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Adoption and sustained use of improved cookstoves

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ABSTRACT

The adoption and sustained use of improved cookstoves are critical performance parameters of the cooking system that must be monitored just like the rest of the stove technical requirements to ensure 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. 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 practices where it fits best. 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 practices 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 cooking practices with the highest indoor air pollution or greenhouse gas contributions.

1. Introduction

Approximately 2.4 billion people depend on wood, dung, charcoal and other biomass fuels for cooking. 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 causes significant negative impacts of several types, including human morbidity and mortality, outdoor air pollution, climate change and deforestation (Smith et al., 2004). Social impacts are also associated with such use, particularly excess time, risk and strain of fuel harvesting for women and children On one hand, it might seem that the existence of a range of potential benefits from improvements 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.

1.1. Improved biomass cookstoves (ICS)

Improved biomass cookstoves 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, 1975; 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 be included in programs, 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).

Improved cookstoves are starting to recapture the attention of governments, development organizations and donors. 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

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performance parameters vary according to the goal. Table 1 illustrates this for six major goals for ICS programs—to limit deforestation, climate change, black carbon, outdoor air pollution, household ill-health and personal risk.

Note that the mix of optimal metrics varies substantially across the different goals. Some metrics like exposure relate only to one goal, in this case health, while other metrics like fuel use are common to several goals. In sum, however, it is 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. Our intention here is not to explore the full implications of these partly overlapping sets of metrics, but to point out that, in spite of their differences, all these goals strongly depend on two fundamental basic performance parameters that are often forgotten or glossed over in discussions of improved stove programs: initial acceptance and sustained use.

Currently more than 160 cookstove programs are running in the world, ranging in size, scope, type of stove disseminated, approach to technology design and dissemination and financial mechanisms (Gifford and Mary Louise, 2010). So far, however, the attention has concentrated in developing new stove designs, improving large-scale manufacturing process, 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), regardless of the dissemination program objectives. In fact, there seems to be little systematic information available about the factors that have been most important for the successful adoption of cookstoves in practice. Anecdotal information would indicate that initially households respond most to fuel savings (when fuel is very scarce or monetized), speed of cooking, convenience, compatibility with local cooking practices, and status of modernity, and relatively less so to pollution-related issues. There is also evidence that the main factors affecting the adoption of stoves can be different at the household and community levels (Zamora, 2010; Pine et al., accepted for publication). 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 like the compatibility of the stove with local cooking practices seem more important for sustained use. Part of the reason for the lack of more conclusive data, however, is that until recently there has not been objective, inexpensive and unobtrusive means of monitoring actual stove adoption and use.

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). 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 (UNFCCC, 2009; Climate Care, 2010). As discussed below, however, the failure to include sustained use in program planning, monitoring and incentives, has been partly due to a lack of good tools for doing so, a situation now changing.

Objective evaluation and impact assessment of ICS programs must clearly differentiate between the number of stoves distributed, those accepted (purchased, or agreed to be installed), the

Table 1

Importance of alternative performance measures for different types of biomass cookstove programs. The rows show the main performance measures that apply to stove programs, including whether special populations or locations need to be targeted and whether fuel use is a direct consideration. The columns indicate the main overall goals pursued by stove programs around the world. Text in bold indicates the most important measures for each goal; italic text indicates secondary or complementary measures. All programs, however, will benefit from higher initial acceptance and sustained use of ICS.

Performance measures	Major improved cookstove program goals					
	Household health	Safety[a]	Deforestation	Outdoor air pollution	Black carbon	Climate under current protocols[b]
Exposures	**Primary**					
Impacts on Vulnerable populations	**Primary**	*Secondary*				
Impacts on Vulnerable locations		**Primary (risky fuel gathering)**	**Primary (impacted forests)**	**Primary (ambient standards exceeded)**	**Primary (impacted glaciers)**	
Fuel use	*Secondary*	**Primary**	**Primary (non-renewable wood only)**	*Complementary*	*Complementary*	**Primary (non-renewable wood only)**
Emissions of PIC[c]	*Secondary*			**Primary**	**Primary**	
Emissions of net CO_2						**Primary (non-renewable wood only)**

[a] Personal safety risks posed by fuel gathering (crime, environmental conditions) or by the use of traditional stoves in the household (burns mainly). An example of the later is the Helps Stove Program (Helps International, 2011) motivated by the numerous facial and hand burns that their medical team encountered in children from falling into traditional open fires.

