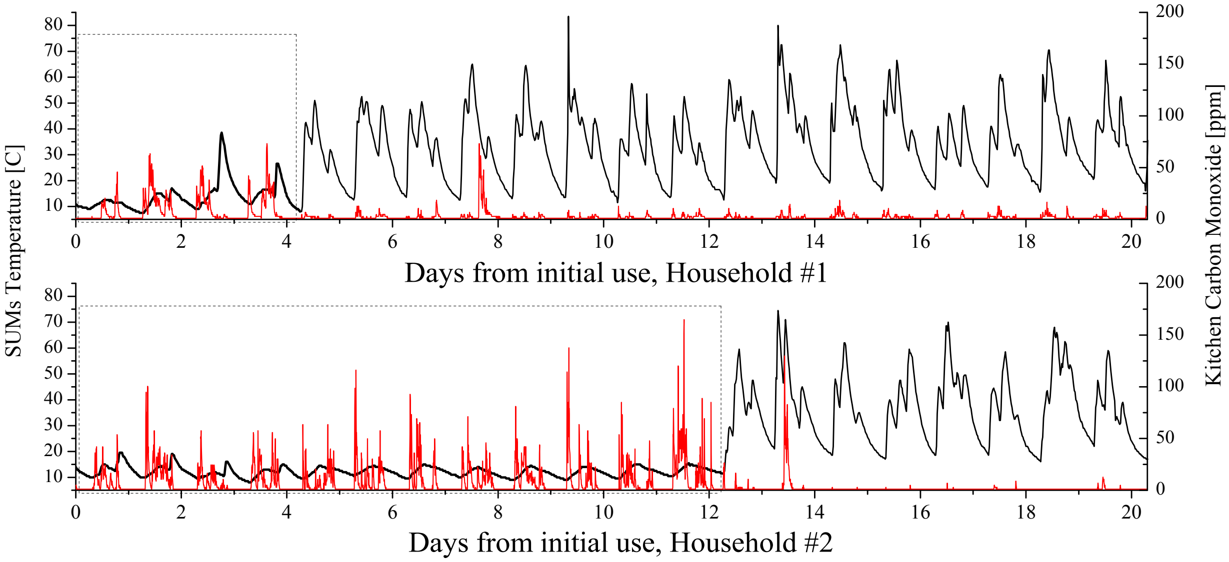

Figure 3.11 Initial adoption of a chimney stove as seen by the increased stove activity registered with the SUMs (black line, left axis) and the reduced kitchen CO levels (red line, right axis) in two different households. A rate of change higher than that of the ambient temperature indicates the lighting of the stoves in both households during the first four days. However, not until day 4 (household #1) and day 12 (household #2) did the homes cook the main three meals with the chimney stove and CO was drastically reduced.

3.3.3.2 Sustained use

The patterns of stoves used and daily meals for the fifteen monitoring periods of sustained use are shown in Figure 3.12. Each point represents the percent of stoves used out of the I_t stoves monitored on that day (upper graph) and the average daily meals on that day across the I_t stoves. The smoothed line (locally weighted least squares) highlights the seasonal variability. The inset in Figure 3.12 details the evolution of initial use during the first monitoring round for the group of newer users only. The population adoption curve shown in the inset is shaped by the average of the individual delays such as those depicted in the dashed boxes in Figure 3.11.

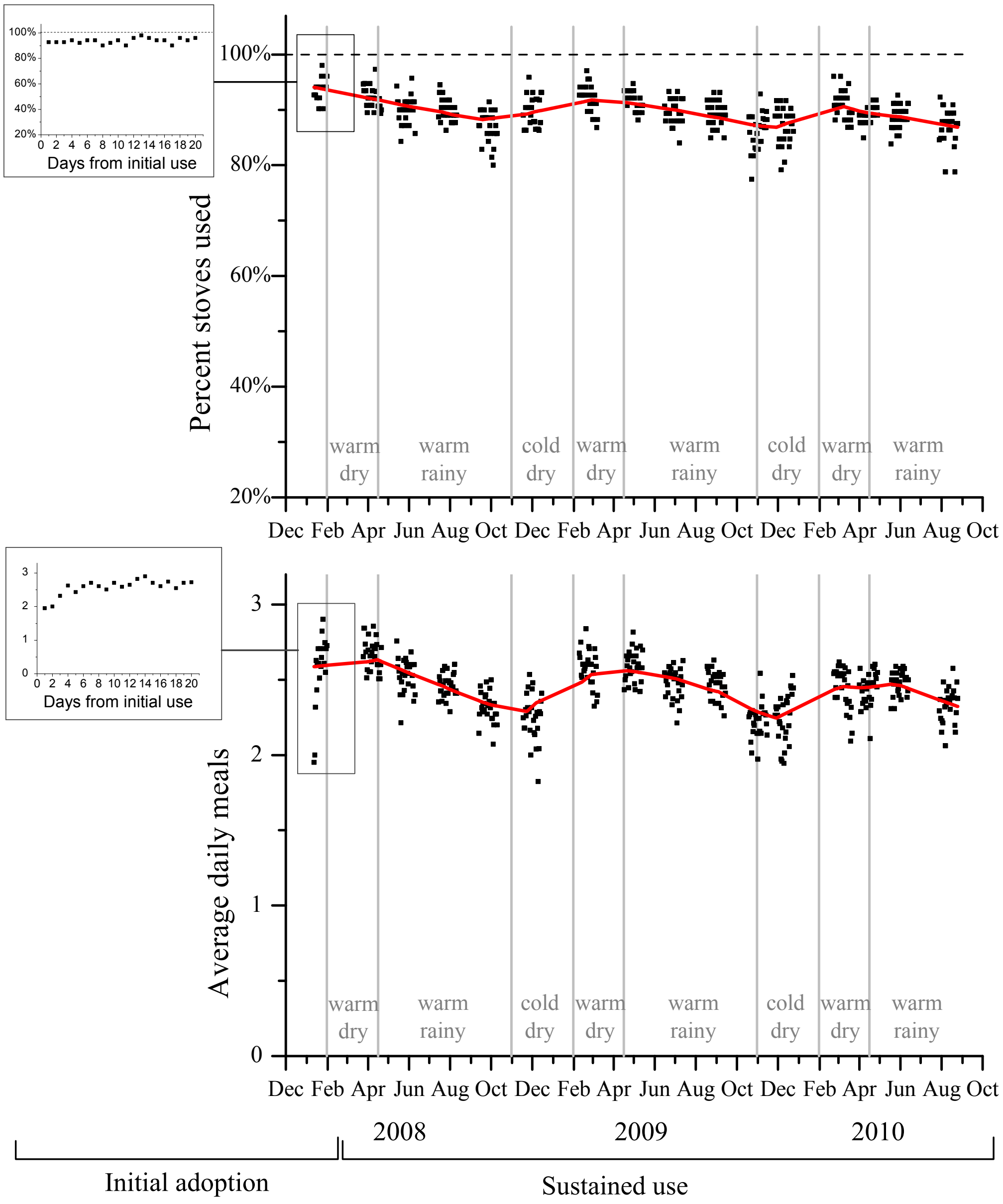

Figure 3.12 Percent stoves used (above) and average daily meals cooked with the chimney stove (below) measured with Stove Use Monitors (SUMs) in the CRECER Guatemala study through 32 months. Every point represents the level of use for the stoves measured in that day and the smoothed line highlights the seasonal cycle. The insets cover the period of initial adoption when percent stove-days were kept nearly constant while daily meals gradually increased in the first few days. The vertical lines define the locally accepted annual seasons.

In the Poisson and mixed effects models of sustained use only rounds 2-16 were included. When no covariates are considered in the Poisson regression, the population estimates are 89.6% stove-days (95% CI: 85%, 95%), 2.43 daily meals (95% CI: 2.26, 2.61) and 2.96 (95% CI: 2.74, 3.20) fueling events.

The regression estimates for the groups of old and new users were not statistically significant either by round or in their two-year averages. The effect of household size at baseline was not significant either.

With the mixed effects model we found that most of the total variability in stove use (76% for percent stove-days and 77% for daily meals) is due to the differences between households, and less due to the variability of repeated measures within each home. The estimates from the models are shown in Table 3.7.

		Population averaged model Poisson (robust)	Mixed effects model Random intercept
		Estimate (95% C.I.)	Estimate (95% C.I.)
Percent stove-days			
Fixed part:	Warm-dry season (%stove-days)	92.0 (87.1, 96.6)$^{+}$	-
	Cold_season (IRR)	0.96 (0.94, 0.99)$^{+}$	-
	Rainy_season (IRR)	0.97 (0.95, 0.99)$^{+}$	-
Random part:	Between-hh variance	-	0.99 (0.72, 1.36)
	Within-hh variance	-	0.31 (0.29, 0.34)
	Intraclass correlation	-	0.76
Daily meals			
Fixed part:	Warm-dry season (meals/day)	2.56 (2.40, 2.74)*	-
	Cold_season (IRR)	0.88 (0.85, 0.91)*	-
	Rainy_season (IRR)	0.95 (0.92, 0.98)*	-
Random part:	Between-hh variance	-	0.61 (0.45, 0.84)
	Within-hh variance	-	0.19 (0.17, 0.20)
	Intraclass correlation	-	0.77
Daily fueling events			
Fixed part:	Warm-dry season (meals/day)	3.11 (2.90, 3.33)*	-
	Cold_season (IRR)	0.89 (0.85, 0.93)*	-
	Rainy_season (IRR)	0.96 (0.93, 0.99)$^{+}$	-
Random part:	Between-hh variance	-	0.61 (0.45, 0.84)
	Within-hh variance	-	0.19 (0.17, 0.20)
	Intraclass correlation	-	0.77

Table 3.7 Regression estimates of population and mixed effects models for the percent stove-days, number of daily meals and daily fueling events in the SUMs study population. The incidence rate ratios (IRR) are the ratios of the cold to warm (or rainy to dry) stove-days or meals (warm-dry is the reference season). The intraclass correlation coefficient is the percent of total variability in the measurements that comes from differences between stoves. P-values: *≤0.0001, +≤=0.013.

3.3.3.3 *Seasonal variability*

The seasonal effect observed in the trends of stove usage in Figure 3.12 proved statistically significant when included in the regression model. Table 3.7 shows the effect of the warm and rainy periods expressed as incidence rate ratios (IRR). The incidence rate ratios are the ratios of the cold to warm (or rainy to dry) stove-days or meals. With the warm-dry season as a reference (*cold_season*=0, *rainy_season*=0), the percent stove-days decreased to 89% (95% CI: 82%, 98%) during the warm-rainy season (a 3% reduction, p=0.013), and to 89% (95% CI: 82%, 98%) again in the cold-dry period (3% reduction, p=0.002). For the daily meals this effect decreased use during the warm-rainy season by 5% (p<0.0001) to 2.4 daily meals (95% CI: 2.2, 2.7) and by 12% (p<0.0001) to 2.3 (95% CI: 2.0, 2.5) during the cold-dry period.

3.3.4 Comparison of indicators of stove use

We compared the stove and open-cookfire use reported by households in recall questionnaires against the actual SUMs-measured use during the periods of 15 days and 3 months preceding the questionnaire. All households in the new users group had at least one matching pair of measurements during the year that questionnaire and SUMs monitoring overlapped, while 75% of the older users had one match (see Table 3.3 in section 3.2.5.1). Figure 3.13 compares the SUMs measurements with the distribution of the binary questionnaire responses for stove use (upper graphs) and the ordinal categories for frequency of open-cookfire use (lower). The following questions were used for the comparison:

Question 1 (Q.1): “Are you using the Plancha stove for cooking?”. With responses: “Yes” or “No”. The reported stove use was consistent with the SUMs measurements (Figure 3.13(A)), as seen by the narrow distribution of measured percent stove-days and the median of 100% stove-days for those admitting use of the stove. The mean measured usage of the admitted users was 96% stove-days (95% CI: 93.5%, 99.3%). The outliers that lower the mean for this category comprise only 5% of the observations and only 3 observations were below the 50% use. The observed median of daily meals for these households (Figure 3.13(B)) was 2.65 meals (95% CI: 2.55, 2.74), with a 75th percentile just below 3 meals per day. The dispersion of those reporting not using the stove is larger but the sample size is less than 10% of the users.

Question 2 (Q.2): ”In the past three months, how often did you use the open cookfire?” With responses: “Daily”, “2-4 times per week”, “once per week”, “twice per month”, “once per month” or “Not at all”. The last three categories were clustered because some had only one or two observations. The averages and medians of the SUMs-measured stove use followed an inverse relationship with the reported frequency of open-cookfire use (Figure 3.13(C-D)), with most of the variability in the SUMS measurements being introduced by those reporting using the open cookfire on a daily basis. For both questions, there were no significant differences between the 3-month and 15-day recall periods.

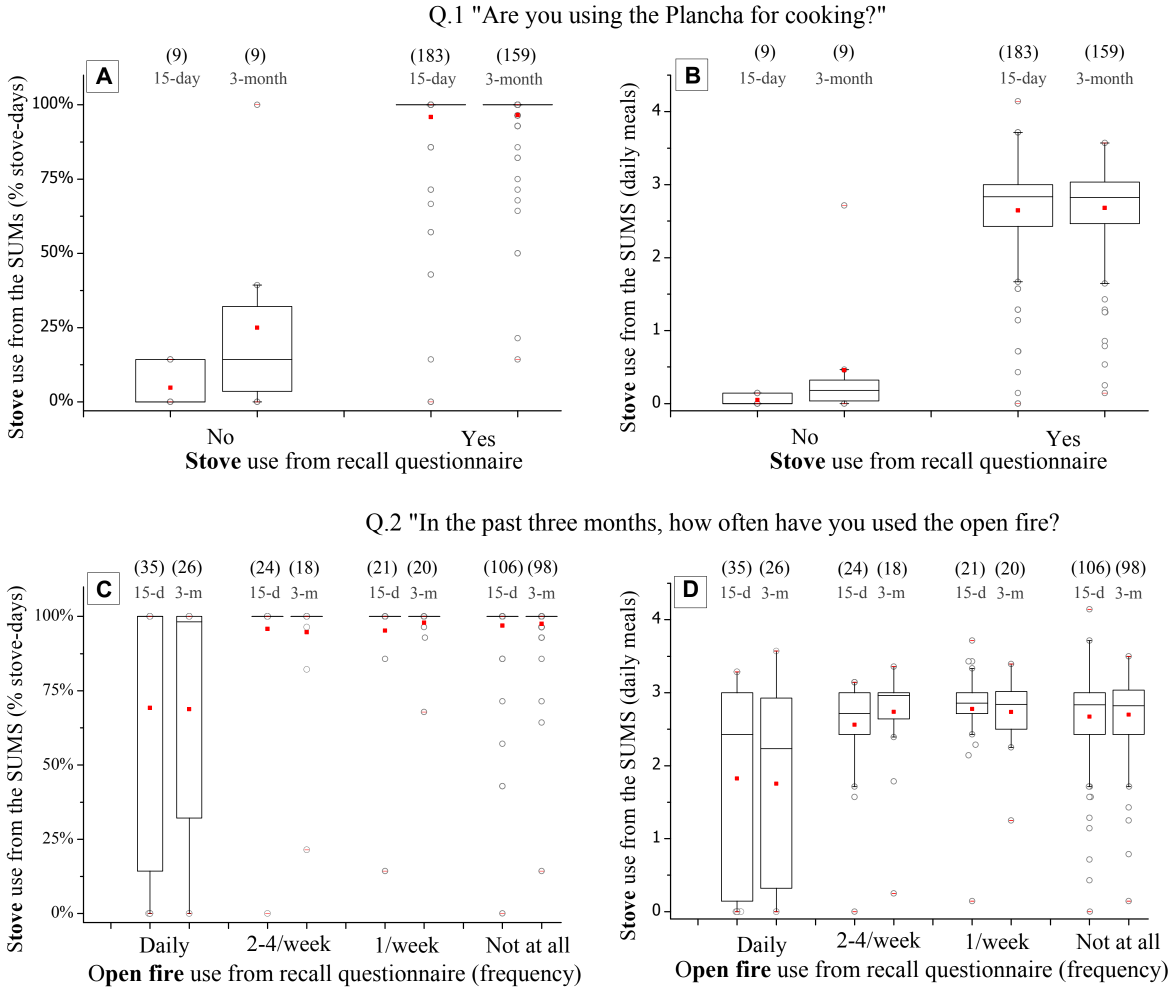

Figure 3.13 Compared stove usage from recall questionnaires (horizontal axes) and SUMs measurements (vertical axes) in the CRECER study. The SUMs usage was quantified in percent stove-days compared to total possible in the period (A and C) and in average daily meals (B and D). The binary reports of stove use (A and B) were consistent with the SUMs measures of the 15-day (left boxplot) and 3-month (right boxplot) periods that preceded the questionnaire. The reported frequency of open cookfire (C and D) followed an inverse relationship with measured stove usage, with daily cookfire users contributing most of the variance in stove use. The estimates for the 15-day and 3-month periods were not significantly different. In the boxplots the red dot represents the mean, the center line the median and the box encloses the interquartile range (25th to 75th percentile). The whiskers show the 5th and 95th percentiles of the distribution and the hollow circles outside this range are outliers. The sample size in each category is displayed in parentheses.

