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Original Contribution

Patterns of Stove Use in the Context of Fuel–Device Stacking: Rationale and Implications

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Abstract: The implementation of clean fuel and stove programs that achieve sustained use and tangible health, environmental, and social benefits to the target populations remains a key challenge. Realization of these benefits has proven elusive because even when the promoted fuels-stoves are used in the long term they are often combined (i.e., ''stacked'') with the traditional ones to fulfill all household needs originally met with open fires. This paper reviews the rationale for stacking in terms of the roles of end uses, cooking tasks, livelihood strategies, and the main patterns of use resulting from them. It uses evidence from case studies in different countries and from a 1-year-long field study conducted in 100 homes in three villages of Central Mexico; outlining key implications for household fuel savings, energy use, and health. We argue for the implementation of portfolios of clean fuels, devices and improved practices tailored to local needs to broaden the use niches that stove programs can cover and to reduce residual open fire use. This allows to integrate stacking into diagnosis tools, program monitoring, evaluation schemes, and implementation strategies and establish critical actions that researchers and project planners can consider when faced with actual or potential fuel-device stacking.

Keywords: cooking, energy ladder, household energy, adoption, stove use monitors, Patsari

Introduction

Renewed interest in clean cookstoves in recent years sparked a wide range of global, national, and local initiatives that promote the dissemination of clean fuels and efficient stoves to improve the health and lives of sensitive populations while achieving environmental sustainability.

In parallel, efforts have emerged to understand the intricacies of the adoption of improved cookstoves (ICSs), a topic that has remained a key challenge in the 40 years of stove dissemination. Recent key advances in the literature on the adoption and sustained use of ICSs have been made in response to a growing body of empirical evidence provided by stove programs and case studies documenting energy choices, using new conceptual frameworks to describe the observed transitions from traditional devices to ICSs and employing novel technologies to monitor stove use and quantify details of the dynamic patterns of household cooking behavior. Combined, these elements brought again to the table the question of what we need to know and to do about stove adoption and fuel choice to ensure that when promising technologies are distributed they are actually used and provide tangible benefits to the target populations.

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One of the main approaches to answering this question has been to understand the factors involved in the adoption of stoves and fuels. These factors have been explored in the academic literature since the 1980s. For instance, in the context of the first wave of large-scale stove dissemination programs, which aimed at conserving forests, Agarwal outlined a series of technical, economic, and social factors affecting stove adoption. She also highlighted the need for user's involvement in stove design and the problems of top-down approaches to diffusion (Agarwal 1983). Others like Evans highlighted users' adaptation and behavior changes as key challenges when trying to change traditional cooking, given that efficient stoves were usually designed for a limited range of cooking activities and never outperformed traditional options. She called for a holistic approach to improve cooking practices as a whole as opposed to interventions that focus only on cooking technologies (Evans 1987). These points were echoed in reports describing improved and traditional stoves in Africa, Asia, and Latin America (Westhoff and Germann 1995). In the context of the second wave of stove dissemination, aimed this time to alleviate the health problems of exposure to indoor air pollution from solid fuels, Bruce and colleagues pointed out that poverty was one of the main barriers to the adoption of cleaner fuels, and emphasized the need for socioeconomic development to achieve healthier household environments (Bruce et al. 2000). During this period, Ezzati and Kammen pointed out that the varying levels of success of fuel change and stove programs implied that the factors motivating household to adopt interventions were not entirely clear (Ezzati and Kammen 2002).

More recently, in the literature on household energy, authors who analyzed empirical evidence from case studies have warned about the exaggerated importance given to factors like income and other household socioeconomics as drivers of energy transitions. They indicate that this critical shortcoming overlooks the role of human dimensions in fuel and stove choice and it oversimplifies the complex dynamic interactions among technology, habits, cultural norms, preferences, and behavior involved in the transitions (Kowsari and Zerriffi 2011; van der Kroon et al. 2013; Andadari et al. 2014; Thurber et al. 2014).

In the stove literature, three stages in the adoption of new stoves and fuels have been identified—acceptance, initial use, and sustained use (Ruiz-Mercado et al. 2011; Rehfuess et al. 2014)—and the factors affecting each have been analyzed. Regarding sustained use, Zamora identified that socioeconomic, socioecological, cultural, and technological contextual factors[1] were key in determining the sustained use of stoves in central Mexico, and that these were shaped by the needs for cooking and heating of the households (Zamora 2010). More recently, Rehfuess et al. performed a systematic review that identified 31 factors associated with the acceptance or initial use of solid fuel stoves. The study found that all factors[2] were required and influential depending on the context and that (similar to findings of a qualitative meta-analysis of fuel choice by van der Kroon et al. 2013) they could not be ranked by degree of importance. None of these factors could be specifically associated with exclusive or near-exclusive use of the stoves, since this was found to be a rare phenomenon (Rehfuess et al. 2014).

In fact, the full displacement of traditional cooking fuels and stoves[3]—either by modern clean fuels or by improved wood-burning stoves—has proven elusive, leading to the stacking or combined use of fuel and stoves (Masera et al. 2000; Ruiz-Mercado et al. 2011). Empirical evidence of stacking has been documented in the energy literature over the last four decades. Since the late 90s, there has been solid evidence from countries like Mexico that households gaining access to liquefied petroleum gas (LPG) stoves in peri-urban and rural settings were only marginally displacing traditional fires (Masera and Navia 1997; Masera et al. 2000). This phenomenon has been documented in

[1]Socioeconomic factors: income and education; socioecological factors: level of access in gathering fuel and climate conditions; technological factors: use of LPG and use of multiple fuels and stoves for cooking; cultural factors: attachment to ancestral ways of cooking and the use of traditional pots.

[2]Fuel and technology characteristics: fuel savings, impacts on time, general design requirements, durability, and other specific design requirements, fuel requirements; household and setting characteristics: socioeconomic status, education, demographics, house ownership and structure, multiple fuel and stove use, geography and climate; knowledge and perceptions: smoke, health and safety, cleanliness and home improvement, total perceived benefit, social influence, tradition and culture; financial, tax and subsidy aspects: stove costs and subsidies, payment modalities, program subsidies; market development: demand creation, supply chains, business and sales approach; regulation, legislation and standards: regulation, certification and standardization, enforcement mechanisms; programmatic and policy mechanisms: construction and installation, institutional arrangements, community involvement, creation of competition, user training, post-acquisition support, monitoring and quality control.