[b] Methane and nitrous oxide plus CO_2 from non-renewable fuel harvesting are the only combustion-related greenhouse pollutants allowed within the carbon-market/offset protocols approved under the UN Framework Convention on Climate Change (UNFCCC).

[c] Products of incomplete combustion: a wide range of carbon-containing gases and particles due to poor combustion of fuels in traditional stoves. Nearly all are both health damaging, with small particles being most important, and have climate implications, with black carbon being probably the most important.

percent that is initially used and the fraction actually used on a sustained basis. In short, providing access to the improved stoves is a necessary but not sufficient condition to achieve any of the goals of ICS programs.

1.2. The adoption of new fuel-devices: conceptual and theoretical backgrounds

Different conceptual models have been used to describe adoption rates and the impacts of new cooking energy technologies in developing countries. The crudest model is the so-called "fuel switching" approach (Hosier and Dowd, 1988). According to it, traditional devices are entirely replaced by modern alternatives as soon as income and access constraints for modern fuels are removed.[1] 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 comparing the energy efficiencies of the traditional and the new devices and the energy content of the fuels (also named the energy efficiency ratio).[2] The implicit premise of this interpretation is that households effectively consider some fuels and devices to be better than others for all cooking practices, thus resulting in a complete substitution of the traditional devices. This approach is currently implicit in the new wave of ICS that focus on laboratory efficiency measures (for example water boiling tests) to estimate the likely savings of the stoves deployed in the field. It is also implicit in the current Clean Development Mechanism (UNFCCC, 2009) methodology for estimating carbon offsets from ICS programs.

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 is total substitution of fuels and devices instant 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 and Navia, 1997; Heltberg, 2004, 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 move the emphasis from the stove alone to the cooking system, a requirement that is a result from the dynamic interaction between users, stoves and fuels. 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.

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). We focus on the behavioral component of the adoption process and its measurable outcomes: the act of using the stove through time and the patterns of use. We do not quantify or try to explain the decision making processes (Wilson and Dowlatabadi, 2007) or other cognitive outcomes of the adoption process that take place before the stove is first used (willingness to pay, intent or agreement to use it or install it). We do not directly address the causal factors associated with stove adoption[3] or other important aspects such as institutional factors related to the role of change agents, some of which are examined in other papers of this issue.

The analysis draws mostly from the experience at two well-documented study sites in Guatemala (Smith et al., 2006, 2009) and Mexico (Masera et al., 2005, 2007) where extensive monitoring studies have been conducted. We end the paper with a discussion of a new set of tools and methods that are being developed to help with the cost-effective and more accurate monitoring of stove use.

2. Adoption and sustained use: multiple stoves and multiple cooking practices

2.1. A new framework to understand cookstove adoption and sustained use

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 (2003) but which can benefit from the theoretical contributions from other authors (Pareek and Chattopadhyay, 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 Chattopadhyay, 1966) of technology absorption (Murphy, 2001), cultural adaptation and "appropriation" of the technology (Overdijk and Van Diggelen, 2006).

The diffusion of innovations theory describes the process by which an idea or object perceived as new (an innovation) is communicated to individuals and accepted by the majority of a population. It requires a time period for the individual members of the social system to receive the information about the innovation through different channels, to evaluate its usefulness, and to decide to use it or not. 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 socio-economic and ecological contexts (Fig. 1). Since the main goal of a stove user is to prepare cooked food[4] rather than the consumption of fuel 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 – making fried rice, ugali, hand-made tortillas – that result from incorporating the new stove technology and/or fuels into the existing household system.

The modifications to the cooking practices brought by new stoves and fuels can lead to different impacts in terms of fuel consumption, exposure to indoor smoke, cooking time, time spent in the kitchen or stove operation.

When a new stove technology is brought into the household, the initial conditions of the system are redefined and each fuel-

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[1] A more elaborate version of the fuel switching (or preference-ladder approach) comes from the studies about inter-fuel substitution in urban households (Barnes and Qian, 1992). In contrast with the fuel transition 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 et al., 1990).

