From Technology to Impact

Understanding and Measuring Behavior Change with Improved Biomass Cookstoves

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Half the world cooks using biomass-fueled stoves. Improved biomass stoves represent an intersection of opportunities to address health, environment, poverty, and gender concerns on a wide scale. However, theories of change implicitly assume the behavior change that translates improved stove performance into desired outcomes and impacts. Experience shows behavior change cannot be presumed. Household stoves are nodes in a complex system, representing sites of interaction between the physical characteristics of the device, user behavior and perceptions, and larger social and environmental relationships. As such, the impacts of an improved stove are highly uncertain and may bear no relation to stove performance. This uncertainty compels us to evaluate stoves not only for performance and impacts, but also for technology uptake. Most stove evaluations lack an evaluation of technology uptake, and high-precision methods of monitoring stove usage have only recently become feasible. I present an example of a randomized-control trial that focuses on stove uptake in tandem with stove performance, illustrating the challenges of connecting stove performance to impacts. I conclude with a proposal for a richer evaluation framework that should be used to create the evidence base for scaling up improved stove deployments

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Contents

Why cookstoves matter

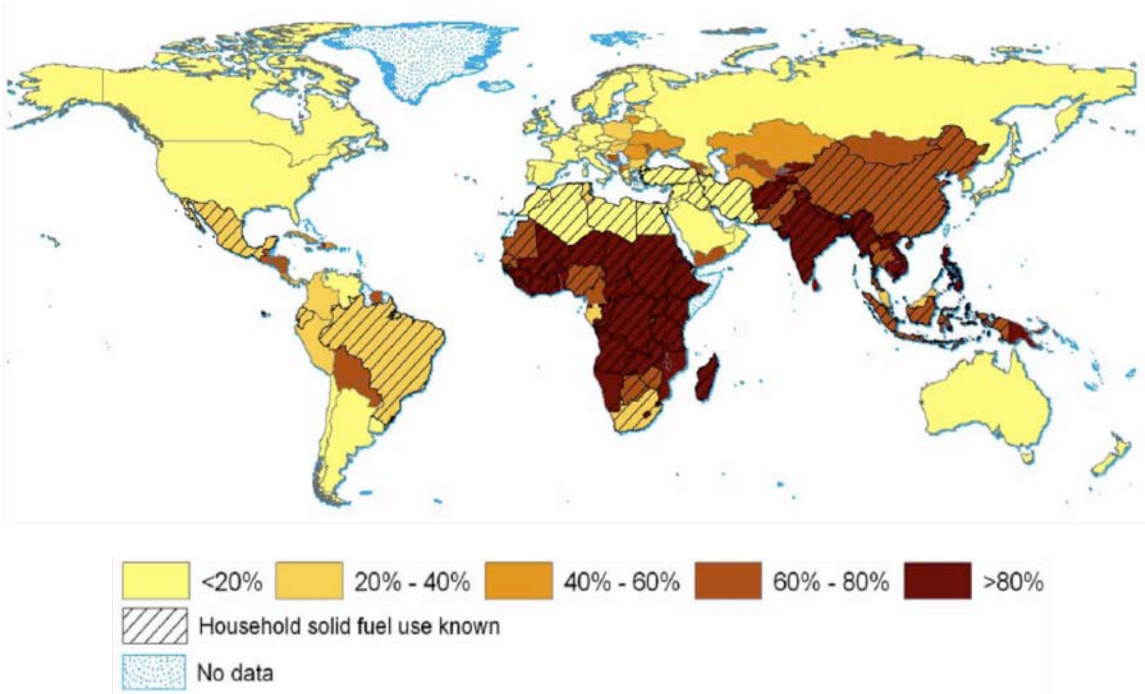
Half of the world's population cooks with solid fuels—primarily wood, charcoal, agricultural residues, and animal dung (see Figure 1.1). In the rural areas of developing countries, perhaps 90% of people cook with solid fuels (Mehta et al., 2006). National rates in sub-Saharan Africa countries are similarly high (Rehfuess et al., 2006). Many of these people are unlikely to have access to liquid or gas fuels in coming decades; as a result the number of people reliant on fuel wood and charcoal in sub-Saharan Africa is likely to double by 2050 from current levels, posing future challenges for energy access (Bailis et al., 2005).

The use of conventional biomass stoves produces indoor air pollution; levels of particulate matter and carbon monoxide emitted from biomass stove far exceed World Health Organization guidelines for ambient air quality (Pope and Dokcery, 2006; WHO, 2005; Gordon, 2004; Bruce, 2002; Ezzati, 2000). Exposure to indoor air pollution, most of which comes from household stoves, is responsible for an estimated 2.6% of the total global burden of disease, or about 1.6 million premature deaths each year (Smith et al., 2004). Emissions from stoves disproportionately affect the health of women because they are usually responsible for cooking in both households and small commercial operations in developing countries (Jiang, 2008; Mestl, 2007; Balakrishnan, 2002; Ezzati, 2002). Exposure to emissions is pronounced among infants and young children, who are often in the care of their mothers while cooking; 20% of deaths among children under 5 in poorer countries are due to acute respiratory infections, often due to indoor air pollution (Rehfuess et al., 2009; Emmelin and Wall, 2007).

The combustion of biomass fuels in stoves may be responsible perhaps one percent of greenhouse gas emissions globally (Smith, 1994). Even though a large proportion of fuel wood and all dung and crop residues are harvested on a sustainable basis, the combustion of such solid fuels in stoves has higher greenhouse gas emissions intensity than even conventional fossil fuels (Smith et al., 2000). Similarly, common methods for producing charcoal in developing countries emit substantial amounts of greenhouse gases per unit of energy gained (Bailis et al., 2005). Moreover, land-use change and timber harvesting are driving deforestation, making the management local forest resources increasingly important (Wallmo and Jacobson, 1998).

Given the overlapping nature of these challenges, public health and development practitioners view work on house-

Figure 1.1 | National household solid fuel use, 2000 (from Smith et al., 2006)



hold biomass stoves as an extraordinary opportunity to address many problems at once. The recently formed Global Alliance for Clean Cookstoves, supported with over $50 million through multiyear commitments from NGOs and governments, declares prominently on its site that "clean cookstoves and other clean cooking solutions save lives, empower women, improve livelihoods, and combat climate change."[1] Some efforts have focused on the fuel side of the equation; replacing biomass with liquid or gas fuels mitigates indoor air pollution substantially, and efforts to produce agriwaste briquettes could potentially mitigate increasing demand for forest products. However, current global efforts are focused predominantly on producing and deploying new, improved biomass stoves, due to their high projected benefit-cost ratio (Hutton et al., 2006).

While improved stove programs have existed for over half a century (Barnes et al., 1994; Manibog, 1984), attention to stoves has increased markedly in recent years with the advent of carbon finance. Recently developed methodologies[2] under the Clean Development Mechanism allow the distribution of improved cookstoves to generate credits that can be used by European nations to satisfy their compliance with the Kyoto Protocol. Voluntary registries like Gold Standard have developed similar methodologies as well.

What makes a stove "improved?"

While improved biomass stove designs vary substantially, all improved stoves attempt to reduce smokiness or reduce fuel use; many attempt to do both. Methods for reducing smoke require improving the combustion efficiency of stoves, since particulate matter is a product of incomplete combustion, or venting emissions away from users. To accomplish this goal, improved stoves are designed to allow air to draft through the biomass fuel by suspending the fuel above the ground with a metal or ceramic grate/latticework. Some improved stoves are also designed with a chimney; together with air draft through the burning fuel, this forces the hot, emissions-filled air out of the combustion chamber and away from the user. Methods for reducing fuel use require improving the heat transfer efficiency of stoves. To accomplish this goal, improved stoves are often designed to increase the surface area of the pot or metal plate exposed to the fire and chan-

1 See http://cleancookstoves.org/overview/solution/
2 AMS-I.C, AMS-I.E, and AMS-II.G. See UNEP Risoe, 2010.

Figure 1.2 | Examples of one older and three recent improved stoves

Clockwise from top-left: Jiko, Envirofit, Patsari, and StoveTec stoves

nel hot air at the surfaces while simultaneously reducing the thermal mass of the walls surrounding the stove. Additionally, lightweight and heat-resistant materials are sometimes used to improve insulation.

Finally, such stoves must be relatively inexpensive. Since it is often poorer households around the world who cook with biomass and lack other options, market-oriented approaches must be realistically affordable. For non-market distribution (such as through NGOs or government agencies), unit prices must be low enough to reach a justifiable scale while meeting budget constraints. Prior improved stoves, such as the Kenyan jiko, sell for less than $5. Next-generation mass-manufactured household models have been sold at prices lower than US$15.[3]

Before proceeding further, it bears mentioning that indigenous technologies are the result of countless years of experience and have great value to users. The three-stone fire commonly found around the world (see Figure 1.3), in which a pot is suspended above a fire by three large rocks, is simple to use, assembled quickly from easily found materials, portable, and scalable to the size of both the pot and the fuel at hand.

Many early stoves weren't any more fuel efficient or less smoky in practice than three-stone fires (Gill, 1987; Manibog, 1984). Moreover, engineers have found that stoves designs that improve performance along one dimension often do so at a tradeoff on the other dimension (Smith, 1989). Appendix A discusses stove engineering in greater detail. It suffices here to say that *stoves are physically complex artifacts*, and decades of work on stoves have only recently produced an understanding of consensus design principles and common pitfalls in stove engineering. Moreover, no single stove is appropriate for all situations, nor has any single stove proven dominant on all criteria. Improved stoves remain a domain of engineering where diversity of approaches is the rule.