[3]This full switch to the cleaner combustion fuel and devices is part of the conventional energy transition theoretical model, known as the "energy ladder" (Hosier and Dowd 1987; Smith 1987). The model considers that as fractions of the population increase their income, prosperity or development, they begin "climbing" from the most traditional fuels at the bottom to the most advanced at the top. Sometimes considered the norm for residential cooking, the energy ladder model has been widely criticized for its lack of empirical evidence to support it for the case of clean cookstoves.

other countries (Leach and Mearns 1988; Davis 1995; Heltberg 2004; Joon et al. 2009) and is also seen after rural electrification in China (Trac 2011), substitution of kerosene with LPG in Indonesia (Andadari et al. 2014), and after the introduction of improved biomass stoves in Mali (Johnson and Bryden 2012a, b), India (Mukhopadhyay et al. 2012; Singh 2014; Thurber et al. 2014), and El Salvador (Redman 2010), to name a few countries. Realization that the use of multiple fuels and stoves is generally the norm rather than an exception has, nevertheless, only recently permeated the thinking in major reviews of solid fuel use (Bonjour et al. 2013) and health risks from indoor air pollution (Gordon et al. 2014).

Most studies, however, still treat the subject in very general terms, noting that stacking happens but without examining it more closely. In fact, although the stacking of fuels and devices embodies the dynamic interplay among household behavior, culture, the environment, energy, and technology, these interactions have received little attention. As we summarized, these elements are often considered as isolated factors and the interactions among them are reduced to problems of consumer behavior, lack of technology information, or lack of health or environmental education. We argue that to successfully implement clean fuels and cookstoves, it is necessary to understand (1) all the types of fuel–stove combinations found in the homes and their dynamic use patterns, (2) the connections among household needs, behavior, and culture that shape the extent of the residual use of traditional fires after the introduction of clean fuels and stoves, and (3) the health, environmental, and socioeconomic implications of the actual patterns of stove use. The aim of this paper is to contribute key elements to analyze these aspects and to examine their implications in terms of diagnosis, program monitoring, and implementation strategies.

Rationale for Stacking of Stoves and Fuels: The Roles of End Uses, Cooking Tasks and Livelihood Strategies

End Uses: Traditional Fires Satisfy Energy Uses and Household Needs That Extend Beyond Cooking

Traditional open fires are used to satisfy needs that extend well beyond cooking. Households that cook with solid biofuels in open fires also obtain from them a myriad of energy services like heating of the living space, lightning of the home, heating of water for bathing and washing, drying of clothes, smoking of crops and meats, disposing of waste, and driving of insects or other animals away. Even when cooking usually represents the largest share of household energy use, other end uses of open fires, like heating water, can account for 50% or more of the energy spent cooking meals (see for example the studies conducted by Johnson and Bryden 2012a in rural Mali and by San et al. 2012 in rural Cambodia). These patterns often prevail after 'modernization' of rural villages; e.g., in rural Mexico, Martinez-Negrete et al. demonstrated the high dependence on and resilience of fuelwood used to heat water for bathing on open fires, the prevalence of which remained essentially the same within a 25-year period, even after the substantial penetration of LPG and electricity in the village (Martinez-Negrete et al. 2013).

Fires fulfill other functions like social gathering, spiritual, healing, and other traditional practices that are central to culture. When the new and cleaner fuel–stove combinations that are promoted are technically optimized for cooking or space heating, they necessarily lose some of the versatility of fires and can no longer embody all the functions of traditional hearths. For example, to reduce emissions and fuel consumption, the optimized stove designs restrict the amount or volume of fuel, limit the cooking surface or isolate the fire thermally or visually or require specific fueling rates. As a result clean cookstoves and fuels can seldom be perfect substitutes for all the traditional fuel devices and inevitably, households stack or combine the use of traditional and new devices to fulfill their needs.

A key consequence of the imperfect substitution of stoves is the residual use of traditional fires. Even if the clean fuel–stoves perform better than fires and their usage level is high and sustained through time, the negative health and environmental impacts of the residual uses will prevail unless the associated practices are modified or other stoves (or devices) that cover these needs are added to the portfolio of options. A second consequence is that the actual benefits of the new clean fuel–stoves, in terms of fuel or emissions reductions, will only come from the subset of uses that they can satisfy and therefore depart from expected technical projections, which usually assume a total displacement of open fires.

Empirical evidence from two studies illustrates how the residual use of traditional fires affects stove implementations. In a comprehensive study on one village in Mali conducted by Johnson and Bryden (2012a), it was found that the use of an ICS reduced fuelwood consumption by 40% compared with the use of a traditional fire. However, since the cooking of meals accounted for only 50% of total household fuelwood consumption, actual potential reductions in total fuelwood use were about 20% at most (assuming the stoves were successfully adopted). Noting that water heating accounts for approximately 20% of a household's wood consumption, the authors suggested that similar reductions could have been achieved by introducing other options like solar water heaters. A second example has been documented in highland Guatemala, where traditional wood-fired steam baths[4] are used for cleansing, healing, and family bonding in some highland regions. Wood consumption in this practice can be about 4–5 kg per episode, with an average of 1–3 episodes per week (Lam et al. 2011). Using aggregate household fuel consumption estimates from the same communities (Granderson et al. 2009) it can be estimated that steam bath activity accounts for roughly 30% of weekly wood consumption for cooking in a typical house. In the context of human exposure, however, the steam bath accounts for 78% of the total weekly carbon monoxide exposure among women who have a chimney stove intended to reduce kitchen air pollution (Thompson et al. 2011). Exposure from steam baths would be greater in both absolute and relative terms following childbirth, when women traditionally use the baths more frequently to aid in recovery.

Tasks: Cooking is a Combination of Tasks and Techniques, Each with Specific Energy Demands and Cultural Significance

Cooking is more than simply heating food. "Successful cookery requires a thousand things done well", says Michael Symons in his *History of Cooks and Cooking* (Symons 2004). Cooking involves combining different techniques or tasks to make a meal, like heating, boiling, simmering, steaming, baking, grilling, frying, or smoking among others. Each task/technique has specific and often contrasting energy demands in terms of the fuel type and rate, cooking times and temperatures, and also specific requirements for the type and size of cooking vessels. Nevertheless, the requirements that need to be met to fulfill a cooking task cannot be understood only by the technical specifications of the task. Clear evidence from several countries illustrates that traditional dishes are often cooked with fuelwood despite the full availability of modern fuels.[5] This has been the case for roasted meat in Nicaragua (Alberts et al. 1997), tortillas in Mexico (Evans 1987; Masera et al. 2000), hard beans, stamp and seswaa in Botswana (Hiemstra-van der Horst and Hovorka 2008), chapati in India (Joon et al. 2009), glutinous rice in Thailand (Nansaior et al. 2011), and slowed-cooked stews in China (Trac 2011).