[2] 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. See Masera et al. (2000) for a more complete description of the model.

[3] The factors associated to the spread of the cookstove are time and scale-dependent and have to do with the characteristics of the user, the device, the fuel and the larger context at the individual, household and community levels (Masera 1994; Valencia, 2004; Troncoso et al., 2007; Pine et al., submitted for publication; Zamora, 2010). For example, in the case of rural Mexico it has been found that at the household level previous utilization of both LPG and fuelwood favor increased use during the initial stages of adoption. On the other hand, at the community level, limited access to premium biomass sources, and the presence of a stable (i.e., non transient) population favor earlier adoption of the stoves.

[4] In many cases the objective of using the devices is also providing space heating or heating water for bathing. For the sake of simplicity, in this paper these practices are also grouped as "cooking practices".

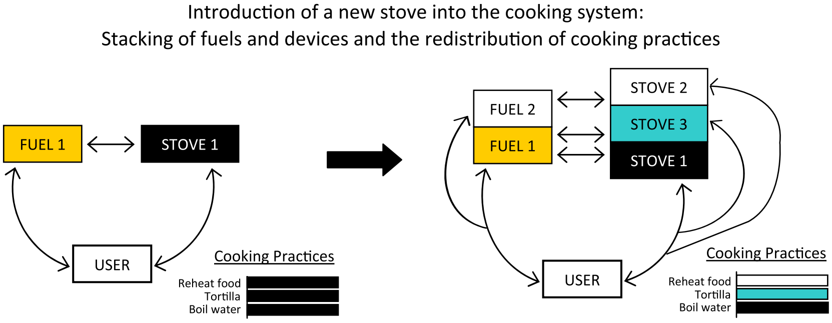

Fig. 1. New interactions between stoves, users and fuels are created when a new stove is brought into the existing cooking system. Very often users initially prefer to "stack" cooking devices rather than a complete abandonment of the traditional stoves. Each stove-fuel combination finds its own "adoption niche" and is used for the cooking practices 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 find a niche in the cooking practices of making tortillas and reheating food, while the old one is still used to boil water.

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 leads many times to the stacking of fuels and devices rather than to complete substitution.

The new devices are initially incorporated into the target population according to a learning curve with specific timing and saturation levels that depend on the characteristics of the user, those of the technology (Rogers, 2003), and on the degree to which the user is able to incorporate and combine them with the existing practices (Pareek and Chattopadhyay, 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. This last requires looking at other factors and at the dynamics of post-adoption usage (Prins et al., 2009). Finally, the study of the extent (or "depth") of use of the new devices requires going beyond "cooking" as a single activity, but rather examining the relative advantages of each device in terms of the main cooking practices. The implications – in terms of energy, health or climate – of the process will heavily depend on which particular practices are substituted by the new technology over time.

2.2. Adoption as a dynamic learning process

At the household-level, the adoption process that we describe in this paper starts at the "initial acceptance" of the stove, which we define as its agreed purchase, construction or installation and its very first uses by the household members.

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 Chattopadhyay, 1966; Shih and Venkatesh, 2004) that defines the magnitude of adoption.

At the population level, we describe the adoption process in terms of three stages: (1) learning-adjustment, (2) stabilization-sustained use and (3) dissadoption. We identified five critical parameters that seem to characterize this process: U_0—the level of initial acceptance or the fraction of the population that initially accepted the stoves and began using them, ΔL—the time to reach saturation 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, U_{sat}—the level of use at saturation or the fraction of the population that initially accepted the stoves and that undertake sustained use, U_{max}—the maximum level of use shown during the process, and ΔU_{sat}—the size of the fluctuations around the mean U_{sat} due to seasonal and regional patterns that affect the level of use. The process is schematically shown in Fig. 2. Fig. 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 in an absolute time scale. In the following sections we document these stages drawing field evidence from the case studies in Mexico and Guatemala.