3.3.5 Sample size calculations

With the intraclass correlation from the mixed models (ρ=76%) we estimated (STATA sampsi command) the sample size required for a 0.05 significance level, 0.90 power, and an effect size equal to the largest seasonal variation (10% of the mean approximately) given the standard error in the observed mean of an initial round. In other words, we estimated how large a sample of repeated correlated measures needs to be so that if the true usage mean actually differed from a hypothesized population mean by 10% then we could reject the hypothesized mean with 95% confidence 90% of the times.

Figure 3.14 (A and B) are plots of the number of households needed in the sample as a function of the number of monitoring rounds per household for an effect size of 10% in usage from hypothesized levels of 70% stove-days and 2.43 daily meals, at various degrees of correlation and different observed standard errors in the samples. In the context of the analysis presented, ρ is the correlation of the round means for a household (bi-monthly rounds, each lasting 28 days), not the correlation at the daily level. The sample size calculations for the percent of stove-days (Figure 3.14(A)) and daily meals (Figure 3.14(B)) apply to rounds of similar duration and frequency. Thus, the horizontal axis represents the length of the study.

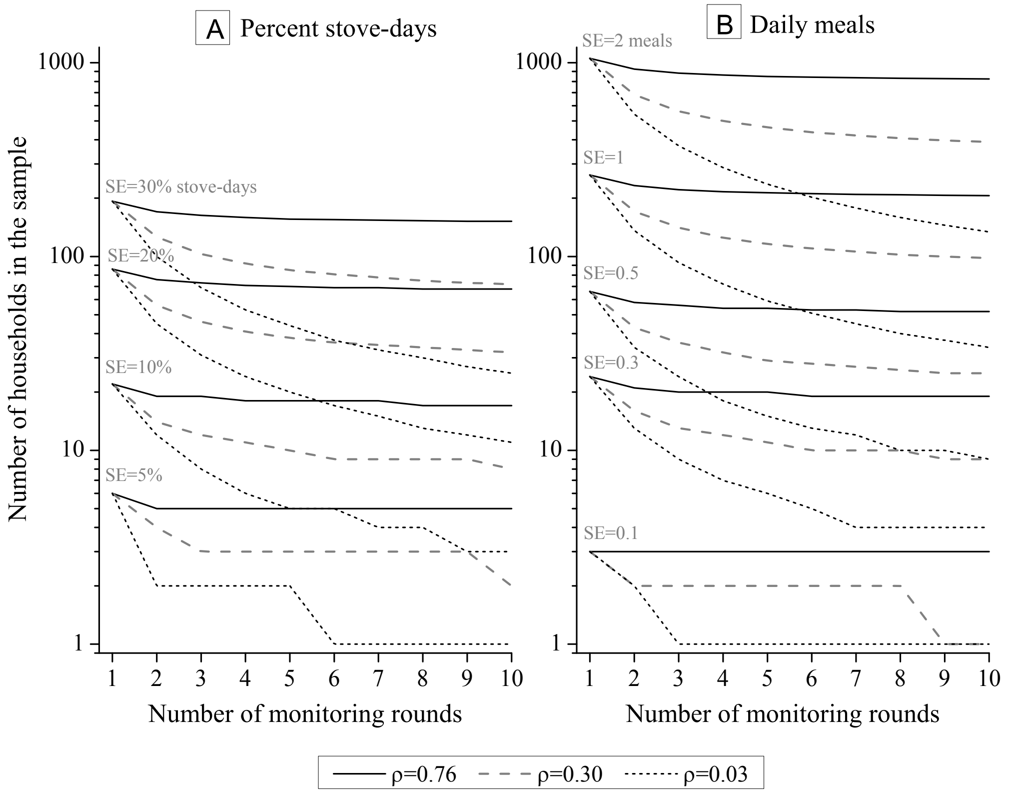

Figure 3.14 Estimated sample sizes (number of households, logarithmic y-axis) needed for a given study duration (number of equally spaced monitoring rounds, x-axis) to detect an effect size of 10% from mean usage of 70% stove-days and 2.43 daily meals at the 0.05 significance level and with 0.90 power, when the repeated measures on households have an intraclass correlation ρ. In the context of a hypothetical 1-year SUMs study with bi-monthly rounds and a standard error of 0.5 meals in measured stove usage per round, to detect a 10% difference in the 2.43 mean daily meals (B) 53 households are needed when the monthly rounds are highly correlated (ρ=76%) and 28 households if the correlation is 30%.

3.4 Discussion

We presented a methodology for the quantification of the stove adoption process. By long-term deployment of SUMs we were able to visualize the dynamics during initial adoption and to quantify the level of sustained use, magnitude of the seasonal variations in usage, and sources of variability. The learning period in the study sample consisted of a few days only. The quick uptake is due to the nature of the stove dissemination in the CRECER project: all households receiving the chimney stove were asked to start usage on the same day. This uptake might be different in other projects where the stove is introduced to the community in different ways. This section focuses the discussion on the measured levels of sustained use.

3.4.1 Measured stove adoption performance in the CRECER study

3.4.1.1 Sustained use

The high levels of sustained use measured with the SUMs were maintained during the 2.6 years of the monitoring study. We identify that the following factors contributed to the high levels of use: 1) high initial acceptance and sustained use of this chimney stove in the region (Boy et al. 2000), 2) the compatibility of the stove design with the cultural practices and main local cooking tasks such as tortilla making, 3) familiarity of the new users with the stove, since their neighbors or family members had received one in the previous years as part of the study, 4) abundance of woodfuel in the region and that this fuel is almost exclusive used for cooking in the study population (only one household of the 557 in CRECER had a gas stove, which was used only for some meals), 5) frequent contact maintained by fieldworkers and study personnel with the participants through the quarterly visits for IAP (indoor air pollution) monitoring, questionnaires and medical checkups, 6) continuous encouragement to use the stove that the household experienced throughout the study visit. Thus, the rapid take up and sustained use of stoves we observed should not be assumed to occur in disseminations undertaken in different conditions.

Even under these optimum conditions there was never a day in the 2.6-year period when 100% of the stoves were used (Figure 3.12). Even after the households with lowest use are excluded from the analysis, 100% usage was measured only in one day throughout the study and an average of 3 daily meals was never detected. Therefore, on any given day there were always a couple of households not cooking all meals with the stove and using instead the open cookfire or not cooking at all in the home. This suggests that 90% stove-days is a best-case for sustained use and a more realistic target goal for adoption performance than 100%, which is sometimes assumed.

3.4.1.2 Seasonal variability

Once users entered the period of sustained use only the seasonal fluctuations affected the population means. The highest levels are seen in the warm-dry season, gradually declining through the warm-rainy period. We know from the fieldworkers and participants that the chimney stove is particularly hard to lite with wet fuel, so it is plausible that the decreased availability of dry fuelwood with the onset of the rainy season contributed to this decline. Seasonal migration and local festivals also affected the use patterns. For instance, the two lowest levels of daily meals during sustained use (Figure 3.12) correspond to the local Christmas celebrations on December 24th, when people are cooking additional food or traditional dishes in the open fires or eating with relatives in other households. Despite this variability, the stove-days and daily meals did not decline significantly over the 2.6-year period. Therefore, changes in the personal and kitchen IAP levels during this period are not due to stove use but rather caused by changes in frequency of open-cookfire use, deterioration or incorrect use of the stoves or changes in the distribution of personal time-activity budgets (Ruiz-Mercado et al. 2011).

3.4.1.3 Partition of variances

Remarkably, the levels of sustained use in the groups of newer and older users were not significant different, despite that their adoption processes started 2-4 years apart. This could also be related to the way the stoves were introduced to the community () and reflects both: the attractiveness of this chimney stove to this population and the stability of the sustained use process. A review of the baseline fuel and cooking characteristics and socioeconomic factors of the two groups reveals no statistically significant differences either (Table 3.7).

We estimated the fractions of between and within household variance of measured usage to characterize at what level the factors influencing this stage of the adoption process operate. This was also done to prioritize individual or group strategies for improved sustained use. The intraclass correlation coefficient from the mixed effects model indicated that differences between households accounted for 76% of the total variability in the 2.6-year population averages. The baseline covariates did not explain these differences, and thus in our case, they are likely to arise from non-seasonal migrations or from the distinct preferences that each household has for using the stove for some or all cooking needs (and potentially, to use the open cookfire instead). Therefore, in our case, a program to enhance use through strategies that influence all households equally (technical improvements to the stove, homogeneous incentives, generic messages) will not be as efficient at increasing the population mean and reducing the number of least benefitted households compared to implementations tailored to those users with the largest variability.

3.4.1.4 Sample size calculations

With the SUMs we could detect the small (3-10%) but consistent seasonal pattern of stove use. This was due to the increased precision, (standard error less than 5% stove-days), the low within-household variability (or high intraclass correlation) and the 2.6-year data coverage of the SUMs measurements. The sample size calculations discussed in section 3.3.5 (Figure 3.14) show that even if the standard error in mean usage observed at each round is 20% stove-days, a 10% reduction in the long-term population-mean can be reliably detected with less than 100 households in a randomly selected representative sample. If the variability within household usage is high, repeated monitoring rounds would be needed to reduce this sample size.

Variance measurements are also essential to guide study design. It is often the case, however, that the dynamics of stove use and the size of the seasonal or relevant effects are unknown from the outset. Thus, an accurate characterization of the level of sustained use in a population requires measurements through several months and often a year after installation of the stoves. When there is no previous documentation of the variability and periodicity of stove use in the population, first the number of monitoring rounds and duration of the study must be determined by the nature of the research question or the target goal that will be verified. Examples of such questions are 1) to characterize the dynamics of initial adoption; 2) to quantify the time that it took for the population to reach sustained use; or 3) to verify that the level of sustained does not decay below a critical threshold after a year. Then the number of households in the sample can be estimated for the desired power, level of significance and size of the effect to be detected as is typical in sample size calculations. The choice of both the number of households and the number of monitoring rounds are often bounded by the availability of resources. Therefore, the intraclass correlation and standard errors reported in other SUMs studies in different populations will be critical to guide future study designs.

3.4.1.5 *Other metrics of stove use*

The relationship between the average daily meals and days in use for the population is shown in Figure 3.15. Each point represents the meal and percent days in use of a household during one monitoring period. The ratio of these two quantities yield the number of meals during the days of use (the meals per stove-days for a group of stoves), since $(M/T) = (M/U) * (U/T)$.

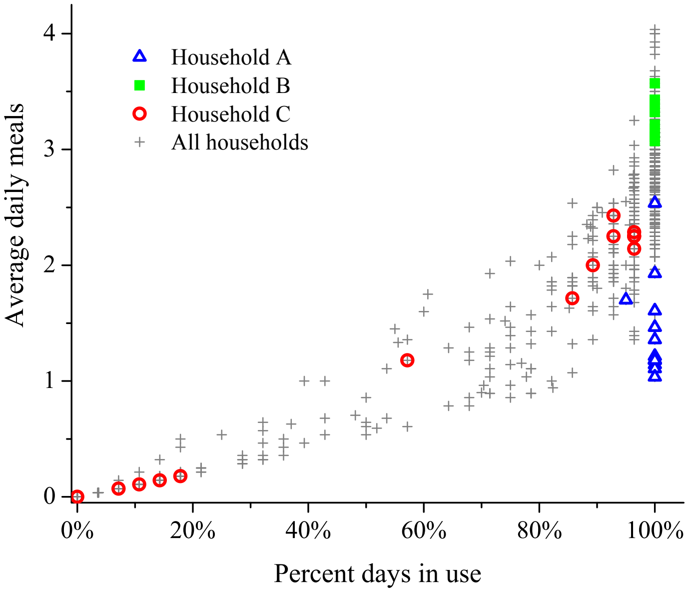

Figure 3.15 Percent of days in a SUMs-monitoring period that households in the CRECER study used the chimney stove (x-axis) in relationship with the average daily meals in the period that they cooked with it (y-axis). Both households A and B score the same intensity of stove use as measured in percent stove-days. However, through the 16 monitoring rounds B consistently cooked all main meals with the chimney stove, while A cooked only 1.4 meals on average, presumably combining the use of an open cookfire. Household C gradually disadopted the stove.

This graph is useful to visualize the patterns of meal frequency in the population and identify households that are using the stove every day but not for all meals and thus are likely to be combining (or "stacking" (Ruiz-Mercado et al. ; Masera and Navia 1997; Masera et al. 2000; Ruiz-Mercado et al. 2011)) the use of the chimney stove with the use of an open cookfire. The figure shows the patterns of three individual households (A, B and C) and illustrate how some users with high and stable daily usage do not necessarily cook all three main meals on the stove (A compared to B), highlighting the necessity to monitor usage at the meal level to quantify such phenomena and that the usage of open cookfire must be quantified as well to understand the dynamics. Figure 3.15 also shows the disadoption of a stove by a household (C) that migrated.

The population metrics of average daily meals and meals per stove-day cannot be compared across populations with different number of main meals. Alternatively, when the number of total possible daily meals for each household P_i is measured then the daily intensity of use can be parameterized by the *percent meals*, defined as the fraction of meals M from the total meals possible P in the group of stoves during a time period:

$$\% \, meals = \frac{\sum_{t,i} m_{t,i}}{\sum_{t,i} P_{t,i}} = \frac{M}{P} \qquad (13)$$

For this metric, careful consideration is needed to ensure that the "meals" or cooking events are defined in the context of the specific population, since the main meals could vary between households and across seasons.

If the sample is representative of the full population of stoves deployed, the percent meals is the fraction of population stove uptake over the monitoring period, and it is a factor that could be used to weight the impacts from multiple devices and/or to correlate with other metrics of fuel use, pollution emissions, concentrations and exposure. Additional research will be needed, however, to validate these correlations. Furthermore, because traditional and new cooking devices could be used in combination during a meal, the sum of the percent meals for all devices in the household will not necessarily equal one.

3.4.2 Indicators of stove use

We compared the SUMs measurements against recall questionnaires and field surveys (Figure 3.13) since the latter are the main indicators currently used in household energy projects. In this population, reported stove use was remarkably consistent with the SUMs measures. The variances of the group of admitted users are small and only few people over-reported their usage (Figure 3.13, Q.1). From the nine households that reported not using the stove eight cooked with it at least one meal during the 15-day and 3-month recall periods as measured with the SUMs. Interestingly, the nine non-users responded affirmatively to question: Q.4 "Is the family happy with the stove?". Indeed, there was no negative answer to this question in the full CRECER population of 557 participants. The fieldworkers' observations that three of the nine non-users seem not liking the stove, and that other three did not have dry wood to use it were more informative than Q.4 in this regard. Of these nine, only three stoves were classified as "in bad shape" upon a brief inspection by the fieldworkers. Although the sample size of non-users is small in our study, these comparisons illustrate how household surveys can complement the stove use indicators from the SUMS and the questionnaires. They also highlight the usefulness of objective SUMs measures to reduce misclassification errors, enabling stove use rather than stove type as the explanatory variable in future analysis for health effects and other impacts.