As such, even for cooking alone, single fuel–stove combinations are unlikely to excel at all tasks and each combination will find a specific niche in the tasks where they best perform according to the requirements and preferences of the households (Ruiz-Mercado et al. 2011). Thus, often a portfolio of options will be needed to satisfy all cooking tasks. This is not any different from the way households in developed countries cover their cooking needs using an electric toaster oven, coffeemaker, microwave oven, charcoal barbeque grill, and occasionally a fuelwood fireplace in addition to an electric or gas stove.

Figure 1 illustrates a set of cooking and non-cooking end uses satisfied by traditional open fires (a) and the portion of the set that can be covered by three fuel–stove stacking combinations (b). The end uses outside the "stacking space" defined by stoves S1, S2, and S3 constitute the residual uses whose impacts are likely to remain unless other fuel–device combinations are introduced. Focusing on the tasks that constitute the circle of cooking end uses (c), it is seen that each fuel–stove combination covers a specific niche of tasks. The stoves in this example could represent, for instance, a fixed massive woodstove (S1) that is preferred for boiling large amounts of water or food and also provides some space heating; a portable rocket-type stove (S2) that is best for heating food and making soups; and a gas stove (S3) that is best for quick and high-heat tasks like frying.

The energy transitions in household cooking hinge on social aspects and household preferences that are rooted in cultural values and traditions, and the importance of these factors may vary from one cooking task to another. Cooking tasks are, therefore, the critical unit of analysis in the stacking of stoves and fuels. In China, for instance, Trac (2011) documented that after 30 years of electrification in a rural village, electricity replaced fuelwood only for cooking noodles, while other traditional dishes were still cooked

[4]For this activity, a house heats a small enclosure, separate from the main house using an open fire. The enclosure has a small entrance and no windows.

[5]Besides being traditional, most of these foods require fuel-intensive cooking, suggesting that economic factors also play a role in the resilience of traditional fuels.

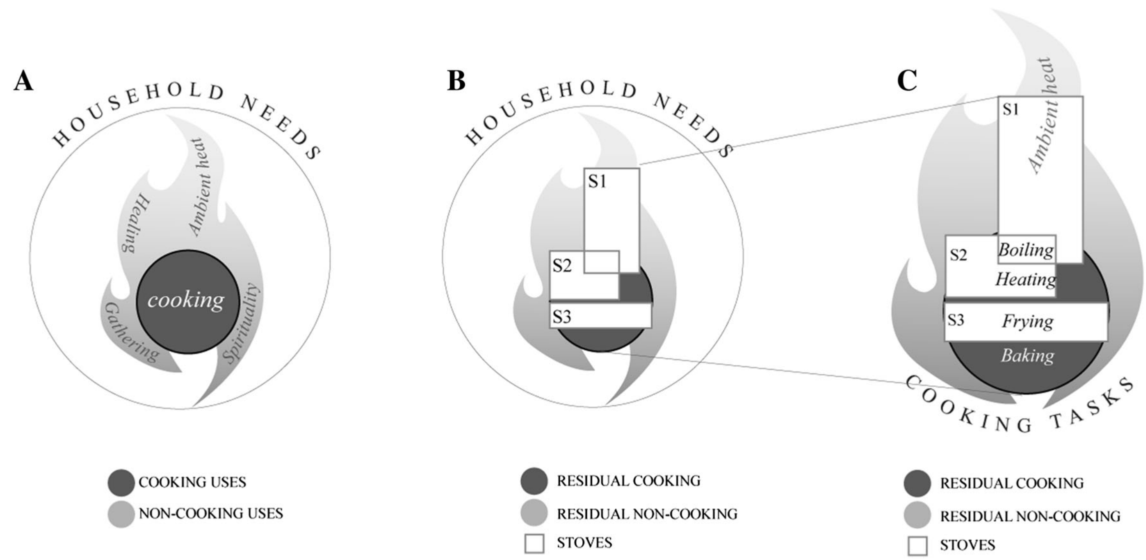

Figure 1. **a–c** Energy end uses met by fires. **a** Cooking is one of the main household energy and social needs satisfied by traditional fires, but other non-cooking services like ambient heating, social gathering, healing, and spiritual functions are also obtained from them. **b** Clean stoves are optimized for fuel and emission performance and often satisfy only a finite subset of the services provided by traditional fires. **c** A portfolio of options is needed to cover all cooking needs and each stove is used for the cooking tasks for which it best performs.

over woodstoves. Social and cultural factors not only affect the decision to adopt a cookstove but also shape the patterns of use (frequency, intensity, closeness to emissions, exposure times, ventilation, and maintenance practices) and thus determine many of the benefits that can be achieved with clean cookstoves for a given cooking task.

Livelihood Strategies: Coping with Uncertain Variability in Cash Incomes, Fuel Prices, and Access to Fuels

Other factors that affect the adoption and usage patterns of clean fuel–stove combinations are marked seasonal weather patterns, the seasonality of and uncertainty in households' cash incomes, and the physical access to fuels (Masera et al. 2000; Singh 2014). Most poor households targeted by stove implementations face uncertain and highly variable cash incomes as they depend on the fate of local crops or on non-formal employment. Additionally, different types of local fuels may be available in different seasons (e.g., crop residues are only available at harvest time, while accessing the forest to get woody biofuels may be difficult during the rainy season). Modern fuels in particular are not always available or accessible, either because of difficulties in physical access across seasons—e.g., during the rainy season—or because of price fluctuations. The stacking of fuels and devices is therefore a strategy that gives households more flexibility and resilience in satisfying their daily cooking needs. As we will show in the next section, in terms of stove use, these strategies show as regular—or occasional—seasonal patterns of different length and intensity.

Patterns of Use in the Context of Stacking: The Case of Rural Mexico

To assess the impacts of a stove program under stacking, it is necessary to characterize the usage patterns of each stove–fuel combination, since in many cases, the usage levels of different stoves within the combination are interdependent and the interactions with household dynamics lead to different patterns in time and space and thus to different impacts. This implies measuring the intensity of use and the main tasks done with each fuel–stove combination, identifying the time–location patterns linked to them, and evaluating the impacts in terms of the niches that both clean and traditional stoves find after the dissemination.