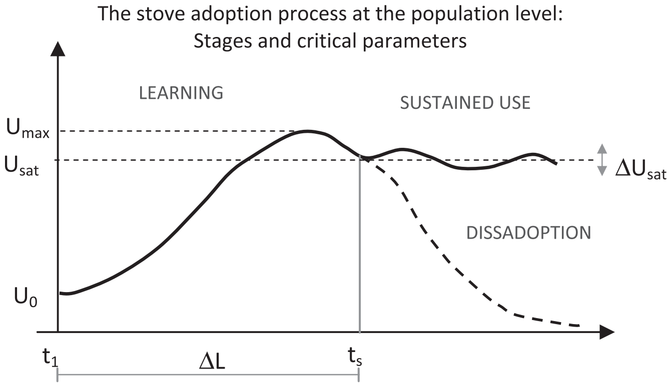

Fig. 2. The adoption process of cookstoves at the population level may be characterized by the following parameters: (a) the initial acceptance (U_0) of a new stove by a fraction of the families, (b) the "learning" time (ΔL) for the population to incorporate the device into the existing cooking practices, (c) U_{max}—the maximum level of use; (d) a stable level of sustained use (U_{sat}); and (e) ΔU_{sat} the size of the fluctuations around the mean U_{sat}. The figure assumes that access to the stoves began on the same day for all households in the population.

2.3. Critical times: time for saturation

In the process described by the diffusion of innovations theory, the rate of initial adoption in a population has an S-shape curve given by the cumulative percent of individual adopters through time. Pine et al. (submitted for publication) 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

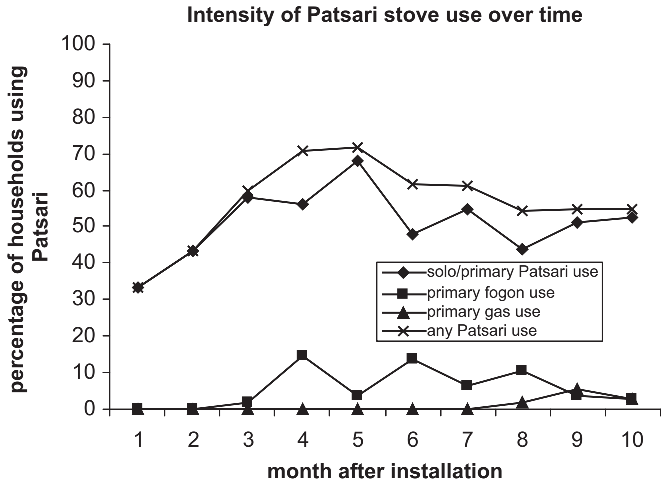

Fig. 3. Process of stove adoption in a stove trial in 112 rural Mexican households (Pine et al., submitted for publication). Users of Patsari stoves showed a learning period of 4 months and a level of sustained use of 50%. Although most users declared the Patsari as their primary stove, many also combined its use with the open fire or a gas stove. Data was obtained from monthly questionnaires.

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. In this population, a 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_{sat}) after the eight month of use (see Fig. 3).

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 we discuss the difficulties of performing such ongoing monitoring, and outline a set of new tools to reduce the resource burden of such measurements of stove use.

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 explained 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.

2.4. Saturation levels

As early as 1966, Pareek and Chattopadhyay formulated an adoption metric 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 adoption processes like cookstoves, where previous and new cooking devices 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.

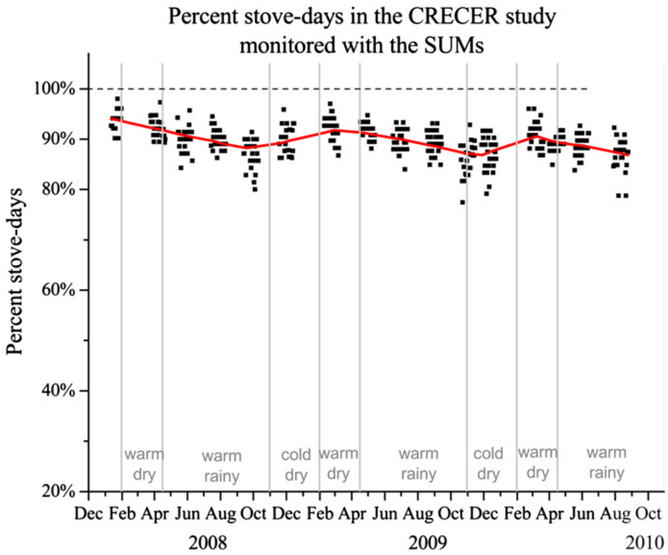

Fig. 4. Use of chimney stoves (Planchas) measured with temperature-based SUMs in the Guatemala CRECER study for a population of 80 households (Ruiz-Mercado et al., submitted for publication). Each point shows the percent of stoves actually used among the total number of stoves monitored, which are all in households of long-term users. The 90% level of use indicates that at any given day 10% of the homes cook with another device, do not cook at all, or cook elsewhere.