Figure 1.3 | Examples of three-stone fires

3 See Levine, 2011. Also see StoveTec's website at http://stovetec.net/shop/

Between new stoves and desired impact

> The poor often resist the wonderful plans we think up for them because they do not share our faith that those plans work, or work as well as we claim. We shouldn't forget, too, that other things may be more important in their lives…
>
> —Abhit Banerjee and Esther Duflo

Promoters of improved stoves aim at a variety of impacts: better health for women and other household members, lower greenhouse gas emissions, time or cash savings for households, and sustainable use of local forest products. However, the path from improved stoves to those desired impacts is anything but certain. First, stoves are physically complex artifacts in which even subtle changes appear to significantly alter performance. Second, the actual benefits of improved stove performance can only be realized through behavior change of users. Finally, the greater impacts of improved stove projects depend critically on context.

Implicit theories of change in stoves

A "theory of change" (alternately, a "logic model") is the causal pathway between an activity and its outcomes (Weiss, 1995). Often, theories of change are understood to connect organizational inputs to immediate outputs, outcomes for participants, and impacts on the problems at hand (White, 2009). Theories of change are often unstated and involve many assumptions. For example, improved stoves are frequently posited as an opportunity to reduce environmental impact, by reducing either greenhouse gas emissions or pressure on local forests. However, even if an improved stove reduces biomass fuel requirements for the same cooking tasks (i.e., an *output*), it is unclear to what extent it will reduce overall household biomass fuel consumption (i.e., an *outcome*). For example, the fuel efficiency of the stove may encourage more overall use, offsetting savings in part or in full.[4] Similarly, if cooks continue to use multiple stoves, the fuel savings experienced by the household will be only a fraction of the savings from the improved stove. Similarly, such *outcomes* may not translate into hoped-for *impacts*. If an improved stove helps a rural household save biomass fuel, proximity to a road/market may enable such a household to sell "saved" biomass fuel to urban consumers—effectively having no impact on greenhouse gas emissions (although having the unintended benefit of adding to rural incomes). Alternately, land-use change may be the dominant driver of local deforestation, effectively canceling out otherwise beneficial impact of improved stoves on demand for forest products.

4 Davis (2008) observed precisely this phenomenon among US consumers of energy efficient home appliances.

The link between emissions performance and health impacts is more straightforward. In an environment where stoves are the primary source of inhaled $PM_{2.5}$ and other hazardous pollutants, a meaningful emissions reduction in stove combustion (*output*) is likely to translate directly into a meaningful exposure reduction for cooks (*outcome*). However, as before, the continuing use of multiple stoves may limit meaningful emissions reduction by a single improved stove. Similarly, someone who traditionally cooks outdoors all or most of the time may be inclined to shift their cooking indoors if a given improved stove reduces emissions to tolerable/"comfortable" levels when indoors, effectively increasing their exposure to harmful emissions.[5]

Getting from stoves to impact is therefore not simply a feat of engineering. While stove performance depends on the physical characteristics of stoves, the advantages of stove performance (*outputs*) only translate into lower emissions exposure and fuel use (*outcomes*) through user behavior. Specifically, stoves must be 1) used in 2) a correct manner 3) consistently over time and 4) in place of other stoves in order to realize outcomes. Thus, stoves require efforts to prompt behavior change, a topic commonly the province of applied social sciences.

Stove uptake as behavior change

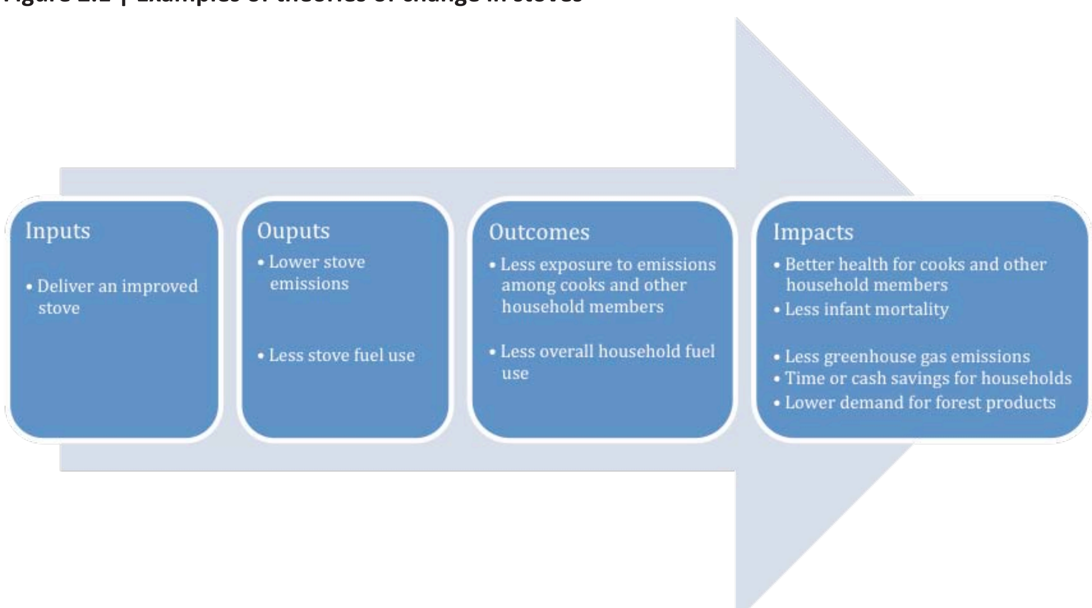
Whether and how users alter their manner of doing things—commonly termed behavior change—is critical to realizing the advantages of new technologies. Drawing on insights from both adoption-diffusion models (Rogers 1962) and use-diffusion models (Shih and Venkatesh, 2004), I propose that *stove uptake* is a set of separable, observable decisions over time (see Figure 2.2):

Adoption

The decision to take up a new technology starts at implementation of the technology. The phenomenon of dis-adoption of technologies suggest that the concept of adoption must include the persistence over time in the use of that technology. For market-disseminated stoves, the purchase decision represents a clear (though not infallible) indicator of adoption. For stoves distributed by an agent or stoves built by users, adoption can be observed in the continuing use over the initial weeks or months following distribution or training.

5 I observed this phenomenon during my 2009 randomized-control trial of a chimney-based improved stove.

Figure 2.1 | Examples of theories of change in stoves

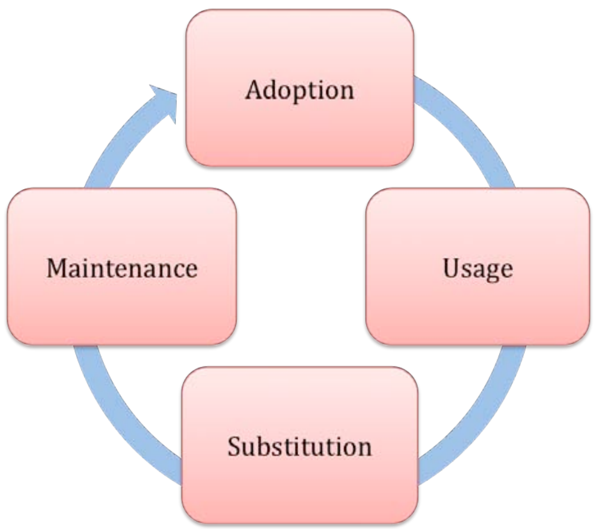


Use

The manner in which a technology is used, as well as the frequency of use, represents a key aspect of technology uptake. Since new stoves often require different methods of use and/or levels of effort than traditional stoves, users that do not adjust their usage behavior can use a stove ineffectively. To the extent that the benefits of new stoves require new use behavior, unchanging use behavior can be seen as incomplete technology uptake. Also, even if a user adopts a new stove, they may elect to use the stove more or less frequently over time.

Substitution

Figure 2.2 | Components of stove uptake



The degree to which use of a technology displaces other technologies that serve similar purposes represents another aspect of technology uptake. Stoves serve several functions, such as cooking food (and different components of meals), boiling water for washing or for tea, and the production of non-food products. Even if a user adopts a stove and uses it correctly and frequently, that user may still employ other stoves. For example, users may see a new stove as well suited for boiling water, but not for meal preparation; alternately, users may wish to reduce time spent cooking by preparing several parts of a meal in tandem, rather than serially on a single stove.

Maintenance

Effort to maintain the use of a technology through repair or replacement is a critical part of technology uptake. If a technology is not renewed in some fashion, then technology uptake is also incomplete. This aspect of stove uptake is not unlike dis-adoption; the difference is that the behavior is prompted by physical degradation of the stove, rather than subjective assessment of its use value.