We compared also the reported frequency of open cookfire-use with the SUMs measures (Figure 3.13, Q.2). We found that although the group of daily cookfire users had the largest variability in measured stove usage, their medians are still close to 100% and 2.5 meals. The group of nine households that reported not using the stove falls in this category. Figure 3.13(D) provides evidence of the "stacking" of cooking devices and depicts again how diverse individual profiles of combined stove and open-cookfire use can be associated with high population levels of stove use. Therefore, although it is important to quantify the intensity and variability in stove usage, it is also critical to simultaneously verify the reductions in open-cookfire practices.

In Figure 3.13(C and D) the sharp difference between the daily cookfire users and the other 3 fire frequency categories suggests an important tipping point in the behavior of stove use. If the responses to the cookfire frequency question were as accurate as those about chimney-stove use, it would seem that an effective starting point to improve usage in this population is to focus in helping daily cookfire users to change the factor that differentiate them from those that limit the fire activity to 4 days per week at the most. As discussed in section 3.4.1.3, this would reduce the between household variance and would be one of the most effective strategies to increase the population average of stove usage. Of course, the cooking needs, cultural practices and other factors associated with daily cookfire use must be considered to determine the feasibility and impacts of such intervention.

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

We consider that the high consistency between reported and SUMs-measured use is associated with the actual elevated level of stove use, the frequent interaction and long-term relationship of the CRECER field personnel with the study participants, and that there was no direct incentive to exaggerate or under-report usage. The small non-monetary incentives given to participants were based on enrollment and not conditioned on levels of stove use or participation in the SUMs monitoring.

3.4.3 Alternative metrics

The relationship between the average daily meals and days in use for the population is shown in Figure 3.15. Each point represents a household during one monitoring period. The ratio of these two quantities yields the number of meals during the days of use (the meals per stove-days for a group of stoves), since (M/T) = (M/U) * (U/T). This graph is useful to visualize the patterns of meal frequency in the population and identify households that are stacking stoves or using "multiple cooking strategies" (Ruiz-Mercado et al. ; Masera and Navia 1997; Masera et al. 2000). The figure shows the patterns of three individual households (A, B and C). The patterns present illustrate that users with high and stable daily usage do not necessarily cook all three main meals on the stove (A compared to B), highlighting the necessity to monitor usage at the meal level to quantify such phenomena. In the Figure, household C gradually disadopted the stove. These patterns will be visualized in a different way in chapter 4.

The population metrics of average daily meals and meals per stove-day cannot be compared across populations with a different number of main meals. Alternatively, when the number of total possible daily meals for each household P_i is measured[5] then the daily intensity can be parameterized by the percent meals, defined as the fraction of meals M from the total meals possible P in the group of stoves during a time period:

$$\%\, meals = \frac{\sum_{t,i} m_{t,i}}{\sum_{t,i} P_{t,i}} = \frac{M}{P} \qquad (14)$$

If the sample is representative of the full population of stoves deployed, the percent meals is the fraction of population stove uptake over the monitoring period, and it is a factor that could be used to weigh the impacts from multiple devices and/or to correlate with other metrics of fuel use, pollution emissions, concentrations and exposure[6]. Additional research will be needed, however, to validate these correlations.

The detailed long-term measures of stove and open-fire use now available with the SUMs open the challenge to formulate metrics and indicators of cookstove adoption that account for the coexistence of both traditional and improved cooking devices. These metrics

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[5] The number of main meals can vary between households and across seasons.

[6] Because traditional and new cooking devices can be used in combination during a meal, the sum of the percent meals for all devices in the household does not necessarily equal one.

must consider also that the weight of the impacts (indoor air pollution, fuel savings, emission reductions) from the substitution or combination of stoves can be concentrated in specific cooking tasks and periods, i.e. that each meal or season might not count the same. In particular, it is important that these indicators explicitly include measures of “open cookfire disuse” to assess the reductions in the incidence of open cookfire practices.

3.5 Conclusions

In this chapter we assessed the field performance of small low-cost temperature dataloggers (Thermochron iButtons) as SUMs and implemented an algorithm to obtain counts of the daily meals cooked. We found that with adequate placement, standardized data collection and careful data management the SUMs can provide objective and unobtrusive data of stove use with resolution accuracy and level of detail not possible before. This new tool promises to enable systematic and scalable monitoring of the stove adoption process, to design strategies to optimize it and verify the impacts of biomass stoves. In Box 1 we listed key recommendations for the deployment of SUMs to quantify adoption.

The slow thermal response of the chimney stove body and the fairly defined cooking and fueling cycles in the study population facilitated the analysis of the signals without the need for smoothing. This might not be the case when faster sampling rates are used on stove surfaces that conduct heat better, such as a portable metal cookstove. In such cases, smoothing or signal filtering and spectral analysis could be more suitable. At this research site, where the seasonal patterns of the maximum and mean daily ambient temperatures are weak, we found that a single temperature threshold is sufficient to identify days of use through the year and select reference days to characterize the peaks of the meals.

We formulated metrics for the objective quantification of stove usage with temperature dataloggers as SUMs. We found that metrics of sustained use like the percent of days in used (for a single stove) and the percent stove-days (for a group of stoves, Eq. 6) can summarize the number of stoves active in a monitoring period and thus, are enough to ascertain seasonal patterns or quantify the stoves completely abandoned. However, these metrics alone are insufficient to measure the actual level of stove activity when the frequency of meals or the time that the stove is used every day vary across households, as it is often the case due to the “stacking” of stoves and fuels. In this regard, other metrics like the average daily meals (Eq. 7), the meals per stove-day (Eq. 8), the percent of meals (Eq. 9) and other metrics of daily usage time seem more accurate to quantify the aggregate level of stove activity, which is the relevant parameter for fuel use, emissions and exposure reductions.

SUMs Placement and Sampling Frequency

- Two-stage protocol:
  1. Determine stove/fire locations and SUMs holder setup that keep SUMs within the temperature limits specified by the manufacturer. Use real-time temperature indicators (labels, lacquers, multi-channel dataloggers) to test locations during a cooking cycle performed at a maximum fueling intensity.
  2. Record temperature with SUMs and holder setup at the selected stove/fire locations during 2/3 days in actual homes. Identify the least obtrusive locations. Examine temperature traces to:
     a. Verify that signals do not saturate and SUMs temperature is not too close to the operating limits.
     b. Determine the sampling rate that is adequate for the level of detail desired (days in use, number of daily meals, duration of cooking events, time that the stove or fire are lit) and for the number of samples needed per monitoring period.
- Slower sampling rates and lower operating temperatures lead, in most monitors, to longer battery lifetimes.
- Avoid stove/fire locations were water could drip into the monitors.
- Consider that some households might change the location within the home were the open cookfires are lit during the monitoring period.

SUMs Data Collection and Management

- Follow and train personnel to follow strict protocols to ensure the integrity of the SUMs data, facilitate batch processing of the datafiles.
  - Implement data collection field forms for every SUMs at each cycle deployment-programming-downloading cycle. Document in the forms relevant observations about household behavior not previously registered in the database (for example when the family has migrated, has a new second stove, does not lives in the house where the stove was built, etc.). Keep track of sensor performance (monitor exploded, was lost, etc.).
  - Establish a data file naming protocol that includes all key identified in the name string (monitor, community, household, stove ID numbers, start and end date of temperature readings, number of the monitoring cycle), to facilitate browsing of files and expedite batch processing.
- Perform in all monitors deployed annual reference measurements. For the comparative procedures simulate heating and cooling cycles with a water bath or a controlled temperature environment and use a calibrated reference thermometer to detect monitors with anomalous behavior.

Box 1. Recommendations for field deployment of iButtons as Stove Use Monitors (SUMs) to quantify the adoption process. A sample data collection form is included in the Supplemental Material.

As discussed in the previous chapters, the cookfire to cookstove transition is gradual and often leads to the combined use of both cooking devices. Therefore, the complete characterization of the stove adoption process requires measures of use in both the traditional and the newly introduced stoves. These issues will be explored in chapter 4 and, separately, in later publications that also incorporate simultaneous SUMs measurements of the continued usage of open cookfires in each household. Two key research development needed to broaden the usefulness of the SUMs are the development of libraries of validated algorithms to quantify usage in different stove types, and the development of algorithms to identify the SUMs "signature" of specific cooking tasks. The latter to correlate the SUMs signals of each task with its fuel consumption, air pollutant emissions and exposures signatures to identify the tasks with the highest impacts and prioritize transitioning these tasks from the fire to the cookstoves.

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Chapter 4

Behavioral patterns of combined cookstove and open-fire use

4 Behavioral patterns of combined cookstove and open-fire use

Summary

This chapter examines the behavioral patterns of stove and fire uses that were measured in the CRECER study with the SUMs and with recall questionnaires. Despite the high levels of stove use measured with the SUMs, fifty-percent of the households in the sample reported continued use of an open fire. The preparation of animal feed was the most common task performed with the fire (46% of the households in the sample) followed by the cooking of corn kernels to prepare tortillas (*nixtamal*, 25%), space heating (13%), boiling water (11%) and preparing food for the family (11%). These levels of fire use tripled the ones reported by the households that participated in the RESPIRE study 2 years prior to CRECER. Using graphic representations for hierarchical clustering analysis known as "heat maps" I identified groups of households that had similar behavioral patterns of combined stove-fire use ("stove stacking clusters"). The stratification of SUMs-measured stove use was strongly driven by the preferences of the households for continue using the fire for specific tasks. Households that performed a larger number of tasks with the fire had lower stove usage. This explains why in the regression models the differences in SUMs-measured stove use between households could not be accounted for by the baseline characteristics of the homes. The combined use of stoves and fires is only one of the behavioral components that critically affect exposure to household air pollution. A summary of the key published research findings from the RESPIRE-CRECER and the Patsari stove trials shows that a large portion of the variability in personal exposure and area concentration measurements remained unexplained after adjusting for all non-behavioral characteristics of the households and individuals. Both case studies attributed the residual variability to behavior – namely, to the patterns of stove stacking, the practices for kitchen ventilation, stove operation and stove maintenance; and, to the daily patters of time-activity and time-location. The objective quantification of these behaviors and the characterization of the behavior-exposure and technology-behavior interfaces are critical to accurately assess the impacts of stove dissemination and to design optimum dissemination strategies. In particular, a clear definition of the different stages of the stove adoption process is needed to understand the distinct nature of the behavioral components embedded in the initial acceptance of a cookstove, its sustained use, the abandonment of the traditional fires and the actual delivery of the stove benefits.

4.1 Introduction

All of the stoves and fires that contribute to household air pollution are operated by people, who remain in close proximity to them in order to obtain the services sought from the devices: the preparation of food or liquids, space heating, gathering, socializing, healing, the fulfillment of traditions and rituals, etc. Therefore, the individual behavior of the household members and the dynamics of the families and communities are central to the actual field performance of the cookstoves. Furthermore, this behavior influences the activities around the stoves, critically affecting the exposure to household air pollutants.

4.1.1 The critical role of behavior in the adoption and impacts of cookstoves

In the case of cookstoves, I discussed in chapter 2 that the innovation being introduced consists of a set of new or modified cooking practices that extend beyond the stove technology. I also discussed that with the introduction of a new stove, each of the new and previous fuel-device combinations create an adoption niche based on the tasks where the combination best fulfills the needs of the user. I described how these processes led to the "stacking" of stoves and fuels, rather than to a complete switch (section 2.3.2). In this chapter I reflect on the prevalent use of open fires and find that when the original end-uses of the fires (before the new cookstove is introduced) extend beyond cooking, the newly introduced cookstove often is an imperfect substitute for all fire tasks, causing households to combine or stack the use of both cooking devices.

An understanding of the concepts outlined above and a clear definition of the different stages of the stove adoption process (section 2.3.3) are needed to identify the distinct behavioral components embedded in the initial acceptance of a cookstove, its sustained use, the abandonment of the traditional fires and the actual delivery of the stove benefits. For instance, the behaviors that could be relevant to understand the drivers of purchasing or initially accepting a new stove (willingness to pay, intent to buy or install, etc.) can greatly differ from the behaviors that promote or restrain its sustained use (traditional cooking practices, household dynamics, etc.). Furthermore, even when the new stove is accepted and used in a long-term basis, there is a different set of complex behaviors that regulate the reductions in exposure to household air pollutants, in fuel use and in emissions.

Not all the dimensions of these behavioral components are connected with or related to the technical characteristics of the stoves. This has two important consequences: one, that there is a "behavioral wedge" (Dietz et al. 2009) to ramp up the benefits of cookstove dissemination by broadening the concept of distributing cookstoves to the promotion of behaviors that can lead to "healthy and sustainable cooking practices". The second consequence is that the interventions to alleviate the household air pollution problem with purely technological approaches will be always limited by behavior -in other words, that even the most advanced biomass cookstove can be used in combination with an open fire on the side.

Relatively few efforts have explored the impacts of behavioral interventions to reduce exposure to indoor air pollution (Barnes et al. 2004; Barnes 2010; Barnes et al. 2011). Fully characterizing the complex behavioral components that regulate the delivery of benefits from cookstoves is crucial, but unfortunately beyond the scope of the current dissertation.

As starting point, this chapter focuses on the identification of behaviors that affect the ability of improved cookstoves to reduce exposures to household air pollution. In the next section I identify a set of key behaviors, drawing from field evidence at the Guatemala and Mexico case studies (described in section 1.3). I focus on the behavior of combined stove and fire use ("stove stacking"). In the third section I examine the prevalent use of open fires reported in the questionnaires of the Guatemala RESPIRE study (2002-2004) and compare them with the levels of fire usage found with questionnaires at the end of CRECER (2010) in a subsample of the population (described in 3.2.2). I then analyze the patterns of stove stacking in CRECER, by performing a cluster analysis of the stove use data collected with the SUMs and the fire usage measured with recall questionnaires. I identify groups of households with similar behavioral patterns of stacking and present the results using graphical tools for hierarchical clustering analysis called "heat maps". The chapter ends with a discussion of the implications that stove stacking has on the variability of exposure to household air pollution and in the researcher's ability to accurately assess the impacts of stove disseminations.

4.2 Behavioral determinants of exposure to household air pollution

In this section I review the results of the Guatemala and the Mexico case studies to identify key household behaviors that regulate the exposure to household air pollution.

4.2.1 Behavioral determinants of exposure in the Guatemala RESPIRE and CRECER Studies

The type of stove disseminations performed in the RESPIRE and CRECER studies differed in that during RESPIRE the participant households were visited every week by the field staff to check to see if the stoves were being used and properly maintained. Households received weekly encouragement to use the stoves and their stoves were repaired as needed. On the other hand, during CRECER, stove surveillance took place quarterly, households were not regularly encouraged to use their stoves or to abandon their traditional fires, and stove maintenance was offered only twice during the four-year period. In terms of monitoring, stove and fire usage data were collected with recall questionnaires during RESPIRE and CRECER, while the Stove Use Monitors (SUMs) were only deployed in CRECER.