Ruiz-Mercado et al. (2008, submitted for publication) performed sensor-based measurements of stove use in the CRECER Guatemala stove study, providing experimental evidence of the levels of sustained use and new insights into the daily dynamics of stove use. Using small temperature dataloggers as stove use monitors (SUMs) they recorded continuous stove temperature signals and identified cooking events. They followed a group of 80 homes for over 2.6 years, measuring continuously stove surface temperature in alternate months. From the analysis of the temperature signals they derived binary indicators of daily use and counted the number of meals per day.

The authors quantified the percent stove-days, which represent the fraction of stove use from the total of stoves and days available.[5] Using this metric, they found that although the population saturation level (U_{sat}) remained more or less constant at 90% stove-days (see Fig. 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.

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 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 in a saturation level that is below 100% for the new stove, even if all users have initially accepted it and undertaken its sustained use.

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[5] Ruiz-Mercado et al. (submitted for publication) defined percent stove-days as a population metric of the level of stove use given by the ratio of the number of stoves n in use every day t during the monitoring period normalized by the product of the total number of stoves N and the total number of days T in the monitoring period. Under this metric 3 stoves used 10 days each are equivalent to 1 stove used for 30 days.

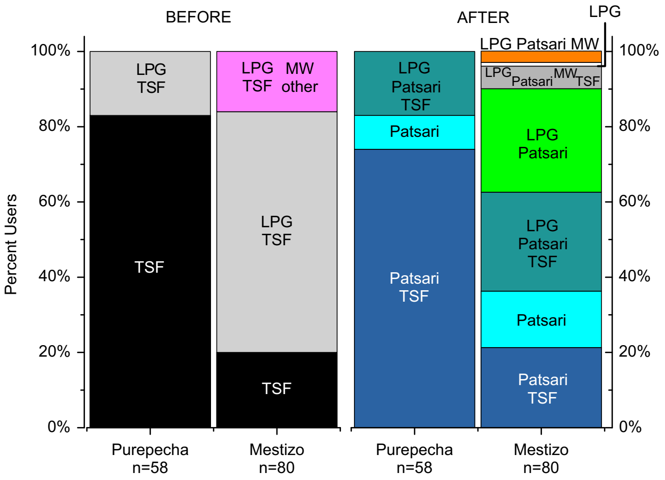

Fig. 5. Stacking of fuels and devices in the case of Mexico's highlands (Zamora, 2010). Even in the non-indigenous population (Mestizo), 50% of the households continue using the three-stone fire (TSF) with gas (LPG) stove and even microwave (MW). In the more indigenous group (Purepecha) after the adoption 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.

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.[6]

2.5. The redistribution of cooking practices brought by multiple fuel-devices

As stated earlier, evidence from Africa, Asia and Latin America increasingly suggest that when new cooking devices are incorporated, it is seldom that the old ones are completely phased out immediately; in many cases old and new devices coexist on a long-term basis. Fig. 5 illustrates this process in the case of 4 villages in Mexico's Highlands, which have been grouped in two population categories: "Purepecha" (indigenous) and "Mestizo"(non-indigenous) according to the dominant ethnic group. "Purepecha" families conserve their own language and follow deeply 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 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, 2010). 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 Fig. 5) rather than getting rid of the TSF.