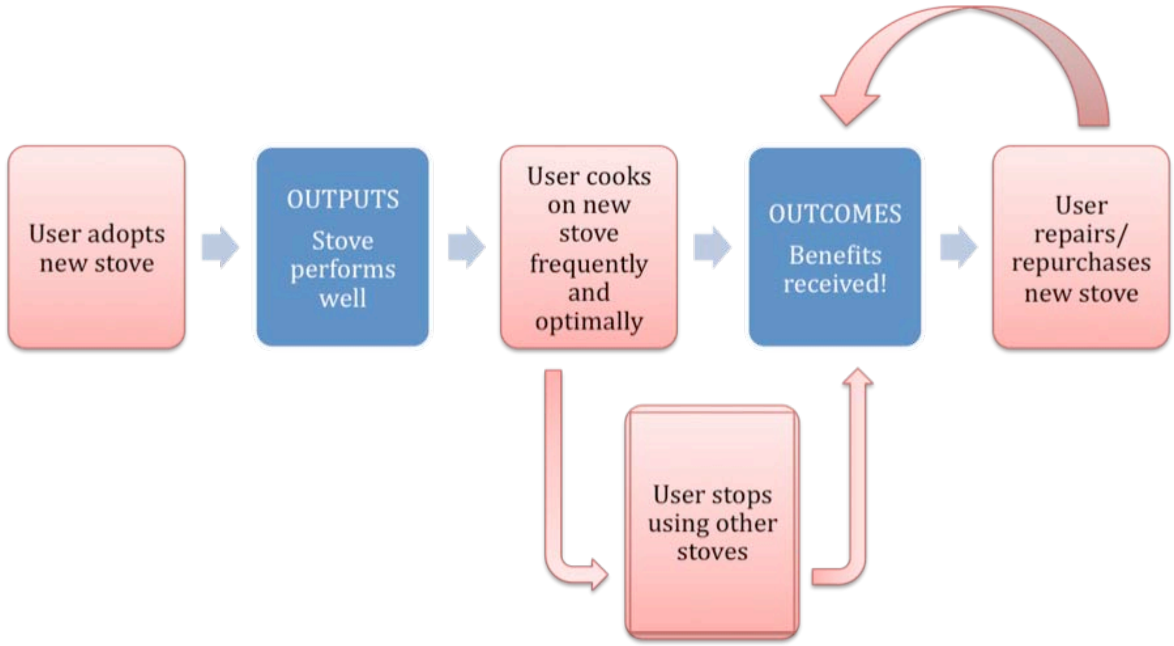
A theory of change with stoves becomes less linear and more complex when these aspects of stove uptake are included (see Figure 2.3). Indeed, transitions to new stoves have been observed as anything but linear, as cooks in developing countries often employ multiple fuels and stove types simultaneously (Masera et al., 2000).

Factors affecting behavior change

Wilson and Dowlatabadi (2007) identify several schools of thought for understanding individual behavior and decision-making associated with household energy (see Appendix B). These perspectives fall along a continuum between individually framed decisions and socially constructed behaviors. Each perspective draws attention to different psychological and contextual factors that affect stove uptake. Microeconomic models focus entirely on the characteristics of technologies and users as determinants of technology adoption. "Diffusion of innovation" models similarly focus on the characteristics of technologies and users; yet, technology adoption is also conceived of as a social process, and adoption decisions are influenced by place in social network and channels of communication. Social psychology and sociological models emphasize contextual factors, where technology adoption is a product of complex relationships between cultural norms, social relations, infrastructure/economics, and environment.

Each approach offers insights critical to understanding stove uptake. Below, I attempt to illustrate a detailed (though not

Figure 2.3 | A theory of (behavior) change



exhaustive) set of factors that influence stove uptake, grouped by aspects of stoves, users, and greater context. Though distinct from each other, these aspects are not cleanly separable.

Stoves: the gap between performance and user perceptions

Conventionally, the performance of improved stoves has dominated the discussion of technology adoption. In their review of stove programs, Barnes et al. (1994) relate technology adoption almost exclusively to the benefits of improved stoves (such as fuel savings or emissions reduction) relative to traditional stoves and the monetary costs of improved stoves. The presumption of a utility-based model of stove uptake does not require consideration of other factors; it suggest that, given all necessary information, consumers will make choices to maximize utility within budget constraints. However, improved stoves represent "experience goods," insofar as their quality can be ascertained only through consumption (Nelson, 1970). The question then becomes: how do cooks get the full information presumed by utility-based models?

The knowledge of engineers rarely matches the perceptions of developing country cooks. As outlined in Rogers' seminal work on the diffusion of innovations (1962), the gap between the advantages of a technology championed by designers or implementers and the perceptions of benefits by its intended users is the rule, rather than the exception. Cookstove projects, almost always designed and implemented by American and European men for developing country women, have been conceived of primarily in engineering terms and have failed to consider technologies as an interaction between users and tools (Crewe, 1994; Subramaniam, 1994). When it comes to stove performance, developing country cooks rely on their *perceptions*, not an objective set of "information." Moreover, what designers think cooks care about has historically been incorrect (Gill, 1987).

Unfortunately, perceptions are not easy to solicit. The deeper the direct monitoring of stove performance, the more change is introduced by the investigation itself; users' reported perceptions change according to interactions with investigators (Smith, 1989). Nonetheless, any model of technology adoption must bear this gap in mind.

Fuel use reductions

How do users perceive fuel use reductions? The magnitude of the fuel use reduction obviously matters. I venture that it is safe to say that a cook using an improved stove is highly likely to perceive a 50% fuel reduction during the course of a single meal preparation compared to use of traditional stove; a reduction of 33% is probably similarly easy to perceive. But what about 20%? Or 10%? At what level does a fuel use reduction fail to be perceived? Now ask what if there is some degree of "noise" in the signal, and it takes two trials to perceive? Or five? Or ten? Or twenty?

Studies of in-field stove performance quantify fuel use reduction in terms of averages, either over time or across a population, or both. From the level of a policy-maker, such aggregation makes sense; stove impacts are generalized to produce cost-benefit evaluations of programs and/or predict observed impacts at larger scale or in different places. Moreover, citizens of industrial economies are accustomed to precise quantification of their fuel use in the form of a monthly electricity and gas bill, allowing the perception of averages directly.

However, averages may not be a meaningful measure when it comes to user perceptions. For example, if average fuel use reduction is measured across a population and has high variance, a substantial proportion of users may experience fuel use reductions well under the mean.[6] What matters, then, is not simply the central tendency, but also the variance of the effect of a new stove. If stove engineers are to convince developing country cooks to use new stoves for fuel use reductions, they must take into account the heterogeneity of experiences and understand some cooks will not experience average fuel use reductions. It also stands to reason that the larger the variance, the greater the average fuel use reduction must be for the average user to easily perceive a reduction.

In addition to variation across cooks, variation "within" cooks—that is, variation over time for a given cook—affects perceptions. A longer period of time must pass before "noisy" averages can be perceived. If decisions to adopt a technology are based on an initial period of usage (Prins et al., 2009), such noisiness poses a challenge to dissemination of improved stoves.

What causes variance in fuel use reductions? It is possible to imagine many covariates. Attentiveness to cooking may vary with other simultaneous activity, such as caring for infants or tending multiple stoves. Some stoves may have a "hot start" while others have a "cold start," depending on preceding activity, which alters fuel use efficiency (Bailis et al., 2007). Users cook different kinds of meals for their households over time, varying the durations of cooking and particular manner in which they add fuel to cooking fires. Moreover, the number of people that they cook for may vary day to day, depending on their social relationships. For that matter, the range of other stove-related activities, such as water boiling for washing and tea or preparation of food for sale, can vary day to day as well. The types of available biomass, as well as their moisture content, vary over the course of the year and affect combustion. Some days will be windier than others, affecting the draft through the firHigh variance is another way of saying there is a "high cost of information" about average fuel use reductions. Cooks are likely to measure fuel use over time through incurred costs, either in cash for purchased fuel or in time/effort for gathered fuel. Users may not perceive benefits in fuel use reductions because the cost of fuel is not precisely measured over time—that is, discovery of marginal savings requires more "attentional burden." For example, users who gather biomass fuel rather than purchasing it may measure cost in terms of time-burden. Time-burden may not scale arithmetically with amount of biomass fuel collected;[7] as a result, modest fuel use reductions may not substantially impact the time-burden of biomass collection.[8] Effectively, such users require a much stronger "signal" to perceive fuel use reductions. On the other hand,

6 A substantial number may also therefore experience fuel use reductions above the mean.

7 People who collect fuel wood make trips that last a certain *duration* on a certain *frequency*. High variance in fuel use activity implies wood collection might occur at non-regular intervals, thereby making time-savings more difficult to perceive. Also, although average fuel savings may decrease the frequency of wood collecting trips, the duration of a given collection trip is not likely to change. While a combined product of the two (duration x frequency) can provide a measure of overall time-burden, it remains for other research whether this measure approximates user perceptions.

8 If the cook is not actually the person doing biomass fuel gathering (e.g., a mother sending a child to gather wood), then this perception may be even weaker. Similarly, if the stock of biomass fuel is shared across cooks,

users who purchase fuel on a cash basis have a strong signal in terms of quantified expenses. Therefore, it is likely that cooks who purchase fuel will be more sensitive to fuel use reductions and will perceive modest reductions more readily than cooks who gather fuel. That said, even cooks that purchase fuel may not have such a strong signal if, for example, the quality of the fuel is uneven (such as in charcoal) or fuel is sold in non- or quasi-standard amounts (for example, by the "bundle" instead of the kilogram).[9]

Ultimately, high average fuel use reductions would offset high variance. However, with more modest average fuel use reductions, high variance may impact perceptions.