In this section, we illustrate four aspects of stacking that are key for impact assessments. We present quantitative measurements of stove use made over a year-long field study in 2012–2013 for 100 homes in three rural villages in Michoacan, central Mexico: La Mojonera, Taretan and Tanimereche. The population is a subsample of a cohort of women who received chimney stoves in 2005–2006 or 2012–2013 as part of a follow-up to a health study initiated in 2005 (Romieu et al. 2009) as reported elsewhere (Schilmann et al. 2014). We use the data to illustrate aspects of stacking at the household level. The population-level analysis of stove use will be presented in a separate paper.

We used coin-sized small temperature loggers (Thermochron iButtons, Maxim Integrated Products) as stove use monitors (SUMs) to measure the intensity and frequency of use (daily hours of use and cooking events) of each stove in the homes. The SUMs were affixed to the chimney stoves and traditional fires following protocols outlined previously (Ruiz-Mercado et al. 2012, 2013). The iButtons were also placed in the kitchen environment to record indoor ambient temperature trends that were subtracted from the stove signals. Communication with the sensor was achieved with laptop computers and individual data files containing date, time, and temperature data were uploaded to a custom software platform for batch processing[6] and statistical analysis. We conducted recall questionnaires and household surveys to document the cooking tasks and end uses completed with each stove, and short interviews about the history of all cooking fuels and devices used by the women throughout their lives.

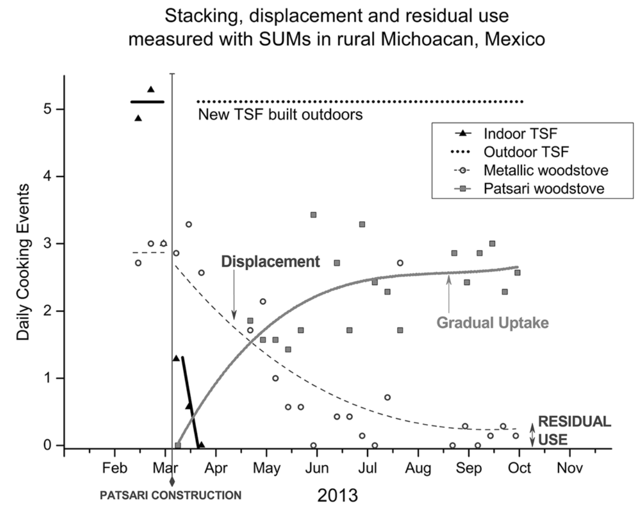

Figure 2. Relationship among stacking, displacement and use illustrated for the case of three stoves. The introduction of a Patsari chimney stove (*gray line*) triggers displacement of an older metallic stove (*dashed line*) and the abandonment of an indoor three stone fire (*black line*). Sustained use of the Patsari and residual use of the metallic stove stabilized after four months at three uses per day and one use per month respectively. A new three stone fire was built outdoors and reportedly used three times daily (*dotted line*), the same frequency than the indoor fire that was abandoned.

Levels of Use and Displacement

In terms of the intensity and/or frequency of use, substitution of the traditional fuels and stoves for new ones is often gradual and incomplete. Thus, the adoption process that is of interest in the context of stacking necessarily includes both the gradual uptake of the clean fuels and stoves and the displacement of the polluting or inefficient ones.

Figure 2 illustrates SUM-measured behavior in one household. This family initially used a three-stone wood fire five times daily and a metallic woodstove three times daily, inside the same kitchen. Each point is a week-long average of daily cooking events. In mid-March an improved woodstove (Patsari) was built right next to the indoor fire, and its gradual uptake (gray, solid line) led to the progressive displacement of the metallic stove through the following half a year (dashed line) until the later was only used once per month. The use of the indoor three stone fire dropped to zero after about 4 weeks (black, solid line), at which point it was physically displaced from the kitchen and a new fire was built outside, 15 m from the home. The reported frequency of use of the new fire outdoors (not monitored with SUMs) is shown by the dotted horizontal line.

The redistribution of cooking tasks and end uses resulting from the introduction of new stoves is what affects the level of use and the time–location patterns associated with each device, with some tasks being shifted to the new device, others still performed with both old and new, and new cooking spaces being opened for tasks that did not exist before. Figure 3 shows for the same home the redistribution of tasks from the deteriorated metallic stove to the new Patsari stove and the preservation of the three-stone fire for the same tasks, but its physical displacement from the indoor environment. Understanding the impacts of the transition requires investigation of the changes in the levels of use in the context of the cooking tasks performed with each device. Similar reductions in terms of days in use, average daily hours or cooking events might have quite different implications in terms of fuel use, emissions or exposures depending on the tasks shifted. The introduction of the Patsari in this household also re-opened a space for the traditional dish *tamales*, which has reportedly not been prepared previously on the metallic or open fire stove.

[6] The platform allowed to obtain differential (stove–ambient) temperature signals and analyze them with peak detection routines to count cooking events and with routines to accumulate the time above temperature thresholds to determine time in use.

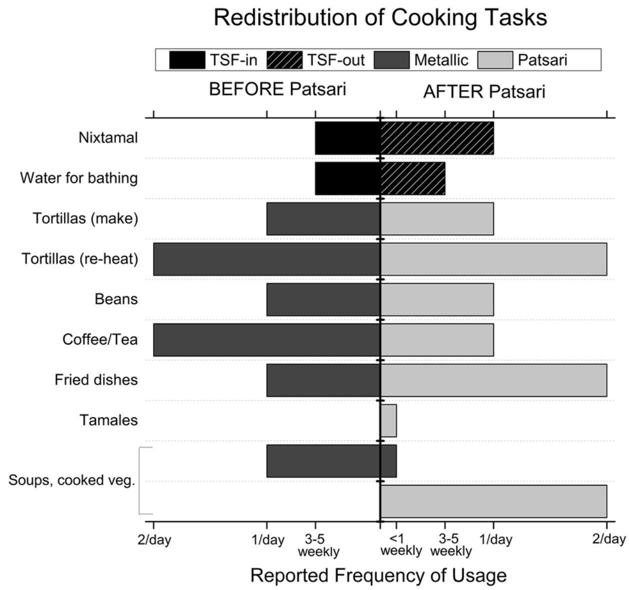

Figure 3. Redistribution of cooking tasks resulting from the introduction of a new Patsari chimney stove.