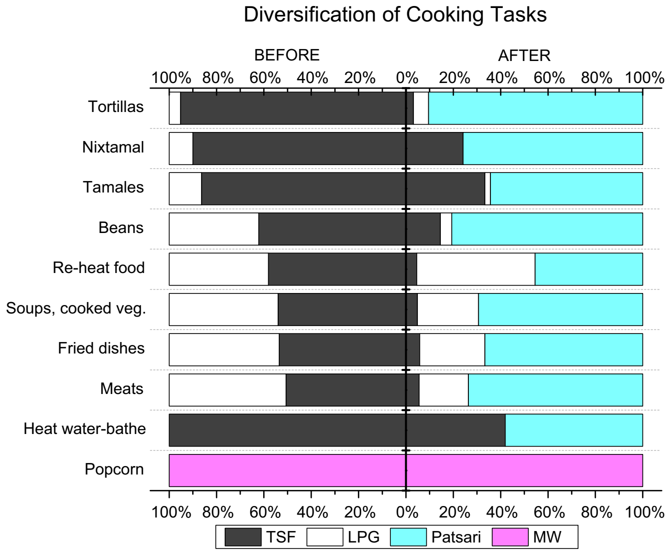

Fig. 6. Distribution of the main cooking practices by device before (left) and after (right) the introduction of the Patsari stove in a Mestizo population in Mexico's highlands (Zamora, 2010). All families have access to gas (LPG) stove, Patsari, three-stone fire (TSF) and small percentage also have a microwave (MW). While the Patsari stove is widely adopted to perform cooking practices 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 practice is still large.

To better understand the process of multiple device use it is necessary to think beyond cooking as a single activity and to examine cooking practices in more detail. When doing so, as illustrated by Fig. 6 for the case of the Mexican Highlands, we see that in most cases each device has marked preferences for specific cooking practices. In other words, the device adoption niche has to do with the compatibility and comparative effectiveness with regards to the different cooking practices.[7]

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 practices such as making tamales and nixtamal. LPG stoves, on the other hand score better for practices 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.

2.6. The importance of cooking practices in weighting the impacts of new fuel-stoves

Examining the initial acceptance and sustained use of stoves at the level of cooking practices is also critical because the impacts of introducing a new stove may be different depending on the particular practices that the fuel-device replaces or complements. In the case of rural Mexican households it has been found (Masera et al., 2005, 2007; Armendariz et al., 2008) that if one is interested in reducing fuel consumption or IAP associated to open fires for example, then tortilla making should be tackled as it accounts for

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[6] The choice of a denominator in assessing the percent meal-days for an improved stove alone is less obvious and requires measurements of stove use from all existing devices in the household. For further discussion of this point see Ruiz-Mercado et al. (submitted for publication).

[7] This process was documented by Pareek and Chattopadhyay (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).

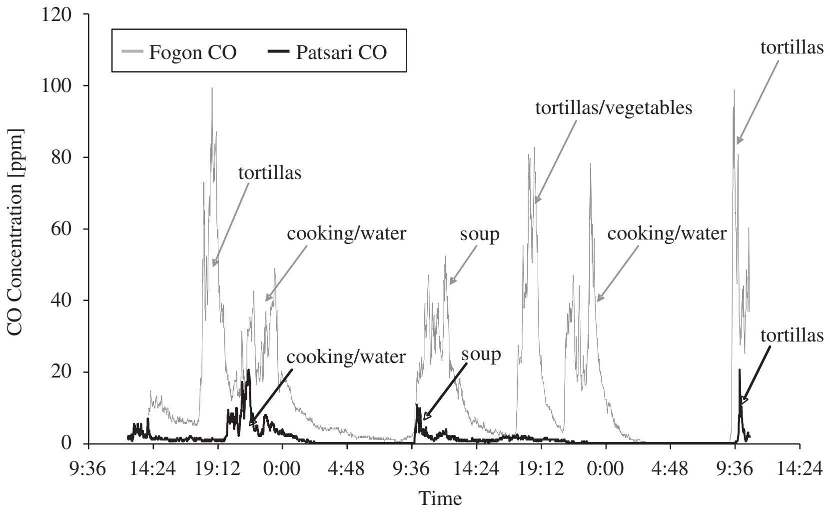

Fig. 7. Different cooking practices can exhibit distinct "signatures", contributing differently to the levels of indoor air pollution. In the case of Mexico the practice of tortilla making accounts for most of the carbon monoxide (CO) and particulate matter emitted indoors by traditional open fires. Due to the high intensity of this activity and close proximity of users to the fire when making tortillas, this practice is a major contributor to personal exposure derived from stove emissions. This figure (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.

a large share of human exposure to IAP and of fuel consumption.[8] 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. Fig. 7 illustrates the ranges of kitchen concentrations of carbon monoxide (CO) for a typical Mexican rural household, where it can be seen that different cooking practices 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 practices.