Indoor air pollution reductions

Similar to fuel use, average reductions in exposure to smoke may not reflect perceptions. Variance here is also important. Exposure to smoke is a combination of factors: methods of initiating combustion; the combustion process inside the stove, including disturbances by the cook; the shape, density, and composition of the fuel; the amount of time the cook remains present beside the stove; indoor versus outdoor location; the air flow in the cooking area; and if indoors, the volume of the cooking area (Ezzati et al., 2000). Again, greater variance in effects increases the "cost" of information for users, and perceptions of stoves' impact on exposure to smoke may not reflect measured average reductions.

It is also unclear whether perceptions of stove "smokiness" refer to time-average exposures, point exposures, or some combination thereof. While most studies examine time-average exposures to carbon monoxide or particular matter, the intensity of exposure varies substantially over the course of cooking, due to burn rates, the addition of new fuel, and other physical disturbance (i.e., adjustment of the fire by the cook). Thus, time-averages can substantially understate users' exposure to indoor air pollution (Ezzati et al., 2000). It is possible that the benefits of lower time-averaged exposure to indoor air pollution may be lost on users who experience continuing, high point exposures.

For most users of improved cookstoves, perceptions of reductions to smoke will be based on subjective levels of comfort, not long-run estimates of health outcomes (Diaz et al., 2008). Levels of comfort may not change with modest reductions in indoor air pollution. Moreover, users may place greater value on reducing smoke exposure from (uncomfortably) high levels to (tolerably) moderate levels, rather than from moderate to low levels. While there is not yet a rigorously calculated dose-response curve for cardiopulmonary/cardiovascular disease and indoor air pollution from stoves, indications are that such a curve is likely to be logarithmic, not linear (Pope et al., 2009; Ezzati and Kammen, 2001). A logarithmic relationship suggests that reductions in indoor air pollution will only impact health when such reductions occur at low to moderate levels. Reducing smoke exposure from extreme levels to simply high levels, though perhaps statistically impressive, will not translate into very different health outcomes. Yet, users may actually value such reductions at the shallow part of the exposure-response curve, rather than the steeper section where long-run health benefits are more likely to be realized.

From a utility-based perspective, the "returns" to health or fuel savings from new stoves may be low compared to the cost of a new stove. Many poorer populations face an array of health challenges, from inadequate nutrition to water- or food-bourne parasites to endemic diseases to elevated risks of secondary infections from injuries. People facing such health challenges may rightly see rather limited increase in utility from better cardiopulmonary/cardiovascular health.

User experience perceptions

User perceptions will also focus on the cooking experience, possibly to a greater extent than actual outputs and sometimes in ways not commonly considered by stove designers. Thus, the performance of stoves (*effectiveness*) results from

or if multiple cooks rotate responsibility, then deriving information on fuel savings will require inordinate attention.

9 This was commonly observed in urban markets during my 2009 fieldwork in Ghana.

a combination of user behavior (*effort*) and physical stove characteristics (*efficacy*).[10]

Rogers (1962) identified the complexity of use of a technology and its compatibility with existing practices, beliefs, and norms to be two critical aspects of technology that affect technology adoption. Complexity and compatibility are factors that affect effort required to realize the benefits of an improved stove. Users may not adopt a stove because they find adjustment of cooking behavior to a new stove challenging. For example, improved wood-burning stoves often limit the opening through which fuel wood can be inserted so as to trap heat and improve heat transfer efficiency. This may require cooks to break up branches and other fodder before being able to use the stove—which many find an annoying or tiring task (Troncoso et al., 2007). It may also limit the cooks' ability to visually gauge the fire for proper cooking temperatures. Moreover, the improved heat transfer efficiency of a new stove may lead users to complain of burnt food. Similarly, the improved combustion of a new stove may actually increase fuel consumption if users do not adjust the rate at which they feed their fires (Gill 1987). Also, the stove may be unstable with larger loads, and users may consider certain designs more of a burn danger than others.

Users may also identify ancillary benefits of the stoves that reduce effort. Improved stoves than make more complete combustion reduce pot-blacking—effectively saving cooks effort in both pot washing and collection of water.[11] Improved heat-transfer efficiency can speed up water boiling times, reducing time needed for cooking or washing. While these particular aspects of stoves may seem like unexpected "bonuses" and not central to the purpose of the improved stoves, it is crucial that stove project implementers and marketers communicate them in order to improve stove dissemination.

10 The medical literature uses the term "effectiveness" to describe the average treatment effect of an intervention. "Efficacy" describes the non-varying effect of the intervention; that is, while effectiveness varies with the beliefs and effort decisions of participants in the experimental population, efficacy does not.

11 Such comments were common during my fieldwork, where 16% of women surveyed offered this response in discussing what they liked about an improved stove.

Users: attitudes and social influences

Characteristics of individuals similarly affect stove uptake, although these factors start to hint at the effect of context. In a utility-based model, users' time-preferences (i.e., discount rates) and risk aversion are critical factors in determining whether to purchase a new stove. Poor individuals in developing countries, most of whom rely on biomass stoves, tend to have high implicit discount rates such that even "sensible" investments may be ignored (Banerjee and Mullainathan, 2010). New stoves also carry potential risks of failure to generate savings or risks of ruined food; poorer cooks will be less inclined to purchase stoves and take on this risk than better-off households that can afford the risk (Foster and Rosenzweig, 2010). In the diffusion of innovations approach, decisions on stove uptake are affected by "attitudes toward innovation," which are often informed by education (Rogers, 1962).

Moreover, how a person gives and received communication will affect their perceptions. Rogers (1962) observed that people often evaluate a technology based on the subjective experiences of near-peers and that communication styles affect which perceptions get transmitted. More recent studies have shown two particular modes of peef-effects. On the one hand, people may take up a new technology due to learning from others' observed experience with a technology (Conley and Udry, 2010; Foster and Rosenzweig, 1995). On the other hand, social influence may be more important than information for technology adoption decisions (Dearing, 2009); as such, users may also make decisions on technology uptake based on status-driven imitation or shifting norms (Miller and Mushfiq, 2010; Sacerdote, 2001). Users' communication of perceptions is crucial in both cases. Moreover, these peer effects are important for technology adoption not only because initial users affect valuation of the technology by others but also because such initial users may teach others how to use complex or non-obvious technology (Oster and Thornton, 2009).

Context: stoves are sites of interactions

Technologies embody systems of interactions—cultural, social, economic, and environmental. Technological progress is a social activity; particular social, economic, and political relationships shape the invention, production, and dissemination of technical devices. As Winner (1986) observed, artifacts have "politics," as they predicate particular relationships in society. Moreover, the particular composition and functioning of a technical device predicate particular environmental relationships.

In this manner, stoves serve as sites of larger interactions. Stoves need to be understood not in narrow technical manners, but also in what Agarwal (1983) terms their "social and economic characteristics."

Cultural

Cookstoves simultaneously conform to the technical requirements for preparing specific cuisines and serve as a site at which cultural values are represented. Levi-Strauss, his seminal work *The Origin of Table Manners* (1978), illustrates how fire and cooking are basic symbols by which culture is distinguished from nature; moreover, he illustrates how receptacles used for cooking can distinguish cultures. Food is also identity; as Ohnuki-Tierney (1993), in her study of the cultural role of rice in Japan, writes, "Food tells not only how people live but also how they think of themselves in relation to others. A people's cuisine, or a particular food, often marks the boundary between the collective self and the other…" The cuisine of people in an area reflects not simply the historical availability of particular plants and animals, but also the strong cultural norms of taste and identity. For example, while other starches are widely available, the dominance of rice in East Asian diets reflects the culturally central role that rice plays.[12] Above all else, cookstoves predicate particular cultural configurations.

Food preparation thus utilizes both technical know-how and cultural information. For example, tortillas serve as a central cuisine in many Central American countries. Their preparation requires a *comal*, or hot flat surface made of metal or stone (similar to the preparation of crêpes in France, injera in Ethiopia, or dosas in southern India); thus, even though a cookstove intended for use with pots might be workable for tortilla preparation, cooks are likely to prefer a configuration with a built in *comal*. Similarly, the particulates and volatile organic compounds emitted from wood fires affect the flavor of a tortilla. Many cooks consider this flavor an essential part of the tortilla and so do not prefer the use of liquid or gas fuels in tortilla preparation (Heltberg, 2005; Masera et al., 2000; Saatkamp et al., 2000). Similarly, cooks may smoke foods for flavor or for preservation, rendering stove smoke desirable.

Similarly, cultural beliefs can affect cooking behavior, and thus, stove configurations. Many of the communities in highland Nepal consider it bad luck to cook animal flesh inside the house where people sleep (Lohani, 2010);[13] as a result, cooks often use separate cooking shacks that lack insulation, and thus cooking fires are valued as much for their heating as their cooking. Moreover, such cooking fires do not use chimneys sometimes found on stoves used for water-boiling within the home, even though the level of smoke may be comparable. Similarly, the association of smoke inhalation with adverse health impacts may not be common knowledge, and so chimneys or venting may be considered unnecessary or inappropriate (Atanassov, 2010; Edelstein et al., 2008). Finally, "superstition" and other particular cultural idiosyncrasies can impact cooking behavior not only between ethnic groups, but even village to village (Agarwal, 1983). Although such beliefs may seem trivial at first, they influence both choices for existing stoves and decisions to adopt new stoves.