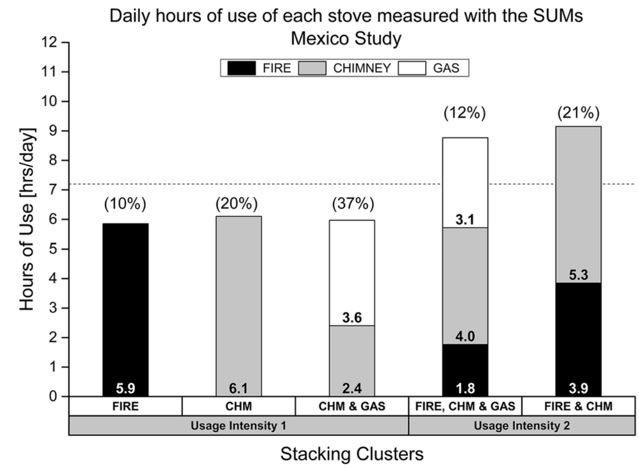

Figure 4. SUMs-measured average daily hours of use per stove for the five stacking clusters found in 100 homes from three communities in rural Michoacan, Mexico.

Fuel–Stove Combinations: Stacking Clusters

At the population level, understanding the impacts of stacking requires broadening the "stove" and "no stove" groups to include all possible combinations after the dissemination. We carried out household surveys to create a detailed inventory of all the fuels and stove configurations in the 100 homes to create a detailed inventory of all the fuels and stove configurations in the sample population and thus identify the main stacking clusters. LPG and wood were the only fuels used by households and the three main stove categories were woodstoves with chimneys (CHM), woodfires without chimneys (FIRE), and LPG stoves (GAS).[7] These categories provided seven possible clusters: three clusters using a single stove type and four clusters combining devices. Analysis of usage data recorded by the SUMs revealed that only five clusters were actually present. Neither exclusive use of gas stoves nor the combination of gas with open fires were observed in the communities after the introduction of the Patsari stove. The analysis presented here used SUM data for each stove type recorded in a 45-day monitoring period in July–August 2013. To graphically display the results, each household was put into one stacking cluster. The average daily hours of use of each stove in the household were obtained on the software platform and each bar denotes the daily usage time for each stove, averaged across all stoves in that cluster. The height of a bar is an upper bound of the average total time that households in the cluster used the stoves, since the overlapping of activities was not taken into account. As shown in the next sub-section, cooking with multiple stoves is not always done sequentially and parallel cooking with multiple devices through the day is common in this region.

Figure 4 shows the proportion of households in a cluster (in parentheses) and the hours of use of each stove within the cluster (the height of the bars). From left to right, the bars present the results for the exclusive use of non-chimney stoves (FIRE, 10%), exclusive use of chimney stoves (CHM, 20%), combined use of chimney and gas stoves (CHM–GAS, 37% of the sample), combined use of all three stoves (FIRE–CHM–GAS, 12%), and combined use of chimney and non-chimney stoves (FIRE–CHM, 21%). In total, 70% of the households sampled showed stacking. In about half of these households, the traditional open fire has been displaced. Two sets of stove usage intensities are observed: Set 1 composed of the FIRE, CHM, and CHM–GAS clusters with 6 h of use, and Set 2 composed of the FIRE–CHM–GAS and FIRE–CHM with 9 h of use. In Set 2, the residual use of traditional fires was 1.8 and 3.9 daily hours (20 and 42% of the total cluster times),

[7] Detailed classification by physical configuration—also necessary for standardization of SUM placement and signal analysis—revealed 14 stove phenotypes: six for traditional fires without chimney (FIRE), five for chimney stoves including the Patsari (CHM) and two for LPG stoves (GAS). Most stoves were stationary and there were no stove phenotypes exclusively dedicated to a single cooking task.

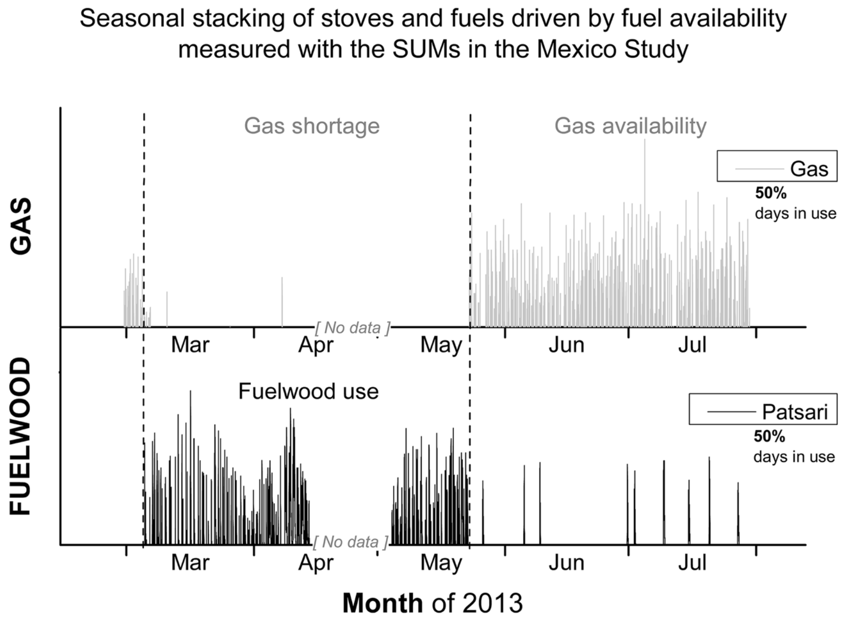

Figure 5. Seasonal stacking of a gas stove and a fuelwood Patsari stove seen during an LPG shortage, as measured by SUMs. The SUM traces represent fluctuations in stove temperature over time due to stove use. Both stoves have a long-term average of 50% day in use.

respectively for FIRE–CHM–GAS and FIRE–CHM, representing a contribution that can have important negative health effects, depending on the time–location patterns of use.

Types of Stacking

The interactions among the availability of resources, climate, habits, culture, tradition, household behavior, and preferences for cooking result in different stacking patterns.

In the study population, we identified stacking patterns of the two fuel types (woodfuel and gas) at different time scales: (a) seasonal alternation of fuels and stoves; (b) weekly alternation of stoves; and (c) simultaneous use of several stoves within a day.