3. Monitoring adoption and sustained use: the need for adoption performance parameters

Since all the benefits from improved cookstoves depend on their long-term sustained use, verifying that the adoption performance parameters of the cooking system are met is equally important to the fulfillment of any other technical specification. Therefore, to complement measures of fuel efficiency and emissions that are used for individual stoves, there is a need for population-level adoption performance parameters that are based on objective measures of individual 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. It is 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 to characterize the process and to develop strategies for its optimization:

1. Level of acceptance (A_0)—The percent of stoves sold, constructed or installed from those initially planned to deploy.
2. Level of initial use (U_0)—The fraction of the population that began using the stoves from all those that initially accepted it.
3. Saturation level (U_{sat})—The fraction of the population at which stable sustained use is observed, from all those that initially accepted the stove.
4. Time for stabilization (ΔL)—The time elapsed from stove purchase or installation to the moment when stable sustained use is reached.
5. Variations of use (ΔU_{sat})—Magnitude of seasonal and local patterns affecting the mean saturation level U_{sat}.
6. Identification of the main cooking practices 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.

3.1. *New tools for cost-effective monitoring and improved dissemination*

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, they are too resource intensive to be performed continuously or at large scale and they can subject to bias, as they often rely on householder's memory or on their desire to respond as they think they should.

A new generation of monitoring tools has emerged, leveraged by the availability of smart, small, fast (near instant results) 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.

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[8] Tortilla making in a typical home is one of the most intense cooking practices that account for 40% of total wood use. It is a major contributor to the 24-h population averages of personal exposure to IAP, since this traditional practice requires for preparation 2–4 h of exposure per day in close proximity to the cooking device.