Social

Social relations intimately affect cooking behavior and, thus, preferences for both physical character and arrangement of

12 See Ohnuki-Tierney (1993) for a thorough exploration of the cultural role of rice in Japan.

13 During my December 2004 visit to the ethnic Sherpa village of Solaban in highland Eastern Nepal, villagers told me of this particular belief as well.

stoves. Family structure can be critical. Cooks who either live with extended family or in multi-family compounds, for example, will often require larger pots and thus larger stoves, whereas cooks who live with nuclear family or alone may not need large stoves very often, if at all. Furthermore, the day-to-day variability in number of people for which a cook is responsible affects the decision to retain multiple stoves. Cooks in multi-family compounds sometimes cook for just their family and sometimes cooks for other families as well. Similarly, ceremonial or social gatherings require stoves with larger capacity than usual daily affairs.

Household decision-making can also affect stove choices. Husbands often control household income and may not see improved stoves as a worthwhile expenditures (Nathan and Kelkar, 1997).[14] Kitchens may be shared among several cooks, inhibiting changes in stoves due to disagreement over preferences (Okello, 2009).

Finally, stove choices may be affected by concerns over social status. The decision to adopt a new stove may be enhanced or discouraged by observing use of a stove by high- or low-status groups, respectively (Miller and Mushfiq, 2010). Similarly, younger cooks may defer to older cooks (Okello, 2009).

1.1.1.1. Economic

The economic context and nature of poverty, moreover, influences stove choices. The decision to buy a new stove will be affected by a household's cash flow and credit constraints (Foster and Rosenzweig, 2010; Banerjee and Duflo, 2007). For example, even if a new stove could pay for itself in savings on subsequent fuel purchases, the upfront costs may be too high, and payment over time may not be an available option (Miller and Mushfiq, 2010). For that matter, many poor consumers have common experiences of malfunction of breakage of low-cost, low-quality durable goods in the local economy; these experiences may color perceptions of new stoves (Levine, 2011).

Household production is critical to understanding stove choices. Many households use their stoves not only for domestic functions but also for economic activities (Banerjee and Duflo, 2007). Some cooks prepare foods for sale at local markets or on roadsides. Some cooks also prepare food or brew alcoholic beverages in large quantities as caterers for local events. Cooks may also process agricultural products intended for sale on their stoves; for example, cooks in Western Africa produce shea butter in pots on their stoves.[15] If the volume of household production varies due to economic activity, then cooks are likely to use a multiple stoves, each suited to different purposes.

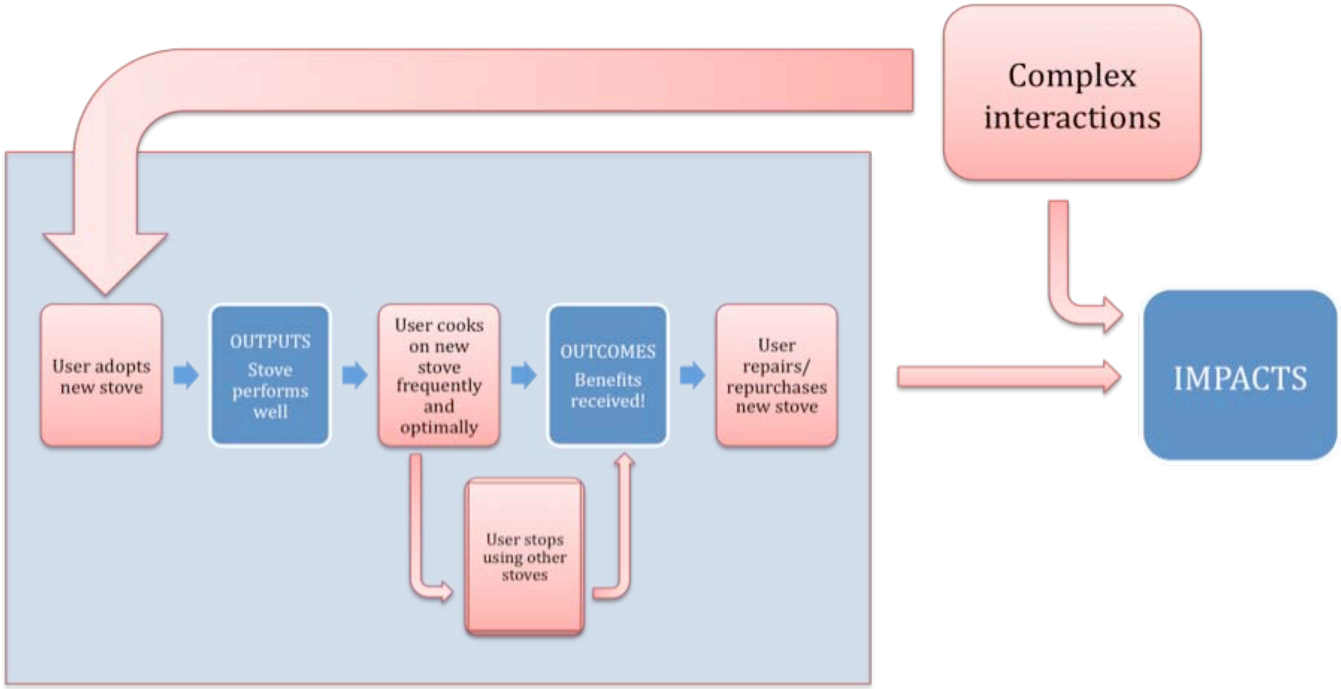
Environmental

Stove choices are also affected by environmental context. Urban cooks and rural cooks differ in that rural cooks may have direct access to forest products, whereas urban cooks do not. For rural cooks, the availability of fuel wood in the local environment may factor into decisions about the relative importance of fuel efficiency characteristics in stoves (Barnes et al., 1994; Gill, 1987). Climactic conditions can affect stove choices as well. In colder climates, the inefficient heat transfer of traditional stoves is a benefit, as the stoves warm the home. Similarly, in tropical climates many people consider smoke from stoves to be beneficial for repelling mosquitoes—although there is not much evidence that stove use correlates with mosquito activity (Biran et al., 2007). Also, temperature and precipitation affect decisions of whether to cook indoors or outdoors. Cooks in areas that commonly experience extremes in precipitation or temperature may retain multiple stove options to ensure a minimum level of comfort during cooking. Finally, seasonal variation in temperature and precipitations means that cooking behavior can change over the course of the year in a regular fashion.

14 Nathan and Kelkar (1997) point out that women generally collect wood and women's time is generally valued less than men's; time devoted to wood collection is thus unvalued, and stoves that improve fuel efficiency are thus not likely to be valued by men.

15 Personal observation during my January 2009 trip to the Sissala West district of Ghana.

Figure 2.4 | A complex theory of change



A more complex theory of change

The complex system of interactions in which stoves are embedded not only influences behavior change but also affects whether lower emissions exposure or fuel use translate into the saved lives, fewer greenhouse gas emissions, empowered women, or improved livelihoods that project implementers wish to attain. Thus, even if desired outcomes are achieved, the path to impacts is easily interrupted. For example, rural households often collect fuel wood or produce charcoal to sell to urban households; fuel savings a rural household derives from an improved stove may therefore translate into surplus for sale, rather than a meaningful reduction in wood burning and thus greenhouse gas emissions.

Therefore, a theory of change related to stoves must include these complex interactions. The resulting picture is not a linear process, but rather an ecology of feedbacks and interactions between technology and impact (see Figure 2.4).

All of the preceding discussion may seem daunting—how can improved stoves ever succeed in making the impacts we wish to see? The lesson from the above is not that practitioners should give up. Rather, stove project implementers should examine their causal assumptions in a clear-eyed manner to better design stove projects and avoid the disillusionment that attends inflated expectations. Specifically, the many factors that affect stove uptake should spur stove projects to expand beyond the narrow assumptions of economic-engineering models. Moreover, factors outside the control of a stove campaign may mitigate (or amplify) the greater effect of stoves. While this may be frustrating to the well-intentioned public health or development practitioner, humility and a more sophisticated view of conditions must surely maximize the incremental impacts of improved stoves.

Complex interactions between stoves, users, and context make it difficult to predict the impacts of introducing an improved stove. Such uncertainty compels us to examine field performance and behavior change related to stoves.

Illuminating the gap with evaluation

> …uncovering the causes of effects excites me more than measuring the effects of causes. An evaluation masters the second, but only hints at the first. The hardest and most rewarding work is the theoretical and investigative work that comes with uncovering the underlying rhythms and rules of human behavior.
>
> —Chris Blattman

Randomized-control evaluations

Only relatively recently have randomized-control trials (RCTs) been used to evaluate stove projects.[16] Led by the Abdul Latif Jameel Poverty Action Lab (J-PAL),[17] Innovations for Poverty Action (IPA),[18] the International Initiative for Impact Evaluation (3ie),[19] and the Center for the Evaluation of Global Action,[20] RCTs have been applied to a variety of development projects. RCTs have become popular in large part because they provide credible and transparent estimates of program impacts that overcome the limitations of other evaluation methods—particularly useful in decisions for scaling up programs (Duflo, 2004). Particularly with stoves, Mueller et al. (2009) show that estimate of improved stove impacts are significantly biased when adopters are self-selecting; random assignment mechanisms avoid this ex-ante through study design, rather than relying on ex-post data analysis.[21] The RESPIRE study stands out as the most rigorously conducted RCT to examine the effect of improved stoves on longitudinal health outcomes among highland Guatemalan families (Smith et al., 2010, 2006). While such methods are becoming increasingly common, examples are still few (Beltramo and Levine, 2010; Miller and Mushfiq, 2010; Masera et al., 2007; McCracken et al., 2007; Alam et al., 2006).