In the RESPIRE chimney-stove randomized control trial Smith et al. (Smith et al. 2010; Smith et al. 2011) measured 48-hr kitchen concentrations of carbon monoxide (CO) and personal exposures in 532 mothers and in their children to assess the effects of biomass smoke. They found that while kitchen levels of CO were reduced by 90% with the introduction of the Plancha chimney-stove, the personal exposures in the mothers and children were reduced only by about 50%. They pointed out that this was consistent with the fact that neither the mothers nor the children spent all day in the kitchen and that other sources of CO could be present, such as other open fires for cooking or for other uses. They also highlighted that the particular chimney stove introduced in the trial, while being widely accepted in the population, does not improve combustion conditions and only moves some of the pollutants from inside the kitchen to the outside, in the larger neighborhood environment, where mothers and children also spend time. The concentrations of CO in the kitchens where only open fires were used (control group) remained constant during the 18-month intervention but the trends of personal exposures for the children and women in this group significantly declined over time. The decline followed the same trend of the personal exposures in the group that had the stove (treatment group). The authors attributed these declines to behavioral changes related to the age of the infants that equally affected the kitchen dynamics of both groups.

In the same study, McCracken et al. (McCracken et al. 2009) analyzed the individual and group level variability in the longitudinal measures of CO performed in children. When considering the stove and fire groups together they found that only 33% of the total variability in personal exposure to CO was attributed to differences between children, highlighting the presence of extremely variable day-to-day behaviors that affected exposure. They found that the classification by stove type based on the intervention group (chimney stove or traditional open fire) only explained 50% of the differences in the exposures between the children. When all the household and children covariates were included, their statistical model explained only 62% of the between-children variability. The authors acknowledged that the occasional use of other cookfires in chimney-stove households could have increased the temporal variability in exposure. They concluded that to improve the accuracy of measurements of long-term exposure it was critical to identify the key time-varying behaviors that could explain the unknown sources of within-child variability.

The interactions between stove type and time spent in the kitchen in the CRECER stove trial were further analyzed by Ruiz-Mercado et al. (Ruiz-Mercado et al. 2011). They analyzed the 2-year longitudinal patterns of the time that 55 women (32 using cookfires and 23 having a chimney stove built) spent in the kitchen on a daily basis. The 24-hr samples of minute-by-minute time spent in the kitchen, were collected quarterly over two years using a Time-Activity Monitoring System (TAMs) (Allen-Piccolo et al. 2009). The authors found no significant differences among the groups in the total time budgets. They suggested that if there were any differences in the personal exposures to pollutants associated with changes in kitchen time-activity, these differences were likely to arise from the re-distribution of the exposure times throughout the day, not from changes in total time budgets. When partitioning the variances of the time-activity measurements, they found that only 14% of the total variability in the time spent in the kitchen was due to differences between the women. Their findings highlight the strong variability in day-to-day cooking behavior in the population, which sharply contrasts with the low day-to-day variability in stove usage measured with the SUMs (chapter 3).

4.2.2 Behavioral determinant of exposure in the Mexico Patsari® Stove Project

In the chimney-stove intervention carried out in Mexico, Romieu et al. (Romieu et al. 2009) measured the lung function and followed the reported respiratory symptoms and level of stove use during the 10 months following the construction of a chimney stove randomly assigned to 552 women. Through follow-up household surveys and recall questionnaires they found that only 50% of the group adhered to the use of the cookstove and continued to use instead the traditional cookfire. The researchers stratified the population by the main type of stove used for tortilla making[7]: stove users (those using mainly the new stove and those combining the new stove and the cookfire) and cookfire users. Within these categories they found statistically significant differences in the health outcomes and symptoms.

In the same study in Mexico, Arnez et al. (Cynthia et al. 2008) measured 24-hr personal exposure and kitchen area concentrations of CO and PM2.5 in a sample of 60 homes from the intervention group that received the Patsari stove. To reduce the between-household variability in exposure measurements, all households were selected from one community and the sample was restricted to homes where the kitchen was an enclosed room, which is the configuration present in 90% of the full study sample. The authors found statistically significant reductions in personal exposures to CO and PM2.5 before and after the installation of the Patsari only in the group of participants that reported exclusive use of the Patsari. They did not detect significant before and after differences in those combining the Patsari and the cookfire. Despite the efforts of the researchers to constrain the between-household variability via household selection, the variability in all groups remained high. The reported between-household variance in was approximately double that of the within-household variance. They postulated that given the similarity in household baseline covariates and the uniform ventilation conditions from the restricted house structure selection, these differences rise from stove usage patterns, differences in cooking habits and to the fact that some of the homes could have been using an additional open cookfire in another location for other cooking tasks.

The evidence from the Guatemala and Mexico stove trials shows that a large portion of the variability in personal exposure and area concentration measurements remained unexplained after adjusting for all the non-behavioral characteristics of the households

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[7] Tortilla making in this population accounts for up to 40% of total fuelwood use.

and individuals. In sum, the case studies attributed the residual variability to behavior – namely: to the patterns of stove stacking or prevalence of traditional fires, the practices for kitchen ventilation, stove operation and stove maintenance; and, to the daily patters of time-activity and time-location. In the remaining sections of this chapter I will focus on the first of these behaviors.

4.2.3 The stacking of fuels and stoves

In the following sections I examine the patterns of stove stacking in the Guatemala RESPIRE-CRECER studies. I previously mentioned evidence from Africa, Asia and Latin America (Masera et al. 2000; Heltberg 2004; Heltberg 2005; Hiemstra-van der Horst and Hovorka 2008; Joon et al. 2009) increasingly suggesting that when new stoves are brought into the homes, it is seldom that the old ones are completely phased out; and that in many cases old and new stoves coexist on a long-term basis. Two case studies of stove stacking are particularly relevant to the discussion of stove stacking in RESPIRE and CRECER: the study by Redman in El Salvador, and the study by Zamora et al. in Mexico. Both studies take place in geographic contexts similar to that of the RESPIRE-CRECER studies; and, both document the introduction of fuelwood chimney stove similar to the Plancha stove design disseminated in RESPIRE and CRECER.

Redman (Redman 2010) studied the integration of the “Justa” stove into the homes of 27 rural households in a community in El Salvador. The Justa is a stove based on the “Plancha” exterior design (detailed in section 3.2.3), with the addition of a “rocket elbow” that provides a more efficient combustion chamber (MacCarty et al. 2008). Redman found that 89% of the interviewed homes combined the use of wood and gas (LPG) fuels. He suggested that the use of multiple fuels and stoves in the community appeared highly stable and not in a transitory state, and documented that at least one-third of the households had been using LPG stoves and fuelwood for more than a decade with no signs of a complete switch to LPG. To understand the transitory or long-term status of the stacking of stoves and fuels, Masera et al. (Masera et al. 2000) suggested, in their introduction of the “multiple fuel model”, that to characterize the mechanisms and factors that regulate the extent to which the use of multiple fuels is a transient state, a long-term condition or a dynamic process sensitive to “switch backs” is necessary to consider— namely, that *“fuel switching as a process resulting from the simultaneous interaction of factors pushing households away from biofuels and others pulling them back toward biofuel use, a bi-directional process.”* The authors point out that due to the complex and bi-directional nature of the adoption process, the causes of the transition cannot be attributed to a particular variable.

In the study of sustained use of the Patsari stove in Mexico (section 1.2.3) Zamora (Zamora 2011) identified at least two factors leading to stove stacking. The need for heat generation and the traditional attachments to ancestral cooking practices, she reported, significantly restricted households from reducing their use of open fires. Zamora found that in all of the 7 communities interviewed the Patsari stove completely replaced the open fire for making tortillas. However, the Patsari only partially replaced the use of the fire and the LPG stove for less energy-intensive cooking tasks like boiling water for tea or coffee and for reheating food. Zamora reports that overall households were more likely to use the Patsari stove for higher energy-intensive cooking tasks like preparing tamales and *nixtamal*. Redman also documented in his study the specific use of each stove type to prepare specific dishes. He found that more than 85% of the population in his study combined the open fire, the Justa stove and the LPG stove.

4.3 Combined cookstove and fire use in the RESPIRE and CRECER Studies

The RESPIRE and CRECER epidemiological studies (Section 1.3.1) investigated from 2002-2010 the effects that cooking with biomass had in the health of children and women from 27 communities in highland Guatemala. The baseline characteristics of the population measured during RESPIRE (2002-2004) (McCracken et al. 2009; Smith et al. 2010; Smith et al. 2011) and at the beginning (2006) and end (2010) of CRECER (Table 3.1 and
Table 3.2) portray a population with very stable characteristics—namely: household size, house structure, asset index, occupational profiles, educational level and receipt of remittances from the U.S.A.. Close 100% percent of the households considered themselves indigenous (Mam) and many of them own their homes and a piece of land. A typical house has an aluminum roof, adobe walls and dirt floor in the main living area. Whereas there is a large degree of homogeneity in the structural characteristics of the houses, determinants of household air pollution exposure vary widely, such as the number of eaves in the houses, the number of windows left opened during cooking and the number of hours spent cooking daily.

4.3.1 Cooking tasks and other end-uses of the open fires

Fuelwood is widely available in the region (Granderson et al. 2009) and it is the exclusive fuel used for cooking, only combined with much smaller amounts of crop residues and plastic bags and bottles. Only two out of the 532 households in the CRECER study reported using LPG for cooking. The use of charcoal was reported during RESPIRE only by four households but it was not exclusively associated with cooking. The configuration of the cookfires in the CRECER households consists of tree-stone fires either on the kitchen floor or made in elevated platforms, with the former being the dominant setup. The population has well-defined meal times: breakfast, lunch, dinner and, in some households, an intermediate snack between meals (locally known as *refacción*, Table 3.5).

In the RESPIRE study, the following tasks were identified as the dominant activities performed with the open fires: cooking food for the family, preparing animal feed (for the

pigs), heating water (for bathing), space heating, *nixtamal* (cooking of the corn kernels in big pots to prepare dough for tortillas), postpartum period (healing period after childbirth when mother and their newborns spend most of the time near an open fire) and preparation of food for special celebrations. A culturally relevant and intense end-use of the wood fires in the region is fueling of the traditional steam bath. More than eighty-percent of the households build fires 1-2 times per week inside small rooms (5.5 m^3 volume) to generate sauna-like conditions and bathe (
Table 3.2). The adobe structures, locally called *chuj*, are separate from the main house and usually have no windows. The significant contributions to the exposure to household air pollution from this fire end-use have been thoroughly documented elsewhere (Thompson et al. 2004; Lam et al. 2011; Long et al. 2011; Thompson et al. 2011).

4.3.2 Patterns of fire use in the RESPIRE Study

In RESPIRE, the frequency of stove and fire use were assessed using weekly questionnaires performed by local fieldworkers. The recall questions were answered by the main cook and included: frequency of stove use during the week (always, sometimes, never), prevalent use of open-cookfire (yes/no) and the tasks performed with the open fire (food for the family, animal feed, space heating, water boiling and other). The questionnaire and the complete RESPIRE research protocols can be found elsewhere (Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith 2011)(Smith). Figure 4.1 shows the adoption process of the cookstove (blue, upper line) and the gradual disuse of the open fire (red, lower line). Each data point represents the percent of usage for cooking devices each week (out of all households interviewed in a given week) during the first 13 months after the Plancha cookstove was built. Only the 269 homes receiving the stove at the beginning of the study (intervention group) had their open-fire use monitored with the questionnaires. The start time of all houses has been synchronized in the figure, as discussed in section 2.3.3, to account for different stove construction times and curing periods.

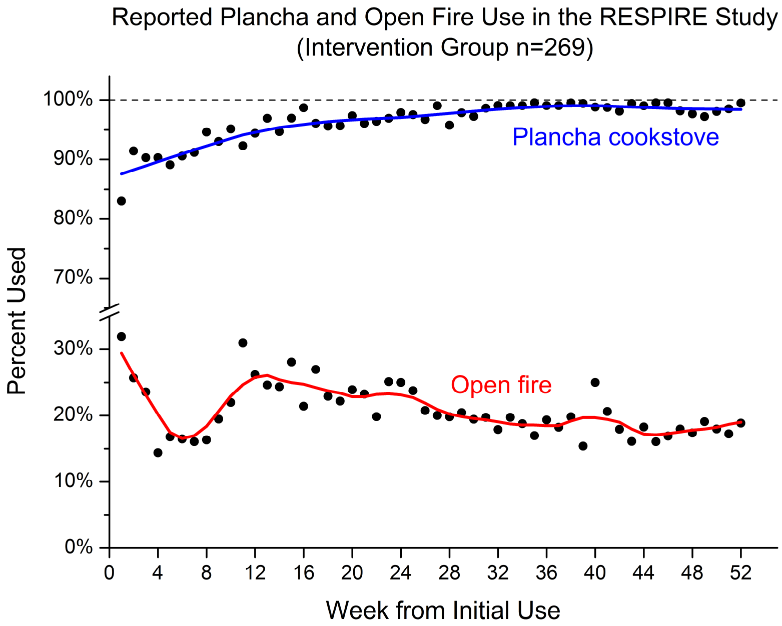

Figure 4.1 Percent stoves used (above) and open fires used (below) from recalled questionnaires during the first 52 weeks of the RESPIRE Guatemala study. Every point represents the percent of stoves or fires used in a given week from all households monitored in that period. The smoothed lines (locally weighted least squares) highlight the gradual increase of stove usage and decreased prevalence of open-fire use during initial adoption during the learning period that lasted 32 weeks. Despite the high levels of sustained stove use (99%), a 18% residual level of fire usage is observed.

The curve of stove adoption started with a level of initial use around 90% and gradually approached 99% sustained use after a learning period of 32 weeks. The shape of this curve is similar to the ones discussed in section 2.3. On the other hand, the level of open-fire use gradually decreased with time but did not reach zero percent. The level of residual fire started around 30% and seemed to experience a dip during weeks 4-8, reaching 30% again by week 11. The fire use falls steadily afterwards to stabilize at 18% by week 32.

When the level of open-fire use is broken down into tasks (Figure 4.2), I find that the preparation of animal feed is the strongest contributor to residual open-fire usage. About 15% of the study homes preserve this fire tasks, such that it is the only one that did not decrease over time. The amount of animal feed that households prepare usually requires cooking of grains in large pots that become heavy when filled. In conversations with the study families, local fieldworkers and staff, it was revealed that there are two main reasons for women to prefer the open fire for this task: the difficulty to lift and remove the heavy pots from the elevated surface of the Plancha and the fear that the stove surface will subside due to the heavy weight. The latter is also recognized as the reason for preparing *nixtamal* in the open fires. All tasks other than cooking animal feed (preparing food for the family, space heating, heating water for bathing, preparing *nixtamal* the postpartum period and special events) gradually decreased the use of open fires to below 5% by week 32. In the questionnaires, the tasks were not exclusive, i.e., households could respond if they were using the fire to perform more than one task.