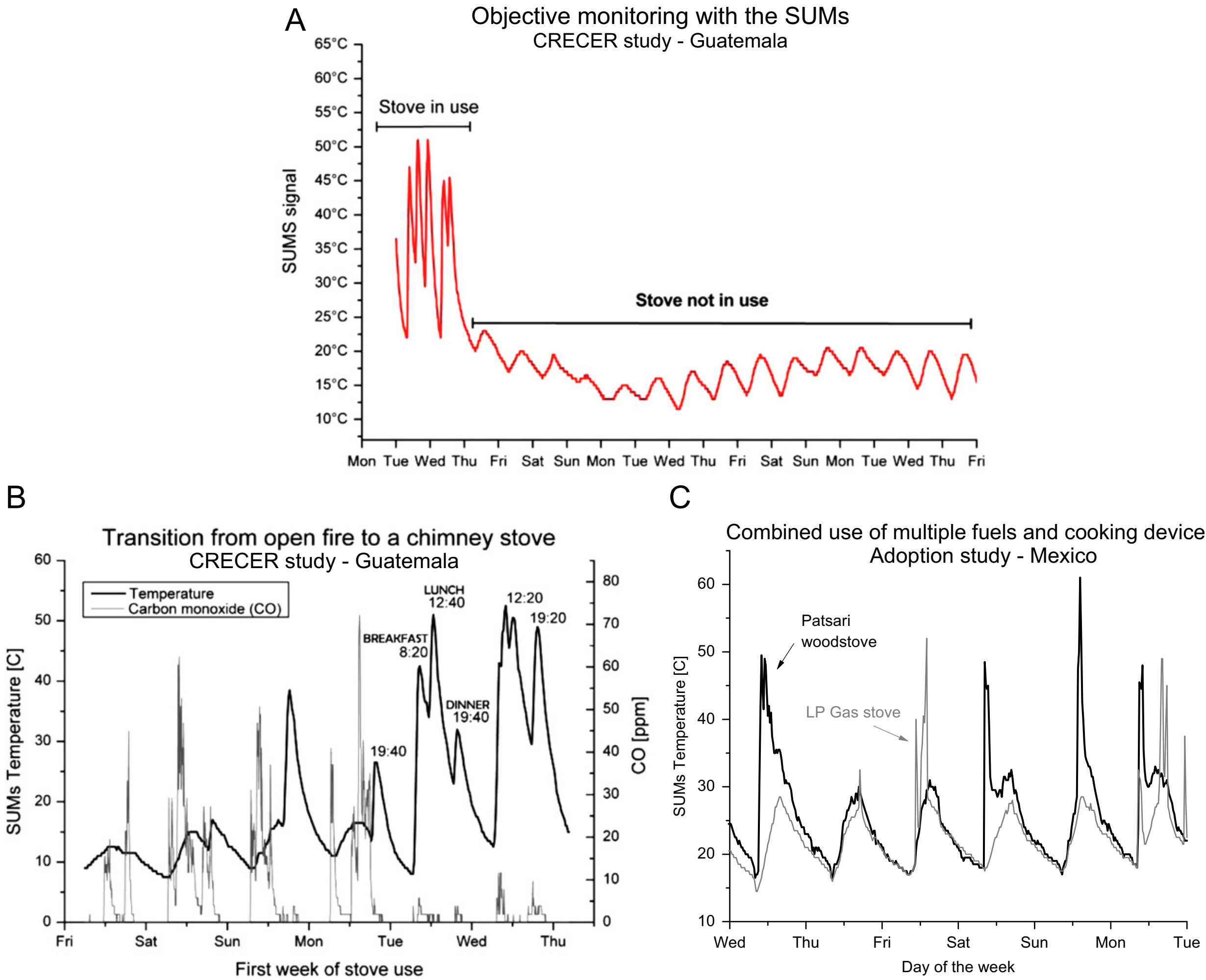

Fig. 8. Measuring stove use with the SUMs. (A) Validation of stove use (up): Stove use monitors (SUMs) data provides unique evidence of how this newly introduced chimney stove was only used during the first 2 days of monitoring as differentiated by the distinct stove and ambient temperature signals. (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). (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 practices.

3.1.1. *Stove use monitors (SUMs)*

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[9] and it has been implemented by Ruiz-Mercado et al. (2008, submitted for publication) in the Stove Use Monitors (SUMs) in biomass stoves and by Grupp et al. (2009) in the Synoptic Use Meter (SUM) for solar cookers. Both 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, and from thermal parameters of the system, the amount of food cooked was calculated and based on those, the fuel consumption and greenhouse gases reductions with respect to a baseline value 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 stove use (Fig. 8A). The data from individual SUMs are analyzed to identify daily use/no use and to count the number of meals per day. From those, the individual household adoption curves are 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 practices are obtained and its frequency is measured, the adoption niche of each cooking device can be quantified from SUMs-based data in terms of the redistribution of cooking practices.

These devices 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

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[9] 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.

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 are 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 like 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 and enables transparent verification. For monitoring agents and research efforts, this translates in 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.

Current research efforts in the development of monitoring tools for stove adoption and use are currently focused in four main avenues:

(1) Development and validation of the protocols and methods to integrate the adoption performance parameters into Adoption Performance Tests (APT) for different stove-fuel combinations. Also the integration of a global database of stove use data, to test different hypothesis and analyze the applicability of different models of adoption and sustained use.
(2) Reliable characterization of the signature of specific cooking practices (e.g. tortilla making, boiling water, etc.) from sensor signals. This with the dual objective of measuring the redistribution of practices brought by a new stove and quantifying the task-specific reductions in IAP, emissions and fuel consumption.
(3) 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 and seems one of the only cost-effective alternatives to allow long term monitoring from remote areas at the scale of millions. Power schemes and sources for reliable unattended data transmission will also be needed. In this regard, thermo-electric generators that are already used to power fans in semi-gasifier stoves seem a good alternative for energy harvesting.
(4) 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.

4. 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 practices rather than to immediate complete substitution. Identification of the main cooking practices performed with each stove-fuel combination is important to optimize the adoption process of improved cookstoves and to correctly weight 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.

We delineated in this paper a framework of stove adoption and identified some critical parameters that should be characterized and that could be part of an Adoption Performance Test. Validation of such APTs is likely to require a collaborative effort and the development or use of open source platforms, particularly for building up libraries of stove use identification algorithms and developing use indicators that can be validated, improved and made widely available in a sustainable way.

Just as the dispatch and initial acceptance of a stove is not a sufficient condition to ensure the delivery of its benefits, the availability and placement of a stove use monitor alone is not a guarantee of improved adoption. Stove use monitoring for adoption must be part of a larger plan for improved dissemination to translate SUMs data into actual benefits for the user.

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