Edwards et al. (2007) demonstrate how power calculations for several study designs increase with the variability in observed stove performance. They argue that, since improved stoves should exhibit significant effect sizes (in their case, reductions in indoor air pollution) to be considered "worthwhile," the use of relatively small samples may be justified. I would argue that, although this provides logistical convenience and lowers study costs, the effective prior of desiring only "worthwhile" results ends up becoming a statistical self-fulfilling prophecy. The use of small sample sizes, in

16 Briefly, the crux of a randomized-control trial is the random assignment of study participants to either treatment or control groups—wherein treatment. With reasonably large sample sizes, such purely random assignment should produce two groups that do not differ systematically on observable characteristics. Finding this so gives confidence that unobservable characteristics do not systematically differ between groups either. Therefore, the difference in outcomes observed between groups can be said to be completely exogenous—that is, due entirely to the treatment, rather than other confounding factors that may not be possible to observe.

17 www.povertyactionlab.org

18 www.poverty-action.org

19 www.3ieimpact.org

20 cega.berkeley.edu

21 See Mueller et al. (2009) for details of nearest-neighbor matching approach.

conjunction with the publication bias-fueled hunt for statistical significance, produces the overstatement of effect sizes and understatement of variability of effect sizes (Gelman and Weakliem, 2009).[22] Moreover, observed effects in ethnically, demographically, and/or geographically homogeneous samples are not likely to generalize in a predictable manner since outcomes from stove use are affected by behavior change and contextual interactions

Moreover, stove projects may have multiple benefits, and small sample sizes can limit findings of smaller-magnitude secondary or tertiary benefits beyond the focus of a given study. To their credit, Edwards et al. (2007) recognize this, saying that increasing sample sizes would be useful to capture the often smaller effect sizes of co-benefits. I would go beyond this and state that, because the link from stove performance to household outcomes and impacts is attenuated by less-than-perfect behavior change, we should also expect average project impacts to be of significantly lower magnitude than average stove performance. Large sample sizes are more likely to capture the smaller magnitudes of impacts, rather than produce a Type II erroneous finding that the impacts of stoves are "not significantly different than zero."

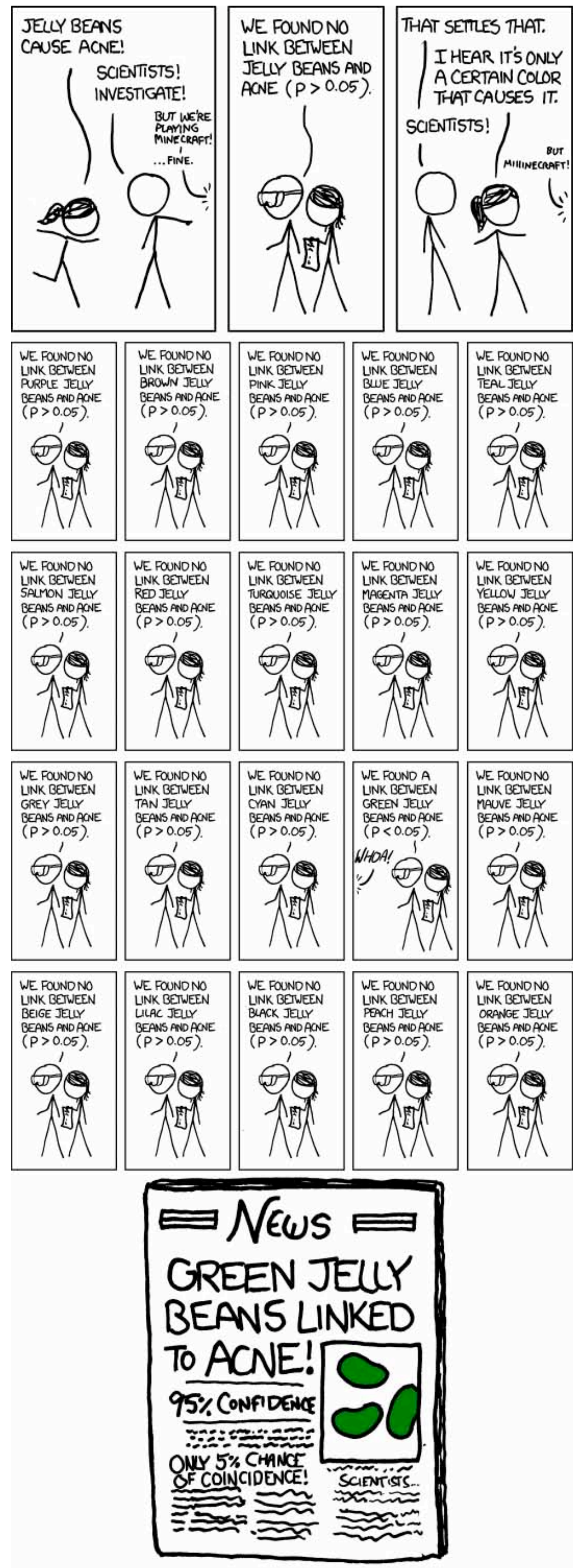
It is also important to distinguish between evaluations of improved stove performance versus improved stove impacts. Evaluations of stove performance focus on the particular outputs associated with use, including measures such as single-stove fuel consumption and stove emissions.[23] While such methods can provide feedback about stove outputs, they lack meaningful power to describe actual impacts on households. Evaluations of stove impacts, such as changes in overall fuel consumption and exposure to emissions, provide feedback about outcomes or impact, they do not actu-

22 Small samples are capable of detecting only relatively large effect sizes given statistical conventions (power of 80%, p-value of 5%, two-tailed test). If publications tend to favor broadcasting findings of effects rather than findings of no effects, then small-sample studies will tend to find significant effects "by chance" and overstate the effects of an intervention. Another way of putting it: if p-value is 5%, then one could reasonably expect one of every twenty small-sample studies to make a Type I error.

23 See Bailis et al. (2007) for a discussion of different methods of measuring fuel use. See McCracken et al. (2009), Edwards et al. (2007), and Smith et al. (2007) for discussions of measuring exposure to stove emissions.

Figure 3.1 | The downside of statistical significance

from XKCD http://xkcd.com/882/



ally illuminate the causal factors involved—important when users of stoves evidence either no impact or less impact than anticipated from expected stove performance. Fundamentally, an RCT is of limited use if it tells only *what* works and does not, not *why* it works or does not (Deaton, 2009). Also, such methods represent only proximate measures of the impacts we generally care about: better health for cooks and household members, lower greenhouse gas emissions, time or cash savings for household members, and sustainable use of local forest products.

The evaluation of improved stove projects has focused much more on stove performance than on stove impacts. In the 1980s and 1990s, many state-sponsored stove programs disseminated stoves, sometimes with participatory approaches and commonly with subsidy; those that even had follow-up generally showed poor adoption or unclear impacts (Barnes et al., 1994; Manibog, 1984). Even in more recent programs, evaluation is still not commonplace: a retrospective look at 101 landmark, large-scale improved stove programs between 1994 and 2010 shows that only a third included a specific evaluation component; of these, only a fraction used field-based trials rather than laboratory tests (Gifford, 2010). Historically, stove deployment programs have rarely included social marketing, training on stove usage, or follow-up oversight. As a result, stoves are disused or misused due to insufficient attention to the behavior change implicitly required for optimal stove use.

The lack of evaluation suggests that stove implementers presume behavior change. Such presumptions are not only shortsighted, but also misleading of less well-informed publics and will lead to wastes of scarce development dollars. Moreover, there is now profit to be had in ignoring behavior change; the methodologies required for producing carbon offsets represent a willful ignorance of the role of behavior change. The project design documents for Ugastoves, the first-ever stove project to receive carbon credits, base their claims on a comparison of pre-installation daily fuel use and post-installation daily fuel use across a sample of users; yet, a brief review of their data and analysis suggests factors affecting stove uptake should drastically limit the claimed impacts of their stoves (see Appendix C).

While stove adoption is generally straightforward to observe, the aspects of stove use, substitution, and maintenance are logistically-demanding to observe. Evaluation of these aspects of stove uptake generally require follow-up over time and decentralized monitoring of household activities. Challenging as this may be, understanding the components of stove uptake is necessary for learning some of the reasons why expected impacts of a stove project do not materialize.

Recently, new technologies have been developed that allow for relatively low-cost, logistically feasible monitoring of technology uptake and user outcomes. Ruiz-Mercado et al. (2008) demonstrate the use of temperature loggers as stove usage monitors and offer a potential method for assessing cooking activity. Also, Allen-Piccolo et al. (2009) have developed an ultrasound personal locator to produce high-precision time-activity assessments associated with cooking—complementing stove usage data with user location in and out of the cooking area. Promising developments such as these allow us to examine the behavioral parts of causal chain that would connect stove performance to household outcomes. The recent Patsari stove deployment in Mexico stands out in its mixed methods study of usage patterns and factors affecting stove adoption and use (Romieu et al., 2008; Troncoso et al., 2007; Masera et al., 2005). However, having occurred over several years, it does not provide a template for a RCT that examines behavior change systematically and can produce feedback in a timely manner.