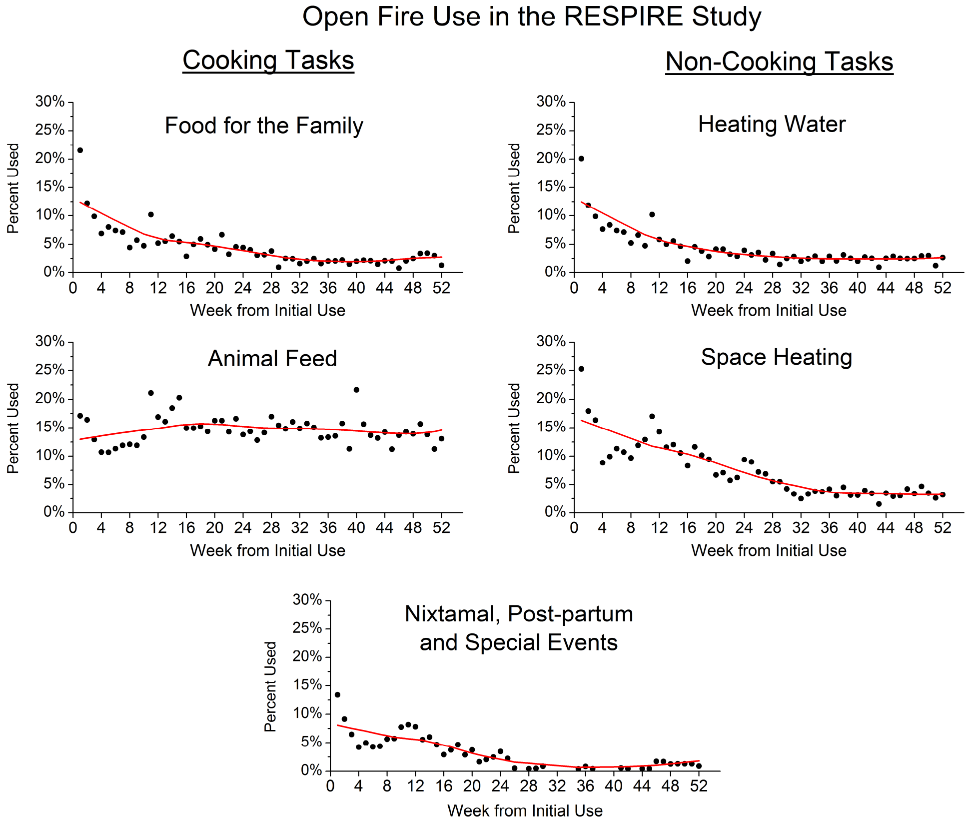

Figure 4.2 Percent of open fires used (from all households interviewed in a given week) during the first 52 weeks of the RESPIRE Guatemala study. Fire usage was assessed with recall questionnaires. The smoothed lines (locally weighted least squares) highlight the decrease use of the open fire for all tasks except the preparation of animal feed, which remained fairly constant at 15%.

4.3.3 Patterns of stove and fire use in the CRECER Study

In CRECER, the stove and fire use frequency were recorded with the quarterly recall questionnaires described in section 3.2.5.1 and with the SUMs. The questions included: stove use in the past three months (yes/no), frequency of open cookfire use in the past three months (daily/2-4 times per week/once per week/twice per month/once per month/not at all), location of the fire (inside/outside the kitchen) and the tasks performed with the fire (yes/no response for: food for the family, animal feed, space heating, boiling water, *nixtamal*, postpartum, special events, other).

I used graphic tools known as “heat maps” to visually identify clusters of households with similar combined stove-fire use behavior in the CRECER households monitored with the SUMs. For the long-term indicator of household stove usage I used the random effects estimate (Chapter 3) of the SUMs-measured stove-days and daily meals of each household. For the long-term indicator of household fire usage I used the fire frequency and fire tasks from the recall questionnaires performed at the end of the 16th SUMs monitoring period. The latter seemed a valid representation of the level of fire use during the SUMs monitoring period, based on the stable fire use observed in RESPIRE after the construction of the stoves (Figure 4.2). Four of the 80 households in the sample (Table 3.1) did not have questionnaire data and thus were excluded from the analysis.

4.3.3.1 Heat maps

Heat maps are colored graphic representations of hierarchically clustered data. They are widely used in genetic expression analysis. Wilkinson et al. (Wilkinson and Friendly 2009) describe a heat map as:

> *…an ingenious display that simultaneously reveals row and column hierarchical cluster structure in a data matrix. It consists of a rectangular tiling, with each tile shaded on a color scale to represent the value of the corresponding element of the data matrix. The rows (columns) of the tiling are ordered such that similar rows (columns) are near each other. On the vertical and horizontal margins of the tiling are hierarchical cluster trees.*

To display the patterns, the data matrix of households -rows in this case- and their variables -the columns- are permuted and ordered in tree-like structures that are built by progressively merging clusters using a similarity metric and an agglomeration method. The hierarchy and similarity between clusters is indicated at the top of each axis by a dendogram. Dendograms are a set of U-shaped lines that connect the objects in the hierarchical tree. The height of each branch of the dendogram represents the distance. The shorter the height of the branches, the more similar the clusters are.

The heat maps in this chapter were generated with the statistical program R (R Foundation for Statistical Computing, Vienna, Austria) (R Development Core Team 2011) using the heatmap.2 function from the package gplots (Warnes 2012) and the colors were enhanced using the package RColorBrewer (Neuwirth 2011). For the cluster function in heatmap.2, I used a Euclidean distance measure and a complete linkage method (Kettenring 2006).

Figure 4.3 is a heat map of 3 indicators of stove usage: SUMs-measured stove-days (right), SUMs daily meals (left) and the stove use from recall questionnaires (middle) in the sample of 76 households. The three variables have been re-scaled to cover the range of 1 to 2 (green to red) and stove usage increases from the bottom to the top of the figure. The recall questionnaires show two distinct categories of households using the Plancha stove daily (in red) and those with infrequent use (green).

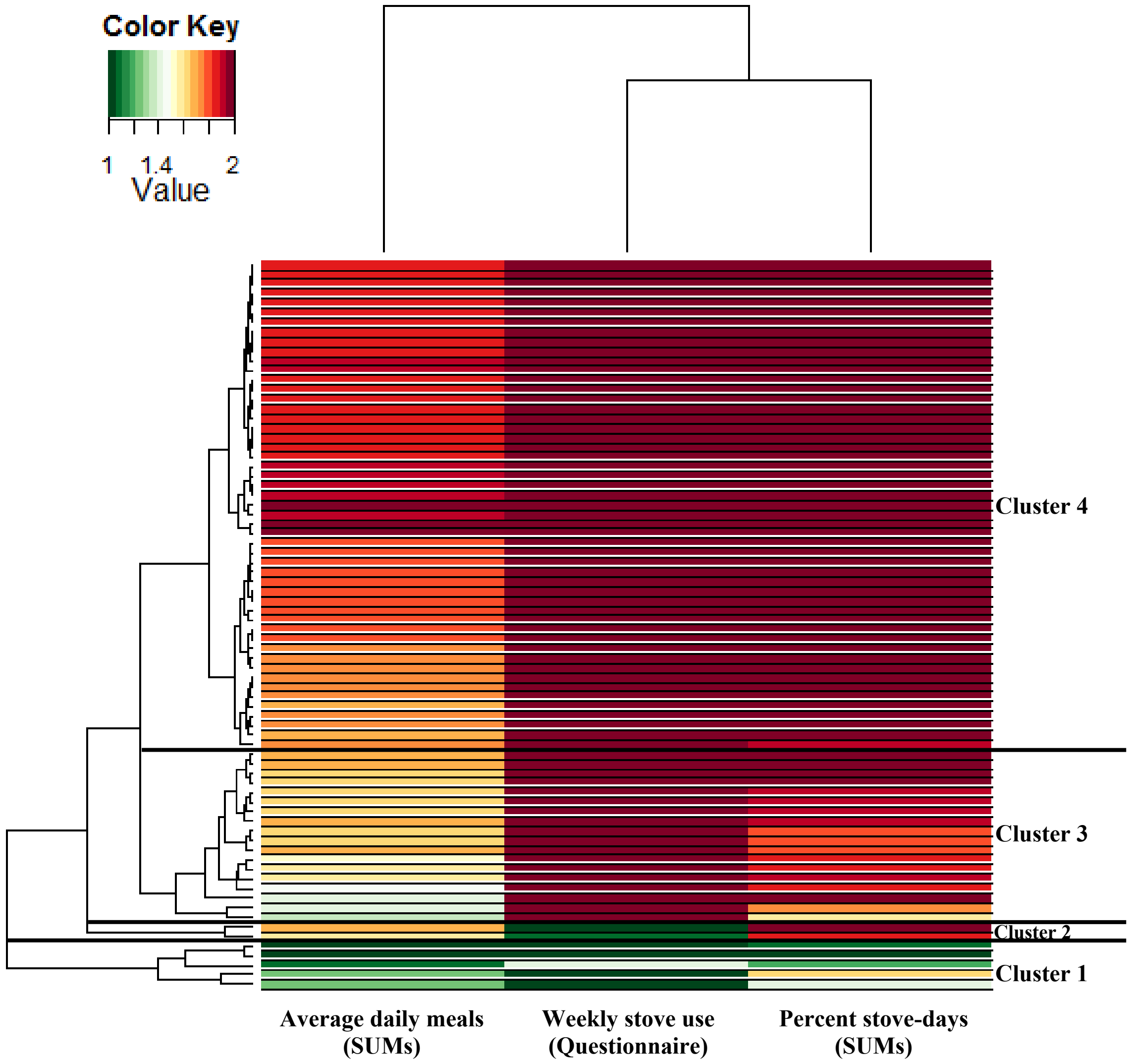

Figure 4.3 Heat map comparing 3 indicators of stove use: the days per week that the chimney stove was used according to recall questionnaires (middle), the average daily meals measured with the SUMs (left) and percent stove-days measured with the SUMs (right). The variables are scaled to encompass the range from 1 to 2. Green dark colors show the lowest value and red dark colors the highest values. The horizontal dashed lines separate clusters defined by the four highest levels of the hierarchical tree on the left.

The lower category of infrequent stove usage agrees with lower daily meals and lower percent of stove-days. Among the households reporting daily stove use, however, a gradient of SUMs-measured usage is observed. Most notably, two groups can be distinguished: one with nearly uniform 100% stove-days (tile on the right hand corner) and high daily meals (darker red tones), and a second one with variable percent stove-days and lower daily meals (white to orange tones). The variability of tones in the left and right columns highlights the increased resolution of the SUMs measures compared to the questionnaires. Four distinct clusters of households can be identified by cutting the first four levels of the hierarchical tree, as shown by the 3 horizontal lines. From bottom to top, Cluster #1 has the 5 households with the lowest measured and reported stove usage. Cluster #2 has 2 households that reported not using the stove but that had high percent stove-days and daily meals. Cluster #3 has 18 households with medium percent stove-days and daily meals; and, Cluster #4 has 51 homes with the highest measured and reported stove use.

In the following section the heat maps of the stove and fire use data for the 76 households are analyzed together to identify "tiles" or clusters with characteristic behavioral patterns of combined stove and fire use.

4.3.3.2 *Stacking clusters*

The frequency, location and tasks performed with the open fires from the CRECER recall questionnaires[8] were used as the indicators of open-fire use to generate a heat map of combined stove and fire use.

Figure 4.4 in the next page is a heat map of the reported and SUMs measured stove use (2 columns on the left) together with the indicators of fire usage. The values for stove use (daily meals and percent stove-days) and fire use frequency (days per week) were re-scaled from 1 to 2. The other indicators of fire use are binary: fire tasks (1=no, 2=yes) and fire location (1=outside, 2=inside).

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[8] The accuracy of these questionnaire responses has not been compared to SUMs measures on cookfires yet, but the strong agreement between stove use questionnaires and SUMs in cookstoves (discussed in chapter 3) indicates that accurate responses regarding fire use would be expected in the population

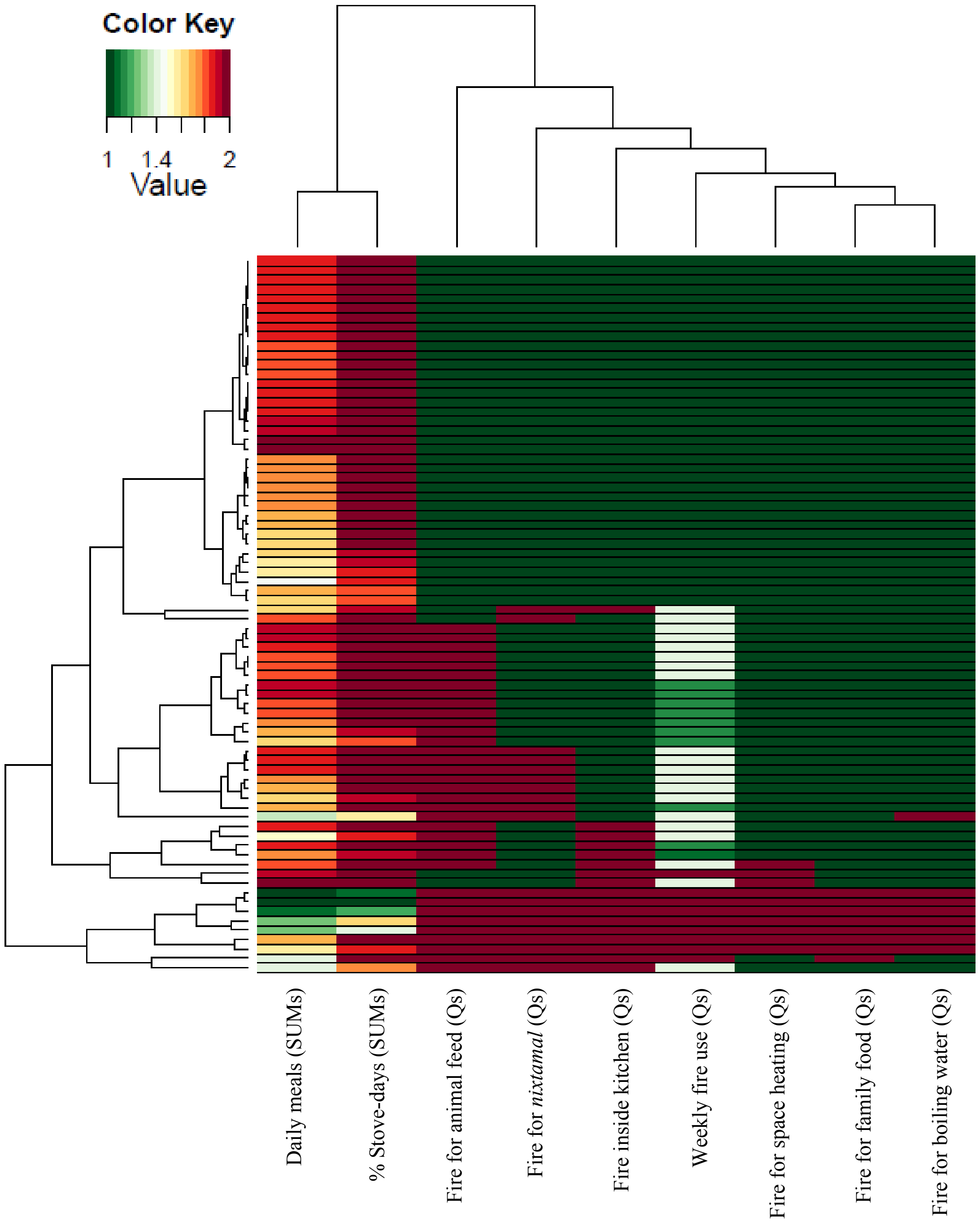

Figure 4.4 Heat map displaying clustering of SUMs-measured (SUMs) stove usage (average daily meals and percent stove days), weekly fire use from recall questionnaires (Qs) , fire use by task (preparation of animal feed, preparation of *nixtamal*, space heating, preparation of animal food); and location of the fire (inside/outside the kitchen). The daily meals, percent stove-days and the weekly frequency of fire use are rescaled to cover the range from 1 to 2, while the rest of the variables are binary (1 = No, 2 = Yes).

Half of the households continued using the open fire (green tile on the right hand corner of Figure 4.4). A salient feature of the heat map is that the lowest levels of measured stove use (green tones on the left) are concentrated in the lower part of the map, in the households that used the fire (red) for almost all the tasks every day. The most common fire task in the sample is preparing animal feed (46% of the households), followed from left to right by: *nixtamal* (25%), space heating (13%), boiling water (11%) and preparing food for the family (11%). The levels of fire use for these tasks tripled the ones found during sustained fire use at the end of RESPIRE: animal feed (15%), space heating (3.3%), boiling water (2.5%), food for the family (2%) and *nixtamal* (1%). The hierarchy of tasks from RESPIRE is preserved in CRECER, except for *nixtamal* which in CRECER was more frequently reported as a fire task. The total percent of households using the open fire also increased from the 18% reported in RESPIRE to 51% found in the CRECER sample.

I identified 9 stove and fire "stacking clusters" (i.e. groups of households with similar behavioral patterns of combined use) by cutting a straight line in the dendogram and treating each of the first 9 branches as a cluster. This is the most common approach to partitioning heat maps into clusters (Kettenring 2006). The clusters are shown in Figure 4.5 and described in Table 4.1, starting from the bottom to the top of the map.