Figure 5 illustrates seasonal stacking for a household that reported cooking on traditional open woodfires since the respondent's childhood (corresponding to about 40 years of use) and a 20-year history of using LPG in alternation with woodfuel. Unlike the majority of the study population, this household does not prepare nixtamal or tortillas in the home. Before the construction of the Patsari, the open fire was used 1–2 times a week for the traditional preparation of beans and soups. After construction of the Patsari in August 2012, the household reported transitioning these tasks from the open fire to the Patsari, with beans now exclusively prepared on the Patsari woodstove and soups made with both the Patsari and gas stove. The graph shows SUM signals in a period beginning in March 2013 (about 6 months after construction of the Patsari) and ending in July, with a gap in SUM data in April when sensors were not in place. The SUM traces show exclusive use of the gas stove (upper gray trace) until March 5th, when the house ran out of gas and the Patsari stove was used exclusively for the next month and a half (lower trace). When the household was able to purchase LPG again on May 23rd, the intensive use of gas resumed and the Patsari stove was kept for making beans and soups. The summary usage statistics for the entire period show (right side of the graph) that each of the stoves were in use 50% of days. Stacking of the two stoves through the year allows the household to face fuel shortages while preserving traditional preparation of beans. In addition, the family is able to cope without a traditional open fire because nixtamal and tortillas are prepared in the store where tortillas are bought. This spatial displacement of traditional fires to other parts of the home or to kitchens of other community members has been previously documented to critically shape exposure patterns (Armendariz-Arnez et al. 2010).

Alternating stacking through the week is illustrated in Figure 6 for the case of a household that uses a gas stove, Patsari stove and traditional fire. Gas is used each day to prepare three meals, while the traditional fire is used every other day to prepare nixtamal. On the days following the use of the traditional fire, the Patsari chimney stove is used to prepare tortillas with nixtamal from the previous day. This weekly pattern persisted during the 1-year monitoring

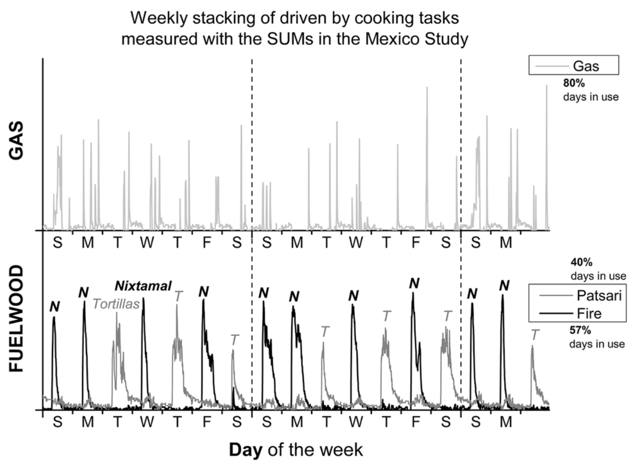

Figure 6. Stacking of multiple stoves and fuels on a weekly basis, measured with the SUMs. The gas stove is used daily to prepare meals and the Patsari stove and traditional fire are used on alternating days of the week for cooking tasks specific to making tortillas.

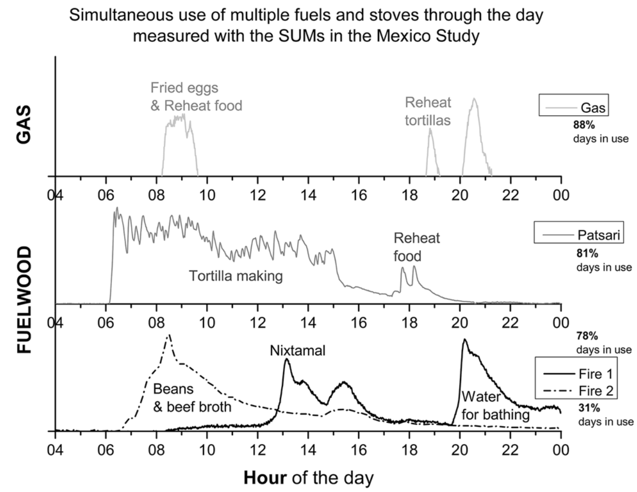

Figure 7. Stacking of gas stove, Patsari stove and two open fires used simultaneously on a typical day, measured with SUMs.

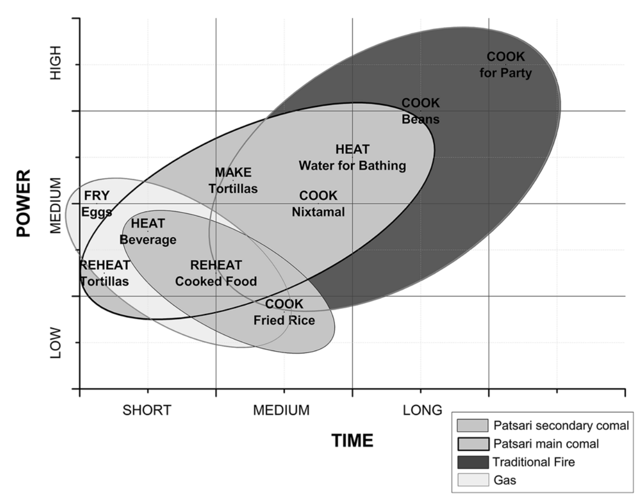

Figure 8. Definition of niches in the context of stove stacking for the case of the Patsari chimney stove, traditional open fires, and gas stoves in Central Mexico (estimated needs for a typical household size of 4–5 people).

period, resulting in summary usage statistics of the traditional fire being used on 57% of days, the Patsari being used on 40% of days, and gas being used on 80% of days. In this case, the levels of use of the traditional fire and Patsari are similar to those in Figure 5 but have very different patterns and different implications.

Simultaneous use of multiple stoves within a day is illustrated in Figure 7 for a household that uses a gas stove, a Patsari stove and two traditional fires. On a typical day, the gas stove is used for low-energy tasks such as frying eggs in the morning and reheating food in the evening (88% days in use in a full 45-day monitoring period). One of the fires is used exclusively for two high-energy tasks that each take a long time but do not require much tending of the fire: preparing nixtamal around noon and heating water for bathing in the evening (78% days in use). The second fire is used to cook the daily meal. On the day shown, two meals requiring much energy to cook were prepared: beans and beef broth (31% days in use). The Patsari is used intensively for half of the day to make tortillas, and also to reheat another meal in the evening (81% days in use). Almost any given time, at least two stoves are simultaneously running, making it clear that no single stove will likely satisfy all the household needs and suggesting that more than one cook is active in the home. The fuel use and cooking behavior described in this section emphasize that to fully assess the impacts of stove usage in the context of stacking it is necessary to analyze the cooking tasks and seasonal patterns associated with the measured levels of use.