It is against this methodological background that I carried out such an RCT in Ghana in 2009.

Case: Evaluating performance and behavior for a stove deployment in rural Ghana

Given the logistical difficulties of obtaining longitudinal measures, as well as the perennial resource constraints and limited technical capacities of many organizations that implement improved stove programs, we sought to demonstrate that a quantitative evaluation adequately capturing both stove usage and stove performance could be carried out rapidly at scale using simple methods. To this end, in collaboration with the Ghanaian Council on Scientific and Industrial Research, we carried out a rapid assessment randomized-controlled trial of an improved cookstove program in rural northern Ghana on behalf of the NGO Plan Ghana.

Appendix D presents the study in full, describing in detail the context, improved stove, implementation plan, study design, and findings. I will summarize relevant points here as part of my illustration of how a randomized-control trial can include study of behavior change.

Plan Ghana chose to implement an improved stove that was built by participants using a mix of locally-available materials and metal parts distributed by Plan Ghana (see Table 9.1). Presuming that fellow women cooks can more effectively communicate with other women cooks in demonstrating and advocating for the stoves, Plan Ghana hired women trainers from a pilot village to teach other women how to build and use the stoves. Participation was free. Following trainings in each village on stove construction, 768 study participants across 8 villages were randomly assigned to treatment and control groups by a lottery; whereas treatment group participants received materials to build improved stoves immediately, control group participants received materials one to two months later.

Measuring stove performance

To measure stove performance, we used a controlled cooking test in which we measured the fuel wood consumed by each participant in cooking a full meal of a traditional dish. To measure exposure to emissions, we affixed a carbon monoxide passive diffusion tube to the collar of each participant during the controlled cooking test, measuring exposure following cooking a meal. We also surveyed participants on self-reported recent cooking activity, fuel wood collection, and health, as well as socioeconomic and household information.

A linear regression specification shows an average fuel reduction of 12% among those in the treatment group (see Table 9.13); when adjusted for non-compliance (i.e., treatment-on-the-treated analysis), this rises to 14%—fairly modest, but significant and robust to a variety of specifications. However, responses in the household survey show no difference in time spent collecting fuel wood (Table 9.14), suggesting that at least one impact is not being realized.

Interestingly, the treatment group also brought 15% less wood to be weighted at the start of the cooking test, a statistically significant difference ($P < 0.001$). This appears to indicate learning-by-doing among cooks with the improved stove, although it is unclear to what extent this learning reflects stove efficacy or cook effort. It is also possible that treatment group participants wished to demonstrate fuel-efficiency behavior when being observed closely (i.e., a "Hawthorne" effect).

A tobit regression specification with upper-limit censoring shows no significant difference in exposure to carbon monoxide between groups (see Table 9.16). Outdoor location of cooking does show a significant difference, indicating a reduction in time-weighted exposure as high as 50%. These findings are robust to a variety of specifications. In response to questions of self-reported health, though, treatment group participants indicate fewer and less frequent respiratory health symptoms than control group participants (see Table 9.18).

Measuring stove uptake

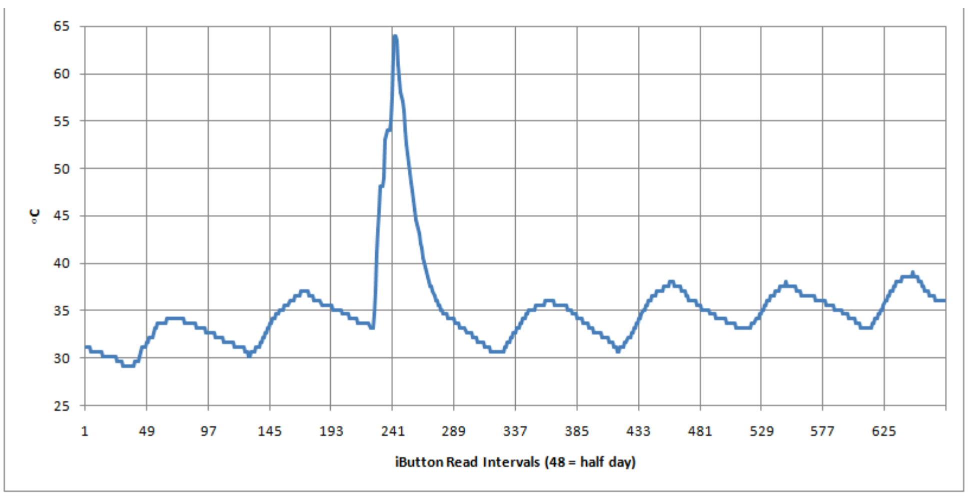
Summary statistics from the household survey show that treatment group and control group participants do not differ on almost all observables in any systematic manner—that is, randomization worked. The single systematic difference between groups is in number of stoves participants report using: treatment group participants report 2.3 stoves on average, compared to 1.9 stoves on average for controls (see Table 9.10). Divergence is expected, since treatments built improved stoves—but an additional stove would be expected to increase average number of stoves by one. When we look only at traditional stoves, treatment group participants report 1.4 traditional stoves on average, compared to the 1.9 traditional stoves that controls report. Thus, initial evidence suggest that improved stoves may be displacing traditional stoves.

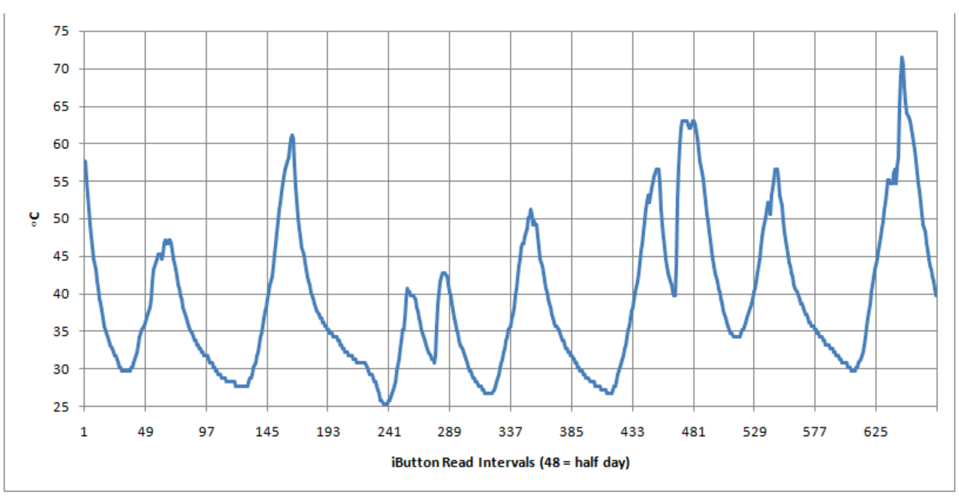
To better observe behavior change and technology uptake, we chose a subsample of households and attached stove usage monitors (SUMs) to all of the stoves reported at each home. This proved less than ideal. Traditional stoves are not standardized, and while we developed conventions for placing SUMs, placements ultimately varied across stoves. Furthermore, whereas the walls of mud stoves were amenable to SUMs, three-stone fires lack any such convenience; as a workaround, we buried SUMs a few centimeters below one of the three stones to monitor such stoves.

We collected SUMs after three weeks of continuous monitoring with readings at 15 minute intervals. Almost a third of stove usage monitors were either destroyed by heat or misplaced. Such non-random survival of SUMs would be expected to understate average usage if, as is likely, SUMs overheated more often when placed on stoves that were used more intensively. In addition, improved stoves' walls were thin compared to traditional stoves; the decreased thermal mass means improved stoves were likely to heat and cool faster than traditional stoves—and so therefore might appear to record less usage than traditional stoves. Furthermore, because rarely-used stoves presumably are less likely to overheat SUMs, the rate of non-adoption is likely to be overstated.

Figure 3.2 | Examples of stove usage monitor readings

Intervals at the bottom represent number of 15-minute intervals; hence, 96 intervals is equivalent to a full 24-hour period.