Branch	**Stacking Cluster (n)**	**Fire Tasks**	**Description**
9	No fire – high stove (37)	0	High stove use. Fire not used at all.
8	*Nixtamal* (2)	1	High stove use. Fire used for *nixtamal*.
7	Animal feed (7)	1	High stove use. Fire outside the kitchen to prepare animal feed.
6	Animal feed & *nixtamal* *(3)*	2	High stove use. Fire to prepare animal feed and *nixtamal*.
5	Animal feed & *nixtamal*& water (4)	3	High stove use. Fire used to prepare animal feed, *nixtamal* and boiling water.
4	Animal feed (inside) (1)	1	High stove use. Fire inside the kitchen to prepare animal feed.
3	Space heating (inside) (7)	1	High stove use. Fire inside the kitchen for space heating.
2	All fire – low stove (inside) (13)	5	Low daily stove meals. Fire inside the kitchen used for all tasks.
1	Some fire – medium stove (2)	2-3	High stove use (% stove-days), moderate daily stove meals, fire used for animal feed and *nixtamal*.

Table 4.1 Description of the nine stacking clusters identified in the heat map of stove and fire usage shown in Figure 4.5.

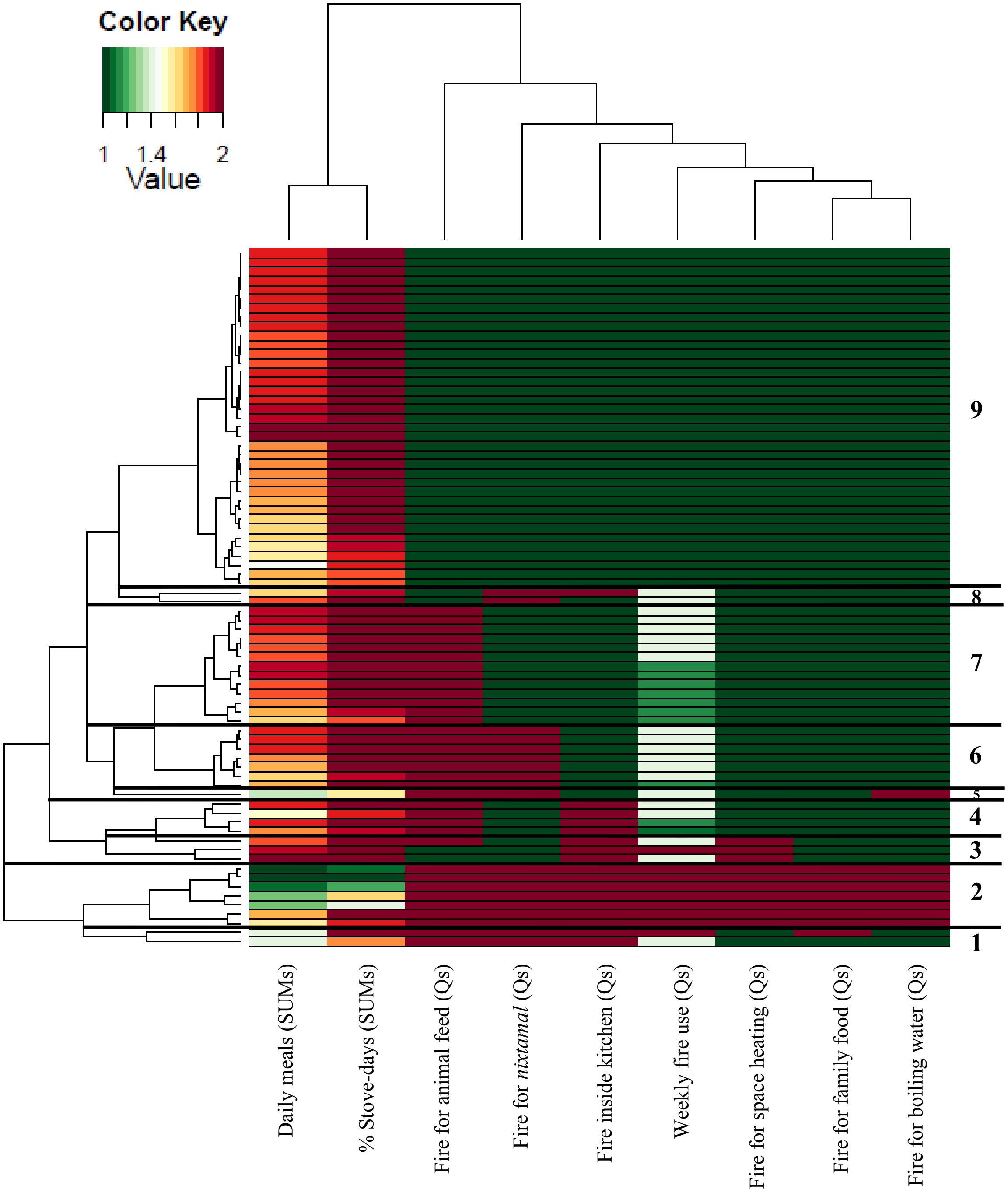

Figure 4.5 Heat map displaying the 9 "stacking clusters" of SUMs-measured stove usage (average daily meals and percent stove days) and reported fire use (weekly frequency, task and location). The daily meals, percent stove-days and the weekly frequency of fire use are rescaled to cover the range from 1 to 2, while the rest of the variables are binary (1 = No, 2 = Yes)

The small sample size causes some branches in the tree to have as few as 1 or 2 households. The heat map portrays a population with the following stove stacking behavior regarding the 5 fire practices analyzed:

- When all the tasks are performed with the open fire (including food for the family) the level of stove use is low and the fire is maintained inside the kitchen.
- The open fire is predominantly used to prepare animal feed. Twenty-three percent of houses performing this fire task built the open fire inside the kitchen.
- Space heating, as expected, is performed with the open fire inside the kitchen.
- When households build an open fire but do not use it to prepare food for the family, the predominant open-fire task that is not combined with others is the preparation of animal feed. Animal feed seems to require specialized open fires that are not shared with other tasks. Only one household in the sample built a fire that was exclusively dedicated to space heating and two households used the open fire exclusively to prepare *nixtamal*.

4.4 Impacts of the stacking of stoves and fires

The clustering analysis performed using the heat maps in the CRECER sample supported the stove stacking patterns found during the RESPIRE study and provided insights into the process of stove adoption. In the following sections I discuss the relevance of stacking clusters to identify groups and tasks that can be targeted to improve stove dissemination and to identify the sources of exposure variability to indoor air pollutants.

4.4.1 Target groups and "anchor tasks"

The selection of stacking clusters obtained by cutting the dendogram allows the identification of target groups that are at risk of high air pollution exposure or that offer clear opportunities to optimize a stove program. For example, the second, third and fourth stacking clusters in the previous heat map (Figure 4.5 and Table 4.1) are likely to have the highest concentrations of kitchen air pollutants due to the fire that is kept inside. Among them, the second cluster is likely the most at risk of high air pollution because it uses the indoor fire to perform all five tasks. An intervention targeted at these clusters could be one of the most cost-effective approaches to improve the effectiveness of the stove program (see the related discussion in chapter 3 Figure 3.13 and section 3.4.2).

The classification of clusters with the heat map also assists in the identification of key tasks, such as the preparation of animal feed. The initial adoption and sustained use of an advanced biomass stove that is appropriate for the preparation of animal feed (built at a lower height to avoid the lifting of heavy pots) would bring significant reductions in fire use. As discussed in the previous section, this task is the only one of the five that when performed with the open fire is found in the population both as the only fire practice in the home and in combination with other fire tasks. This hints at the possibility that this task can act as an “anchor task” in the sense that if preserved it can trigger the preservation of other fire tasks. A similar phenomenon has been observed in the adoption of the Patsari stove in Mexico, where tortilla making is the first task that “anchors” the sustained use of the Patsari for other cooking tasks. Further analyses in the full CRECER and RESPIRE populations will be necessary to confirm the existence of anchor tasks for the case of the open fires.

4.4.2 Increased variability in the population exposure to indoor air pollution

One of the main consequences of the stacking of cooking devices is the contribution of the residual open-fire use to the variability in area concentrations and personal exposures to air pollutants otherwise caused by an improved stove alone. This increase is not only due to the more variable combustion behavior of the open fires, but also to changes in other household behaviors that affect exposure (time-activity and ventilation). The latter has been previously documented in the Guatemala and Mexico case studies and is summarized in the following sections. The key findings of these studies show that correct categorization of the fire and stove usage levels (i.e. identification of the stacking clusters) is crucial to accurately assess the effectiveness that an introduced stove has over reducing exposure to household pollution. Systematic identification of the stacking clusters can help avoid the misclassification errors that significantly bias the relationship between reductions in pollutant concentrations and reduction in personal exposures and health effects. The identification of stacking clusters, together with the characterization of the exposure “signatures” (Section 2.3.7) of the cooking tasks performed with each device will be key to understanding the role of other behavioral sources of variability within the clusters.

4.5 Conclusions

Open fires are a baseline option that households often preserve or come back to even after a new cookstove is brought into the home. Evident reasons for this behavior are the ease of building open fires quickly almost anywhere, and that these can be adapted to perform the different heating tasks that households require. In many cultures the end-uses of the open fires go beyond cooking. Thus, often, the introduced cookstoves are imperfect substitutes for all fire tasks and the stacking of cooking devices occurs.

Households with very high levels of sustained stove use could still be exposed to elevated concentrations of air pollutants from the continued use of open fires. Therefore, quantifying and monitoring the residual use of these fires is crucial to understanding the dynamics and to evaluate the impacts of the stove adoption process.

The concept of “stacking clusters” enables the development of a new framework of analysis that encompasses the whole cooking system and the behaviors related to usage: the old and new cooking devices and fuels, the users, the household dynamics, preferences and their contexts. When stacking occurs, households do not combine the old and the new devices and fuels at random. Evidence from the adoption studies in Mexico, from a study in El Salvador and the findings from the RESPIRE and CRECER studies discussed in this chapter confirm that each fuel-device combination creates an adoption niche based on the tasks where the combination best fulfills the needs of the user. Therefore, the cooking task is the relevant unit of analysis for understanding the stacking of cookstoves.

The heat maps are useful cluster analysis tools that capture the distribution of fire and stove usage in a population. The heat maps reveal information about household cooking behavior, needs and preferences and allow the design of strategies to increase stove usage and decrease fire use according to these preferences. The systematic identification of the stacking clusters using the heat maps enables the identification of groups at risk of high air pollution exposures based on their behavioral patterns of usage. Classifying households based on their combined level of usage for each device (the stacking clusters) is a better approach to represent their cooking behavior than simply stratifying them by the main type of stove used. Improving the classification reduces misclassification errors and bias in the assessment of the total exposure, health and environmental impacts of cookstove programs.

In the RESPIRE and CRECER studies cooking animal feed was the open-fire task that most households preserved and the only one whose frequency did not decrease after the introduction of the Plancha chimney stove. This task seems to act as an anchor to other tasks, i.e. once a fire is built to prepare animal feed, the preparation of *nixtamal* or other tasks seem more likely to be performed with that fire. The accuracy and the drivers of the increase in the population level of reported fire use observed in the CRECER subsample (51%) with respect to RESPIRE (18%) require further study, to understand the dynamics of prevalent fire use in this population. The stratification of the SUMs-measured stove use in the CRECER study observed with the cluster analysis is strongly driven by the preferences of the households for using the stove or the fire for specific tasks. This explains why the household covariates alone could not account for the 76% of the total variability in SUMs-measured stove use that was contributed by between-household differences.

The stacking of stoves is only one of the behavioral components that critically affect the performance of the so called improved cookstoves. There is a need to develop tools and methods, like the Stove Use Monitors, to objectively quantify other household behaviors that regulate the exposure to household pollutants, such as daily patterns of time-activity and time-location and the practices of kitchen ventilation, stove operation, stove maintenance and fuel preparation. In particular, there is a critical need to expand the analytical framework proposed in this chapter to clearly differentiate the distinct behavioral components that affect the initial acceptance or purchase of a cookstove, its sustained use, the abandonment of the traditional fires and the reductions in fuel use, household air pollutants and greenhouse gas emissions.

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Chapter 5

Conclusions

5 Conclusions

5.1 Summary of findings and conclusions

The dissemination of cookstoves with verified improved combustion efficiency has long been identified as one of the most cost-effective health, energy and climate measures to meet goals of improved health, reduced poverty, social welfare, environmental sustainability and simultaneously reduce emissions of climate-active pollutants. Stove programs have captured again the attention of governments, development organizations and donors in recent years. Nevertheless, the focus has been in developing new stove designs, improving large-scale manufacturing processes and implementing market-based models to disseminate stoves. Relatively few efforts have been dedicated to understanding the behavioral aspects of stove adoption and to design strategies to optimize it. Although central, the role of the stove user in the cooking system is often overlooked and there have been no quantitative metrics to assess adoption dynamics and understand the factors that affect user behavior to assess and design dissemination strategies.

In this dissertation I presented framework of analysis to characterize the stove adoption process. I introduced the concept of Stove Use Monitors (SUMs) and developed field methods, signal analysis, metrics and visualization tools to quantify the process using low-cost temperature dataloggers as SUMs. The conclusions of this dissertation are detailed below. The first section is written in the form of 12 claims about the stove adoption process, each explained by the key findings from the chapters. The second section covers the findings about Stove Use Monitors. The third section contains the two concluding claims about the role of behavior in the adoption and impacts of cookstoves. Lastly, the fourth section refers to the SUMs-measured levels of stove use and the patterns of stacking found in the CRECER study.

5.1.1 The stove adoption process

1.- Providing access to the stoves is necessary but not sufficient to deliver actual benefits to the households: people need to use the stoves on a the long-term basis, reduce their open-fire use and the introduced technology needs to maintain its performance over time.

The extent of the impacts from stove disseminations depends directly on the extent to which people continue using the stoves and reduce the fire practices that initially exposed them to household air pollutants. Therefore, impact assessment of these programs need to clearly differentiate between the number of stoves distributed or initially accepted (purchased or simply brought in to the household) and those actually used and maintained in good condition through the years.

2.- Understanding of the stove adoption process requires consideration of the whole "cooking system" that is beyond the stove technology alone.

The few frameworks that exist to characterize stove adoption have been developed slowly considering that improved cookstoves have been disseminated for more than thirty-five years. The premise that previous approaches to the stove adoption problem do not explain the processes documented in field studies confirms that the emphasis of previous frameworks needs to be redefined. I conclude that the dynamic complex interactions that take place among stoves, fuels and household behavior within the greater socioeconomic and ecological contexts require consideration of a group of elements (the cooking system) to describe the adoption process. Although this dissertation focuses on the specific behavioral outcomes and patterns of stove use, I acknowledge that stove adoption is both a process and a stage in a larger process of technology absorption, cultural adaptation and appropriation of the technology.

3.- Stove adoption is a dynamic learning process that can be characterized by defined stages and critical parameters.

The case studies presented in the dissertation, and the literature discussed, indicate that a new stove that is brought into the home is incorporated following a learning curve. The adoption curve has specific timing and saturation levels that depend on the characteristics of the users, the stoves, and the degree to which households are able to incorporate and combine them with the existing practices. I find that at the population level the stove adoption process can be described in terms of three stages: (1) initial adoption (or learning-adjustment); (2) sustained use (or stabilization); and, (3) disadoption. Furthermore, the adoption process can be characterized by the critical parameters: (a) the initial acceptance (A_0) of the fraction of the families that were offered the new stove; (b) the learning time (ΔL) after acceptance for the population to incorporate the device into the existing cooking practices; (c) the level of initial use (U_0) during the initial adoption stage; (d) U_{max} – the maximum level of use observed; (e) the stable level of sustained use

(U_{sust}) after initial adoption; and, (e) ΔU_{sat} the size of the fluctuations around the mean U_{sust}.