Stove Niches and Redistribution of Cooking Tasks

The examples in Figures 6 and 7 analyzed above illustrate that each stove fills a specific niche within the universe of household energy needs (cooking and non-cooking) covered by traditional fires. This can be further examined mapping the different power and time demands of the main cooking tasks in a qualitative diagram (Fig. 8). Taking into account a series of field studies that have measured the energy, power, and time demands of main local meals (Masera and Navia 1997), we divide the power demand into three categories—high, medium, and low—and time into hourly intervals. In the case of Central Michoacan, Mexico, there are tasks that require medium–high power and short cooking times like frying eggs (mid left), tasks that require high power and long cooking times like preparing beans (top right), and tasks that require medium power and not long cooking times like reheating cooked food for the household (center).

Mapping the main cooking tasks we can delineate the niches that each stove fills. On the left of the figure we find gas stoves, which are preferred for frying eggs or meat, heating beverages, reheating tortillas or cooked food, and sometimes cooking fried rice. In the center we see the Patsari chimney stove, which has a main cooking flat metal surface or "*comal*" at the front and two secondary "*comales*" at the back. The main surface is used primarily for making tortillas reheat them or reheat other food, to cook usual food items such as beans and in some cases to prepare nixtamal. The secondary comales provide lower temperatures for heating and are often reserved for slowly warming beverages, keeping food warm, and sometimes finishing the steaming of fried rice. When the Patsari and gas stove are combined, the use niche of the residual open fire are mainly the cooking of nixtamal, the heating of water for bathing, sometimes the preparation of beans or other intensive-energy tasks, and the cooking of large meals for parties. The use niche overlap, allowing key tasks to be performed with different stoves if needed. Furthermore, new cooking technology can bring new tasks and niches to the picture. For example, microwave ovens open the niche of heating frozen food or, in the case of Mexico, making popcorn (Zamora 2010).

Successful Introduction and Effective Monitoring of Cookstove Programs in Stacking Contexts

Health and Environmental Effects in the Context of Stacking

Fuel and device stacking lead to health and environmental consequences very different from those arising when completely switching from traditional fuels or fully adopting clean devices. The following have been documented in particular.

(1) Woodfuel savings from the introduction of modern fuels for cooking, like LPG or electricity, are in general very modest or non-existent, particularly in small urban and rural settings. As a result, the demand for traditional bioenergy has remained high even after long periods of modern fuel adoption. For example, in rural Mexico, actual fuelwood savings made by mixed fuelwood–LPG users in case studies ranged from 6 to 37% (Masera and Navia 1997; Berrueta et al. 2008), and reductions are not expected in the mid-term (Serrano-Medrano et al. 2014). No significant reduction in woodfuel use was observed in Indonesia after the introduction of a national LPG program (Andadari et al. 2014), in rural and sub-urban settings in Northen Thailand (Nansaior et al. 2011), in a region of rural China after 30 years of electrification (Trac 2011) or in urban Botswana (Hiemstra-van der Horst and Hovorka 2008).

(2) Energy savings from the adoption of clean fuels are minimal compared with their technical potential. Exclusive use of LPG should theoretically save 80–90% of energy, taking into account the differences in efficiency and energy content of an LPG stove compared to traditional woodburning open fires. In fact, case studies report that mixed users consume more energy than single woodfuel users in many cases, as the former enjoy more extended energy services and put fuels to other uses (Masera et al. 2000; Nansaior et al. 2011; Andadari et al. 2014).

(3) Reductions in household air pollution (HAP) and the subsequent health benefits are also marginal, as even small residual use of highly polluting fires leads to high concentrations of pollutants (Armendariz-Arnez et al. 2010; Sambandam et al. 2014; Schilmann 2014). For the same reasons, reductions in greenhouse gas emissions, while not specifically reviewed in this paper, are also likely to be marginal to negative, depending on the fuel introduced.

Implications for Initial Diagnosis, Dissemination Strategies, and the Monitoring and Evaluation of Stove Programs

Stacking and, specifically, the residual use of traditional fires have strong implications for two agendas critical to the cookstove sector: the design of cookstove implementation programs with specific goals and the design of monitoring and evaluation schemes that effectively and realistically estimate the actual effects of stove implementations.

We summarize in Table 1 some of the most critical implications that stacking has for stove programs and what

Table 1. Critical Implications of Fuel–Device Stacking for Stove Programs and Strategies to Address Them

Issue	Implication	What needs to be done for		
		Initial diagnosis	Implementation strategies	Monitoring and evaluation
A single clean fuel–stove combination does not satisfy all end-uses, does not work for all cooking tasks and it is seldom a perfect substitute for traditional open fires	A portfolio or "stack" of options (fuels, stoves and practices) is needed to fully displace traditional inefficient/polluting open fires that have negative health and environmental effects	Identify all energy end uses and household needs met by traditional open fires Characterize the subset of end uses that the new clean fuel–stove combination can cover Identify other stoves, fuels or practices needed to mitigate the residual uses not covered by the clean stove	Move from promoting a single stove–fuel combination to the promotion of multiple fuels, devices and practices like the use of hoods or pressure cookers Give equal importance to the promotion of the use of the new stove and to the displacement of the negative effects of traditional fires Target users who already have access to clean fuels but still rely on traditional fires	Stratify users by stacking clusters, not just as stove/no stove groups. Estimate sample sizes accordingly Assess effects by cluster including both the reductions and improvements brought by the clean fuel–stove combination and the effects of the residual use of inefficient devices
Each cooking task has specific energy demands and cultural significance	Each fuel–stove combination plays a niche role for a specific set of cooking tasks for which it best performs according to the user	Identify the most critical cooking tasks: the most frequent, most culturally relevant and those tasks with the greatest negative effects (not necessarily the same) in terms of emissions, exposures or fuel consumption	Design stoves that perform traditional cooking tasks in ways compatible with local practices Design stoves that target the most critical tasks Design stoves and devices specifically aimed at covering residual tasks For critical tasks that are strongly "anchored" to traditional fires consider promoting improved practices (soaking of seeds and grains, fuel drying or chopping, re-location of open fires, etc.)	Evaluate the technical performance of fuel–stove combinations under field conditions and for the specific set of tasks of actual households Evaluate effects in terms of the weight of the tasks that are redistributed among new and existing fuel–stove combinations Assess the effects of modified practices and household habits resulting from the transition (lighting, fueling, ventilation, time in the kitchen, etc.)