4.- The complex interactions of the adoption process require analysis from a systems perspective. The dynamics of the process requires monitoring at different points in time.

The analysis and, particularly, the optimization of the adoption process require understanding of the cooking technology-behavior interface and an integrative systems perspective to analyze the socio-cultural, economic, ecological and infrastructural factors that regulate the performance of cookstove programs. The dynamic nature of the adoption process requires measuring usage at different times and on all the devices present in the households, to identify critical parameters such as levels of equilibrium or tipping points where the process can be influenced.

5.- The innovation being introduced in the case of cookstoves is not only a technological device but rather, a set of new or improved "cooking practices" that involve changes in household behavior.

The main goal of a cookstove user is to prepare cooked food rather than the consumption of fuel per se or the utilization of the cooking device itself. Therefore, the introduction of a new stove technology into the existing cooking system modifies the cooking practices and/or creates new ones.

6.- The "cooking tasks" are the relevant unit of analysis to understand the changes in cooking practices.

Cooking is not a single activity, but rather, the aggregation and interaction of different cooking tasks. Each task (e.g. fry rice, make tortillas, boil water, etc.) has specific energy demands (fuel consumption, energy output), characteristics (household preferences) and relevance for the households (cultural traditions). The definition of the tasks themselves is dynamic in nature and their changes have different time scales. The findings from the patterns of use in the RESPIRE and CRECER studies confirm that, when a new stove is introduced the changes in household cooking practices do not occur at random. Rather, as described in the stove adoption studies in Mexico, the changes in cooking practices are task-centered, whereby the cooking practices adapt to fulfill the requirements of the tasks.

7.- When a new stove is brought into the home each cooking device redefines its own "adoption niche" and is used for the cooking task(s) where it best fits the needs of the household.

With the introduction of a new stove the interactions between the user and the previous cooking fuels and devices are redefined. Each fuel-device combination creates its own adoption niche based on the compatibility and comparative effectiveness to fulfill a given task. For instance, the patterns of stove and fire use in CRECER confirmed a marked preference of the open fires for specific cooking tasks.

8- When the original end-uses of the open fires extend beyond cooking, the cookstoves are imperfect substitutes for all fire tasks and households combine or "stack" the use of both cooking devices.

The redefinition of adoption niches for each cooking devices leads to the combined use (or stacking) of new and traditional stoves and fuels rather than to complete switching. The field evidence from the two case studies discussed in this dissertation shows that this process is regulated to varying degrees by tradition, resource availability and perceived costs, and that it often leads to the redistribution of the cooking tasks that are performed with each device.

9.- The transition from open fire to stove of each cooking task has different impacts.

The modified cooking practices brought by the new stove being introduced can have different impacts in terms of fuel consumption, exposure to smoke, pollutant emissions, cooking time, time spent in the kitchen or stove operation. The adoption studies in Mexico document these "signatures" for the case of indoor air pollutant concentrations.

10.- The residual use of open fires impacts the exposure assessment of household air pollution: it increases variability and can induce misclassification errors.

One of the main consequences of the stacking of cooking devices is the contribution of the residual open-fire use to the variability in area concentrations and personal exposures to air pollutants otherwise caused by the introduced stove alone. This increase is not only due to the more variable combustion behavior of the open fires, but also to changes in other household behaviors that affect exposure such as time-activity and ventilation. The prevalent use of the open fires is a crucial component of the stove adoption process that must be measured and monitored together with stove usage to assess the total impact of the cookstoves. The residual use of fires affect the researcher's ability to accurately assess the impacts of stove disseminations because groups with high levels of stove use could still be exposed to high concentrations of pollutants from the fires.

11.- The classification of household into "stove stacking clusters" enables identification of groups at risk of and opportunities for targeted improved dissemination.

The categorization of the households according to their combined levels of fire and stove usage (stacking clusters) enables analyses of a more complete cooking system of household characteristics, devices and fuels and users preferences. The heat maps proved to be useful graphic tools to identify stove stacking clusters, key cooking tasks, and to capture information about household cooking behavior, needs and preferences.

Identifying the households that preserve a large number of open fire tasks or that keep the fire indoors allow rapid identification of groups at risk of high exposure to the household air pollutants. Households that regularly use the improved stove could still be exposed to the air pollutants from the prevalent use of open fires, particularly if they keep the fires indoors. With the heat maps these clusters can be easily identified to design of strategies to reduce their exposure taking into consideration their cooking needs and preferences. The information about the nature and frequency of the key fire tasks can inform interventions to target the users with the highest adoption potential to reduce those tasks and the substitution of the cooking tasks with the highest indoor air pollution or greenhouse gas contributions.

12.- Stove adoption is a complex topic that merits its own line of scientific inquiry.

The stove adoption process affects the extent and impact of stove programs both directly and indirectly. The elements, boundaries, critical parameters and contexts of the adoption process proposed in this dissertation need to be further characterized and the factors that affect it understood and quantified. Interdisciplinary research and a systems perspective to address the stove adoption problem are needed to understand the interactions and interrelations of this process with other household behaviors that are also involved in the exposure to air pollutants from biomass use.

5.1.2 Stove Use Monitors (SUMs).

1.- The Stove Use Monitors (SUMs) enabled the parameterization of stove use behavior as a critical stove performance parameter that is equally important to the other stove technical specifications.

I introduced the Stove Use Monitors (SUMs) as devices that objectively quantify stove use through direct measurements of physical or chemical parameters on stoves, cookware or food. With the SUMs the parameters of the stove adoption process can be objectively measured, unobtrusively monitored and systematically evaluated together with the reductions in air pollution exposures, fuel consumption and greenhouse gas emissions.

2.- With adequate placement, standardized data collection and careful data management the SUMs can provide objective and unobtrusive data of stove use with resolution, accuracy and level of detail not possible before.

This new promising tool has enabled systematic and scalable monitoring of the stove adoption process, the design of targeted strategies to optimize it and the verification of the impacts of biomass stoves.

3.- Quantitative metrics of stove usage need to capture the number of stoves active in a monitoring period (the "percent stove-days") and the level of individual stove activity (daily meals or time of use) to capture seasonal patterns, patterns of daily use and differences across households.

The patterns of sustained stove use that I measured with the SUMs show that users with high and stable daily usage do not necessarily cook all three main meals on the stove. Therefore it is necessary to monitor usage at the meal level to quantify such phenomena. I find that metrics of sustained use like the percent of days that a single stove is used and the fraction of days that a group of stoves is used during a monitoring period (the percent stove-days) can summarize the number of stoves active in a monitoring period and thus, are enough to ascertain seasonal patterns or quantify the stoves completely abandoned. However, these metrics alone are insufficient to measure the actual level of stove activity when the frequency of meals or the time that the stove is used every day vary across households, as it is often the case due to the stacking of stoves and fuels. Other metrics like the average daily meals, the meals per stove-day or metrics of daily usage-of-use seem more accurate to quantify the aggregate level of stove activity and to capture patterns that take place at the level of the individual cooking tasks.

4.- Summary of findings regarding SUMs data collection and field performance of the iButton sensors as SUMs.

Perforated metal sheet holders made at the research site worked well to attach the sensors to the back surface at the chimney base of the Plancha stoves, where they recorded stove surface temperature every 20 minutes. Placement and sample rate of the SUMs can be determined with a two-stage protocol to first ensure the sensors operated within the manufacture specifications and to then determine the sampling rate and location that would provide enough data resolution to track usage at the meal level without interfering with the householder's activities. The choice of sampling frequency is a tradeoff between: (1) the temporal resolution required to measure stove use at the desired level of detail (day, meal, cooking task) given the thermal inertia at the stove location and the nature of the cooking cycles; and, (2) the frequency of visits that can be afforded given the maximum storage capacity of the devices. During the 32 months of the study, stove temperature signals from a total of 31,112 stove-days were recorded, with a 10% data loss rate (sensors lost, broken, exploded or about to explode from becoming too hot, programming incorrectly or anomalous behavior). This is a low bound estimate given by the strict protocols followed in the study. Only 5% of the 112 sensors used in total in the project had anomalous behavior. For high mass stoves like the Plancha the estimated overall sensor lifetime of the 1921G iButton is expected to exceed 1.5 years but shorter lives are likely for sensors placed in metallic surfaces or close to the fire, as they are exposed to higher daily swings and to temperatures closer to the manufacturer's limits. The sensors are not waterproof, only water resistant. The slow thermal response of the chimney stove body and the fairly defined cooking and fueling cycles in the study population facilitated the analysis of the signals without the need for smoothing. The peak detection algorithm based on the instantaneous derivatives and the statistical long-term behavior of the stove and the ambient temperature signals accurately counted the number of daily meals and determine daily usage. This might not be the case when faster sampling rates are used on stove surfaces that conduct heat better, such as a portable metal cookstove.

5.- Stove adoption performance measured with the SUMs in the CRECER study.

After Initial adoption (few days) daily stove use behavior was stable within households and highly variable between households (intraclass correlation coefficient=76%). During the first weeks of stove use carbon monoxide sensors co-located with SUMs showed reductions in indoor air pollution with increased stove use. During sustained stove use the highest variance and the lowest levels of stove usage were contributed by homes that reported combined use of stove and open cookfire. The population level of stove use had small (3-12%) but statistically significant seasonal variations, while the age of the stove and household size at baseline did not have an effect. Usage was highest during the warm-dry period from February to April, with 2.56 daily meals (95% CI: 2.40, 2.74) and 92% stove-days (95% CI: 87%, 97%). The seasonal behavior is potentially related to the easiness to operate the chimney stove with dry fuel. The high levels of sustained use found reflect optimal conditions for stove adoption in the CRECER trial. The narrow confidence intervals highlight the precision and accuracy of the SUMs to detect the small seasonal fluctuations. Recall questionnaires were consistent with the SUMs measurements of the 15-day and 3-month periods preceding the questionnaires and there was no significant difference between recall periods, indicating stable sustained use and questionnaire accuracy.

5.1.3 The role of behavior in the adoption and impacts of cookstoves

1.- Individual, household and community behavior are central to the actual field performance of the cookstoves technologies. Behavior also influences the activities around the stoves, critically affecting the exposure to household air pollutants.

All the cookstoves and open fires that contribute to the household air pollution are operated by people, who remain in close proximity to the stoves and fires tobtain the services sought from the devices: the preparation of food or liquids, space heating, gathering, socializing, healing, the fulfillment of traditions and rituals, etc. Therefore, the individual behavior of the household members and the dynamics of the families and communities are central to the actual field performance of the cookstoves. Furthermore, this behavior influences the activities around the stoves, critically regulating the exposure to household air pollutants.

2.- The behaviors affecting the purchase or initial acceptance of a cookstove can greatly differ from the behaviors that determine its sustained use and from those that prevent the abandonment of the traditional fires.

It is necessary to clearly define the different stages of the stove adoption process to identify the distinct behavioral components embedded in the initial acceptance of a cookstove, its sustained use, the abandonment of the traditional fires and the actual delivery of the stove benefits. The behaviors that are relevant to understand the purchase or initial acceptance of a new stove (willingness to pay, intent to buy or install, etc.) can greatly differ from the dominant behaviors that promote or restrain its sustained use (traditional cooking practices, household dynamics, etc.). Furthermore, even when the new stove is accepted and used in a long-term basis, there is a different set of complex behaviors that regulate the reductions in exposure to household air pollutants, in fuel use and in emissions: the patterns of stove stacking and the prevalence of traditional fires, the practices for fuel preparation, kitchen ventilation, stove operation and stove maintenance; and, the daily patters of time-activity and time-location of the household members.

5.1.4 Patterns of combined open-fire and stove use in CRECER

Despite the high measure levels of stove use, fifty-percent of the SUMs-monitored households in CRECER reported continued use of an open fire. This was triple the reported fire use found in RESPIRE. Animal feed was the most common fire task (46% of the households) followed by *nixtamal* (25%), space heating (13%), boiling water (11%) and preparing food for the family (11%). The percent of households that performed these fire tasks also tripled the percentages from RESPIRE. The stratification of the SUMs-measured stove use in the CRECER study was strongly driven by the preferences of the households for using the stove or the fire for specific tasks. This explains why the household covariates alone could not account for the 76% of the total variability in SUMs-measured stove use that was contributed by between-household differences. Providing the population with an improved stove that is appropriate for cooking animal feed (built at a lower height to avoid lifting of heavy pots) could significantly reduce fire use for this task and arguably for other tasks. The significant contributions to air pollutant exposure from the wood-fired traditional sauna (*chuj*) in this population need to be addressed.

5.2 Current research efforts and future directions

5.2.1 Stove use monitoring

The concept of the SUMs is not limited to temperature measurements or to the particular device used in this work. Future SUMs implementations measuring different parameters (heat flux, light, motion, current or voltage in fan-assisted stoves, etc.) are likely to contribute insights about aspects of stove and fire use not discussed here or about other types of household behavior relevant to stove adoption. In particular,

The SUMs measures of stove activity have unique characteristics. Unlike available methods to measure pollution and fuel use, SUMs measures offer higher resolution while being less intrusive, more objective, and potently quite cost-effective as sample size increases. These features are depicted in Figure 5.1, which is based on the "exposure pyramid framework" (Naumoff 2007). The current "gold standard," direct observation in people's kitchens to record stove use, becomes impractical and resource intensive over extended periods and numbers of households and changes householder's behavior. The SUMs are a passive, unobtrusive, and objective measuring system that would seem to offer the highest resolution and the lowest reactivity in stove use now available for biomass-using households, arguably offering a new "gold standard".

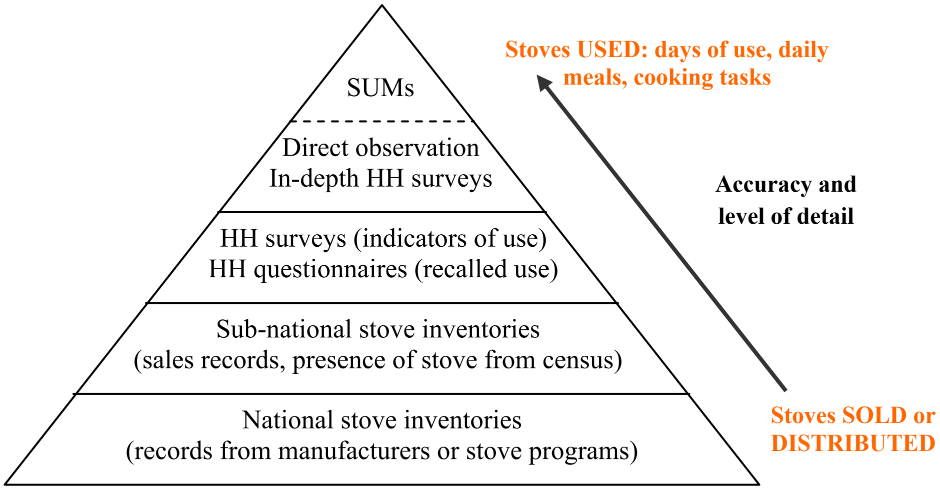

Figure 5.1 The stove use pyramid. The indicators currently available to assess stove of stove use are displayed in increased level of detail and accuracy from the bottom to the top. The SUMs measurements offer the highest resolution, lowest reactivity and the possibility to characterize usage at the cooking task level. Unlike national stove inventories, the SUMs quantify stoves used and not only those sold or distributed.

The SUMs have enabled and simplified the systematic data collection of the critical parameters of the cooking system to characterize the complex process of stove adoption. Furthermore, to contextualize the information on stove use, the data collected with the SUMs can be integrated with demographic, geo-location, fuel consumption, users' perceptions, field surveys, sales records, health, emissions or indoor air pollution information. To ensure that the combined data sets can be translated into useful information, reliable data storage, transmission, and management are necessary. In the context of rural energy projects this often requires robust user-friendly and low cost interfaces for data entry and transmission to remote databases, which depending on the scale and scope of the project, also require resources to maintain and manipulate. Luckily, the pervasiveness of cell phones and the lowered cost of other devices for mobile data collection such as smartphones, PDAs and small laptop computers have enabled transmission of these types of data without the need of new infrastructure. There is a growing number of robust platforms (both open source and proprietary) available for mobile data collection, some of which have been critical in health, social and marketing research areas. More recently, the combined reduced cost of short range wireless modules for sensor data collection and the utilization of existing protocols such as short text messaging promise innovative approaches to the management of stove use data.

Continuous and low cost stove use data collection has an intrinsic value, since it provides cost-effective assessments of adoption performance and enables transparent verification. For monitoring agents and research efforts, this translates into directs savings from reductions in sample sizes, frequency of household visits, amount of personnel and field resources needed to assess use. It also reduces the burden on the participant households, lowering the dropout rates in follow-up studies. For implementers and community groups, the systematic verification of use opens up a unique link with other IT-based platforms like mobile payment systems for micro-finance or carbon-financing that leads to very low or zero transaction costs. Similarly, it seems to enable new ways to test incentive mechanisms for the dissemination or marketing of the stoves. If consolidated, the data generated as more groups deploy sensor-based SUMs could provide a valuable database for understanding the adoption process for different stove types and contexts, to test models for fuel and device stacking, and to speed up the translation of the lessons learned from models and previous implementations into practice. This database can further provide insights into household dynamics that are also relevant for the adoption of other technologies for clean water or sanitation.

My current research efforts in the development of monitoring tools for stove adoption and use are currently focused in the following avenues:

1) Development of libraries of validated algorithms for identification of stove use for different stove types and fuel combinations.

2) Development and validation methodologies to integrate SUMs measures and qualitative parameters of stove adoption performance into robust metrics and indicators that can consider stove and fuel stacking. Consolidation of such metrics and of the libraries mentioned above will likely require a collaborative effort across groups working with different stove types, in different geographic locations and cultural contexts. For this, the development or use of open source platforms and support communities to maintain them will be crucial.

3) Integration of a global database of stove use data, to test different hypothesis and analyze the applicability of different frameworks of adoption and sustained use.

4) Reliable characterization of the signature of specific fuel consumption and exposure “signatures” of specific cooking tasks (e.g. tortilla making, boiling water, etc.) from sensor signals. This with the dual objective of measuring the redistribution of tasks brought by a new stove and quantifying the task-specific reductions in household air pollutants, emissions and fuel consumption.

5) Further systematization of sensor data collection, analysis and transmission. This includes the validation of robust algorithms that are tamperproof and that can reliably identify meals and cooking events. In particular, the use of short- and long-range wireless data transmission protocols will reduce intrusiveness, reactivity and seems to be one of the only cost-effective alternatives to allow long-term monitoring from remote areas at the scale of millions (Vodafone Americas Foundation 2011). Power schemes and sources for reliable unattended data transmission will also be needed. In this regard, thermo-electric generators (TEGs) that are already being used to power fans in semi-gasifier stoves seem a good alternative for energy harvesting.

6) Customization of the management, visualization and reporting data processes for household energy projects, to: (a) enable real-time feedback of adoption performance to the personnel in the field for cost-efficient remediation strategies; and, to (b) provide an integrated platform to seamlessly merge sensor data with other databases of population demographics, indicators of adoption performance, health surveys, or for carbon verification.

Figure 5.2 in the following page is graphic representation of a Stove Use Monitoring System Platform integrating the aspects outlined above.

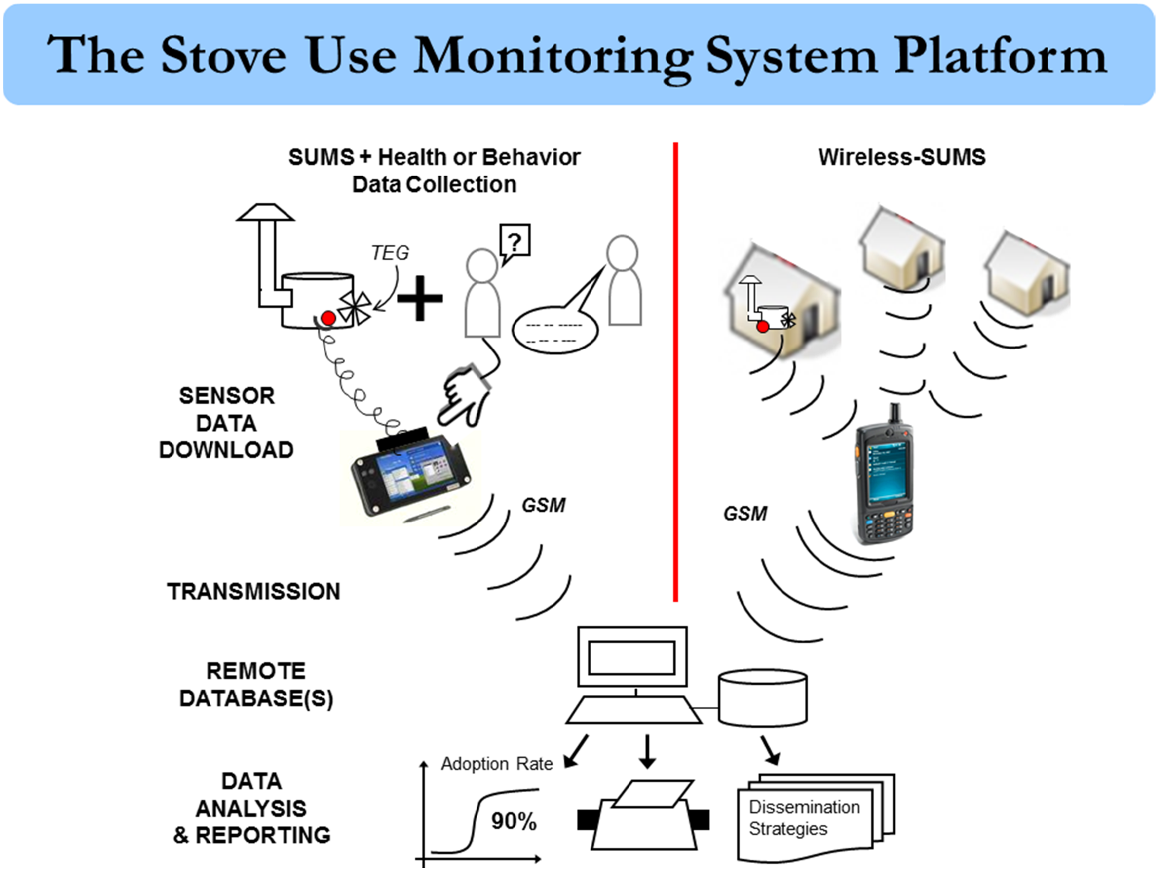

Figure 5.2 Graphic representation of a hypothetical Stove Use Monitoring System Platform (SUMS Platform) to seamlessly collect, transmit and analyze stove use data from Stove Use Monitors placed in stoves. The right side depicts the wireless SUMs to retrieve data using mobile devices without the need to enter the households. The left side depicts data download by contact with the SUMs placed on the stoves and collection of surveys of health and behavior data with the same mobile device. Both SUMs and transmitters can be powered by thermo-electric generators (TEGs). In both cases the mobile devices provide summary statistics of stove use to the surveyor to enable immediate intervention. Data transmission to a remote database is via GSM for systematic analysis of adoption performance, reporting and to design of optimum dissemination strategies.

5.2.2 Behavioral dimensions of the stove adoption process

The behavioral components embedded in the dissemination of cookstoves have been overlooked in the past, despite the central role of the household members and communities in the actual field performance of the cookstoves and in the delivery of its benefits. Individual and household behavior strongly affected the reductions in exposure to household air pollutants measured in the two stove controlled trials discussed in this dissertation. This triggers a warning message to study in detail the role of behavior in cookstove disseminations undertaken under less controlled conditions.

As a starting point, behavioral research is critically needed to:

1) Identify the distinct behaviors that affect each of the stages of the stove adoption process. As discussed earlier, the behaviors that drive the purchase of a stove could greatly differ from those that enable its sustained use. Differentiation of these behavioral components will be crucial for the success of the current large-scale marketing approaches to cookstove dissemination.

2) Develop conceptual frameworks to understand the direct and indirect behavioral pathways to reductions in household air pollution, fuel consumption and greenhouse gas emissions from cookstoves.

3) Expand the few efforts that have undertaken the determination of the impacts of specific behavioral interventions to reduce exposure to indoor air pollution.

5.3 Final remarks

The dispatch and initial acceptance of a cookstove is not a sufficient condition to ensure the delivery of its benefits. Furthermore, households with high levels of sustained stove use could still be exposed to elevated concentrations of air pollutants from the continued use of open fires. Therefore, quantifying and monitoring the residual use of these fires is crucial to understanding the dynamics and evaluate the impacts of the stove adoption process.

The relevance of this dissertation is four-fold: it presents a framework to understand the adoption process, outlines a methodology for the use of the SUMs to quantitatively characterize it, presents a graphical approach to identify relevant usage patterns and it introduces a framework to study the role of behavior in the adoption and impacts of cookstoves. In particular, the work with the SUMs heralds a new era of research to elucidate the behavioral determinants of stove usage and cookfire prevalence, which had not been possible previously at larger scales due to a lack of objective measures of usage.

The adoption problem is shared by other fields promoting technologies and behavior changes to improve household health, like clean water and sanitation. The methodology and analyses presented here can also contribute methods to those fields. The nature of the practices and behaviors promoted in other technologies could be different and the implementation contexts diverse. Nevertheless, the characterization of the individual adoption frameworks can greatly benefit from collaborative efforts to understand the origin of their differences and similarities in their dynamics. In particular, joint discussions can help uncover potential positive feedbacks between the adoption of different technologies and practices in the same household or community.

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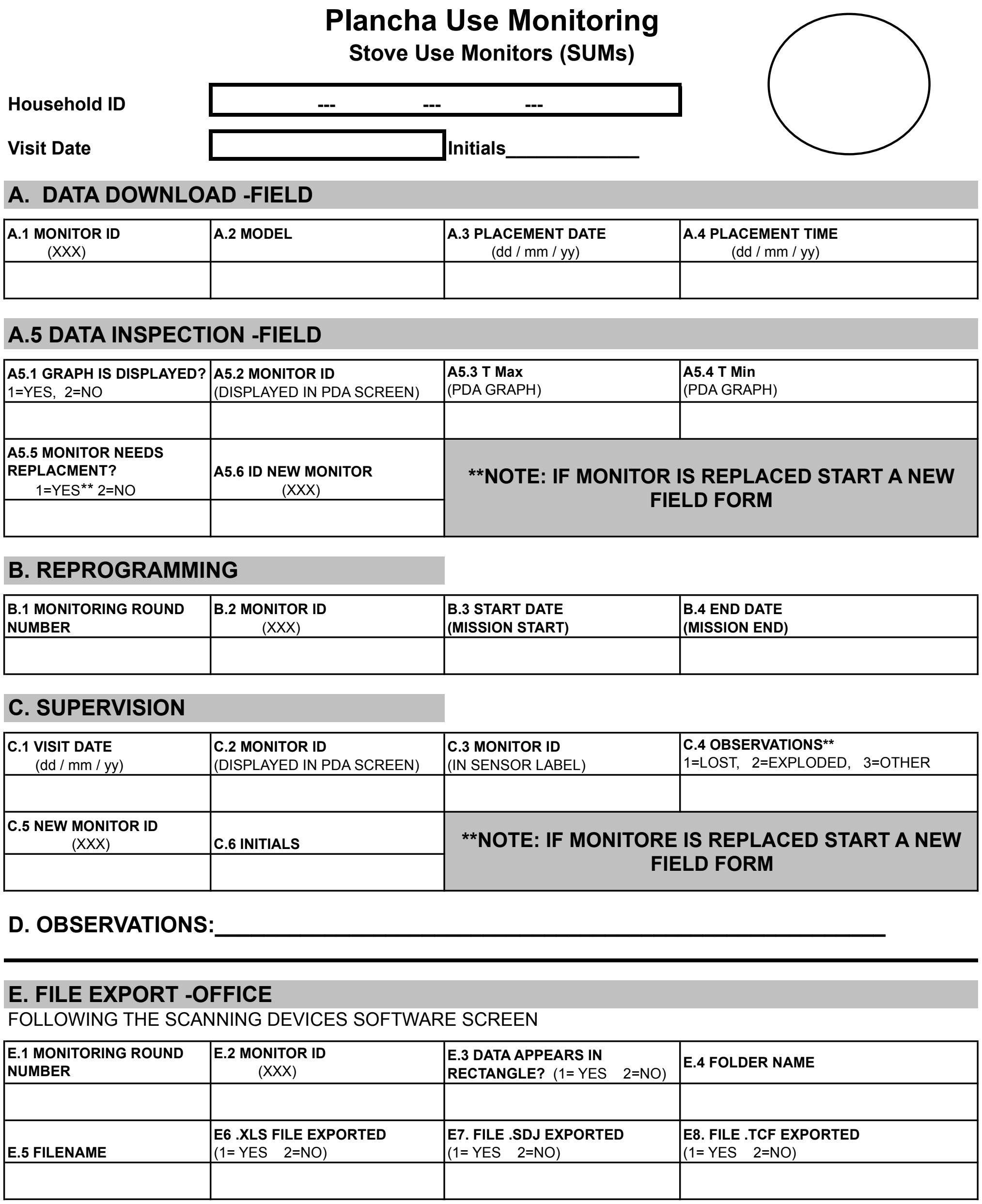
Appendix

Appendix



Plancha Use Monitoring

Stove Use Monitors (SUMs)

Household ID --- --- ---

Visit Date **Initials**____________

A. DATA DOWNLOAD -FIELD

A.1 MONITOR ID (XXX)	**A.2 MODEL**	**A.3 PLACEMENT DATE** (dd / mm / yy)	**A.4 PLACEMENT TIME** (dd / mm / yy)

A.5 DATA INSPECTION -FIELD

A5.1 GRAPH IS DISPLAYED? 1=YES, 2=NO	**A5.2 MONITOR ID** (DISPLAYED IN PDA SCREEN)	**A5.3 T Max** (PDA GRAPH)	**A5.4 T Min** (PDA GRAPH)
A5.5 MONITOR NEEDS REPLACMENT? 1=YES** 2=NO	**A5.6 ID NEW MONITOR** (XXX)	****NOTE: IF MONITOR IS REPLACED START A NEW FIELD FORM**	

B. REPROGRAMMING

B.1 MONITORING ROUND NUMBER	**B.2 MONITOR ID** (XXX)	**B.3 START DATE (MISSION START)**	**B.4 END DATE (MISSION END)**

C. SUPERVISION

C.1 VISIT DATE (dd / mm / yy)	**C.2 MONITOR ID** (DISPLAYED IN PDA SCREEN)	**C.3 MONITOR ID** (IN SENSOR LABEL)	**C.4 OBSERVATIONS**** 1=LOST, 2=EXPLODED, 3=OTHER
C.5 NEW MONITOR ID (XXX)	**C.6 INITIALS**	****NOTE: IF MONITORE IS REPLACED START A NEW FIELD FORM**	

D. OBSERVATIONS:____

E. FILE EXPORT -OFFICE

FOLLOWING THE SCANNING DEVICES SOFTWARE SCREEN

E.1 MONITORING ROUND NUMBER	**E.2 MONITOR ID** (XXX)	**E.3 DATA APPEARS IN RECTANGLE?** (1= YES 2=NO)	**E.4 FOLDER NAME**
E.5 FILENAME	**E6 .XLS FILE EXPORTED** (1= YES 2=NO)	**E7. FILE .SDJ EXPORTED** (1= YES 2=NO)	**E8. FILE .TCF EXPORTED** (1= YES 2=NO)

Table A Field form for stove use monitoring with the SUMs in the CRECER study.