Table 1. continued

Issue	Implication	What needs to be done for		
		Initial diagnosis	Implementation strategies	Monitoring and evaluation
Stacking allows households to cope with periods of uncertain income, fuel prices, access to fuels and stove repairs	Usage, stacking and displacement patterns can be seasonal and their dynamics dependent on household and community contexts	Identify the length and timing of relevant seasons (climate, harvest, local economy, traditional celebrations) and key events that affect energy use, cooking practices or that drive stacking patterns. Use this information to schedule implementation and monitoring	Provide cost-effective alternatives to fuel storage and drying in the rainy season Include, in the portfolio of options, clean stoves specifically for the larger demand needed during celebrations Implement mechanisms to secure access to spare parts and repairs for the clean stoves	Whenever possible, perform quantitative measurements of stove usage in a subsample to assess usage patterns and/or validate other tools Complement cross-sectional measurements of stove use with storylines of lifetime fuel–stove use to correlate usage patterns with cooking tasks and contextualize the dynamics, drivers and effects of stacking
Stacking embodies the complex dynamic interplay among household behavior, culture, energy, environment and technology	Factors that affect use, stacking and displacement are interrelated and context dependent	Move from identifying single factors that enable/prevent stove adoption to the characterization of the processes and the interaction of factors that regulate the benefits delivered by the uptake of clean fuel-stoves	Stove dissemination programs cannot be designed similarly to campaigns for repairing house roofs, building new floors, planting trees or like vaccination campaigns Design the implementation to scale up the benefits from the stoves, not just their production or sales Foster innovation not only in technology but in the community processes that generate the desired changes and are capable of sustaining them	Conduct longitudinal assessments to identify the main cultural and social aspects (perceptions, beliefs, traditions, etc.) related to specific cooking practices and end uses of fires, and the changes brought by new fuels and stoves Foster participatory approaches to impact monitoring that can trigger processes of local capacity-building and empowerment

needs to be done in terms of initial diagnosis, implementation strategies, and monitoring and evaluation schemes to realize intended goals.

Unless the new stove can cover all the existing tasks and needs, the residual uses of traditional fires need to be addressed by stove programs. The complete realization of the benefits of clean cookstoves will then require the provision of solutions that are locally appropriate and that can satisfy the tasks and end uses having the most critical effects in terms of health, energy, or other metrics. Rather than aiming to eradicate all adverse effects with a single cookstove in a one-time vaccine-like fashion, projects need to offer a larger portfolio of options and to evolve into more integrated approaches. This includes the promotion of task-specific devices not covered with a single cookstove (like area heaters, water boilers, rice cookers or, in the case of Mexico, stoves with which to prepare nixtamal), and also the improvement of practices and habits that can mitigate the consequences of the residual use of traditional fires (like using hoods, improving ventilation, relocating traditional fires, using pressure cookers, soaking beans, and drying wood). In general, it has been documented that when stoves are well designed and adapted to local cooking practices, displacement of traditional fires is more effective, and significant wood savings and other environmental benefits can be achieved. For example, in Mexico, field studies revealed that up to 67% fuel savings, 80% reductions in IAP and 50–80% in greenhouse gas emissions, depending on the renewability of the fuelwood use, were achieved with the adoption of Patsari stoves (Johnson et al. 2008; Cynthia et al. 2008; Berrueta et al. 2008). Unfortunately, so far, this has not been the case with some of the more advanced biomass stoves as they still have problems displacing traditional fires (Sambandam et al. 2014; Thurber et al. 2014).

It has also been documented that ICS interventions targeting mixed users (i.e., those households who already have access to clean fuels but still rely on traditional fires) have been most effective in terms of health and fuel/energy savings. In rural Mexico, for example, when adopting Patsari stoves, mixed users reduced wood consumption by 74% (Berrueta et al. 2008) and reduced IAP levels by 80%, while also enjoying the benefits and versatility of both fuels and devices. Therefore, promoting access to both clean modern fuels and clean stoves for traditional fuels in the same households should not be seen as competing but rather complementary objectives of cookstove programs.

Initial diagnosis for program design needs to begin with a clear characterization of the target users, the energy end uses and household needs met by the existing fuel–stove combinations to identify the subset of tasks that the clean cookstove can actually cover. In terms of monitoring and evaluation, programs need to monitor, at a minimum: 1) the extent to which introduced stoves fulfill their potential task niche, 2) in-field performance and its maintenance over time (including both technical performance of the stove and performance of the user), 3) the frequency of use in the long run, and 4) the degree to which the less efficient and more polluting stoves and practices are actually displaced. Progress has been made recently on at least the first three points. For example, there is now much more emphasis on linking field and laboratory tests through stove usage behavior to better estimate the actual performance of stoves and to better adapt the stoves to local conditions and practices (see, for example (Clean Cooking Catalog 2014)). Electronic monitors for stove usage (Ruiz-Mercado et al. 2012, 2013) have enabled better data on long-term usage and stacking patterns.

Accurate impact assessment requires expanding the stove/no stove intervention groups into stacking clusters. Integrating impact data will involve developing and validating multi-criteria indicators that more heavily weigh the most critical cooking tasks to capture the multiple effects resulting from the combined use of stoves in terms of the redistribution of tasks. Specifying guidelines for use or displacement outside the context of cooking tasks will likely be insufficient, given the diversity of cooking cultures, the observed task-dependence of stove emissions and the multiple interactions and dynamics of the fuel–stove transitions.

Closing Remarks

Implementing programs that result in widespread technology adoption and translate into tangible ecological, health, and other social benefits for the poorest citizens in a developing country is a challenge not only for clean fuel and stove programs but also rural programs relating to many other technologies, like those for improving housing or providing clean water and sanitation.

While progress has been made in recent years in the cookstove sector, several conceptual and practical challenges remain. We have argued in this paper that cookstove adoption and sustained use result from the interplay among culture, environment, energy, and technology. One key outcome of these interactions is the prevalence of fuel–stove stacking and the residual use of traditional fires, which have strong implications in terms of the long-term impacts of interventions (basically, the reduction of the expected benefits of the introduction of clean fuels and devices). As the new stoves are necessarily optimized for a subset of tasks and cooking practices performed by traditional devices, they are often imperfect substitutes of their traditional counterparts. Therefore, more integrated approaches that offer a portfolio of options to respond to people's priorities and needs, cover the full set of end uses of traditional fires and enable resilient solutions should be promoted. Ultimately, we would like to foster innovation not only in technology but more fundamentally in the social processes that generate a change and are also capable of sustaining it. We should then aim at scaling up not just the production, sales, or distribution of stoves but also the benefits of the stoves.

More broadly, programs need to establish a dialog to learn what people want in a new stove in the first place and what type of stove(s) they want and to assess the conditions of the community and program that will ensure acceptance, good performance, maintenance, sustained use, and displacement of traditional fires. This ambition has been stated by the development policy community for almost 50 years, yet has been pursued by very few programs in reality.

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