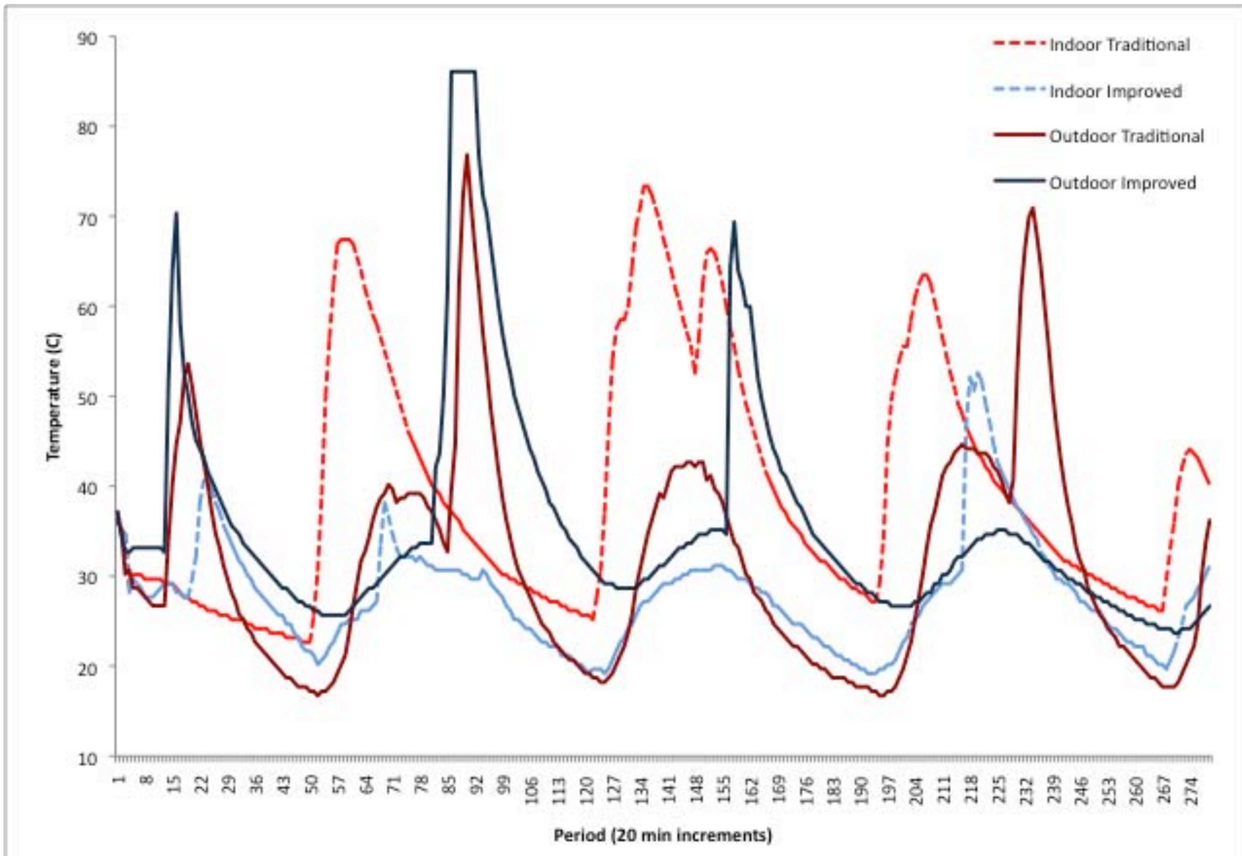




Temperature data from the SUMs were challenging to interpret. Figure 3.2 illustrates two examples. The first graph presents a straightforward and fairly easy interpretation: the monitored stove remained unused with the exception of activity during the third day, as evidenced by elevated temperatures. The second graph presents a less obvious interpretation: while frequent activity is evident, it appears that some of this activity occurs at significantly lower temperatures than on other days.

Figure 3.3 | Example of stove usage monitor readings for all stoves used by a single household

Note that the amplitude of the activity varies across stoves due to non-standard placement of stove usage monitors.



Thus, it appears that both high temperature levels and periods of rapid temperature change are evidence of usage. We chose 50° C as a cutoff point, assuming that stoves bodies could not exceed this temperature from ambient temperature and insolation. We also assume that a rise of 5° C or fall of 3° C over an hour is evidence of initiating and extinguishing a stove, as these measures of activity show the highest correlation with each other and the 50° C threshold.

Interpreting these data in light of multiple stove usage is complex. Figure 3.3 presents an example of stove usage monitor data from the four stoves of a single household over three days during the winter "harmattan" season.[24] Taken together, there is clear periodicity in the signals. Regular spikes in activity correlate with the morning and evening meal preparation; a third spike between these represents other activity—potentially preparation of snacks for children or water boiling for washing. The cook shifts activity between the stoves, using only indoor stoves in the (colder) mornings and using only outdoor stoves (where moonlight is available) in the evenings. The outdoor improved stove is used as frequently as the outdoor traditional stove; however, the indoor improved stove is used far less than the indoor traditional stove. In sum, while we observe improved stove *adoption*, improved stove *usage* varies over time, and it is only partially *substituting* for traditional stove use. Multiple stove use is dynamic day to day and patterned over time; monitoring of only a single stove would distinctly limit our understanding of cooks' behavior.

24 This household was not part of the study population, but rather from Kupulima, the pilot village we worked in initially. Moreover, we gave this household materials to build multiple improved stoves so that we could better understand how activity might shift among multiple stoves.

> *Adoption*
>
> Our stove usage monitors showed that 70 of the 78 (80%) monitored improved stoves registered temperatures over 50° C on a continuing basis over the three-week period, indicating *adoption*.
>
> *Usage*
>
> On average, these improved stoves registered temperatures over 50° C at least half of all days in the three-week monitoring period, indicating level of *usage*.
>
> *Substitution*
>
> In addition, treatment group participants reported fewer traditional stoves in regular use than controls, suggesting some *substitution* of traditional stoves. At the same time, many treatment participants continued to use one or more traditional stoves. On average, traditional stoves were also used more often and for longer periods than improved stoves. The net result is that treatment and control households did not register significantly different durations of overall stove activity, and there was mixed evidence for decline in use of traditional stoves among treatments.
>
> *Maintenance*
>
> Importantly, we also conducted walkthroughs of three villages eight months following the initial study. Usage of the improved stoves appears to have declined over time; perhaps 50% of improved stoves remained in use (see Table 9.20). Additionally, 25% of improved stoves were found to be broken, indicating levels of stove *maintenance*. (However, given the non-random nature of village walkthroughs, in which outdoor stoves were more likely to be observed than improved stoves, it may be difficult to generalize these findings for the unobserved sample.)

During the eight-month follow-up, we also observed behaviors consistent with valuation of stoves. We observed several instances of women fashioning improvised grates from zinc (commonly used as roofing material) to try to imitate the improved stove design of others. We also found some women had widened the mouths of their improved stoves to accommodate larger pot sizes, suggesting some cases of adaptation rather than dis-adoption. We observed freshly made and drying bricks, suggesting possible repair or reconstruction of some stoves. These behaviors, while limited and not as prevalent as counts of broken or unused stoves, suggest some amount of sustained behavior change. As a final note, one or two cooks were observed using wood charcoal in their improved stoves—a heretofore unobserved phenomenon in the villages we worked in. Such fuel-switching suggests learning-by-doing, as some cooks value some marginal consumption of charcoal in the improved stove over marginal sales of that charcoal.

Although SUMs provide real-time objective monitoring and some descriptive value, our inferences remain less than conclusive. The lack of standardized placement of temperature sensors, the variation in thermal mass, and the partial coverage of households due to sensor attrition all add error to the stove usage measures. In addition, cooks use multiple stoves, and some stoves are used by multiple cooks, making it difficult to measure who is cooking where. Furthermore, it is unclear to what extent we accurately monitored all stoves in a given households; 25 of the 31 participants identifying only a single stove for SUM placement reported using multiple stoves in the household survey—suggesting enumerator error or negligent reporting by study participants. Furthermore, some participants reporting only a single stove show very little time over 50°C on that stove, suggesting some degree of misreporting of number of stoves and/or inaccurate monitoring of stove activity.

Regardless of these concerns, it is clear adoption of a new stove does not imply the household uses the new stove, and adopting or using a new stove does not always directly reduce usage of an old stove. Furthermore, even if new stoves are used and substitute for old stoves, some new stoves may fall into disuse from breakage. To accurately assess the impact of improved stove programs, future evaluations must focus on all four, separable behaviors associated with new technology uptake: adoption, usage, substitution, and maintenance. It remains beyond the scope of this paper to consider how remote sensing technologies, such as SUMs, may better assist in this effort.

Moving to richer evaluation

The intent to scale up the distribution of improved biomass stoves demands that future evaluations generate findings that both shine a light into causal pathways and lend themselves to generalization. We should study the causes of effects at the same time that we study the effects of causes (Deaton, 2009).

Because stove designers generally intend to deploy not hundreds, but thousands or millions of stoves, evaluations ought to have large, heterogeneous samples to improve external validity of results. At first blush, the goal of external validity may appear contrary to previous observations of how contextual factors affect stove uptake—how can results generalize when conditions vary region to region? Indeed, given that many projects are geographically bounded and thus unintentionally culturally and socioeconomically homogeneous, results are not likely to generalize well. More to the point, the selection of site for evaluation may reflect biases toward trying stoves where they are expected to receive the most positive results—a not unreasonable approach, since targeting interventions is a valuable way to deploy constrained resources (White, 2009). The alternative is to deploy stoves across a diversity of areas in an effort to increase unobserved participant heterogeneity.[25] While such an approach may decrease the magnitudes of observed effects, modesty of outcomes is a fair trade for results that can be reasonably generalized.

Stove performance remains something of a black box in current trials. The performance of stoves results from a combination of stove uptake and physical stove characteristics. Stove uptake is itself based on priors; users of new stoves will put in more effort to use them effectively or frequently the more they expect the new stoves to render benefits. Simple randomized-control trials may reveal an average treatment effect, but such an effect fails to disentangle the user behavior from the stove efficacyChassang et al. (forthcoming) propose using selective trials to tease out the role of effort. In a selective trial, study participants are assigned to the treatment group according to a probability that increases with stated "willingness to pay"[26] for the treatment. This effectively decorrelates user behavior from treatment status. With a reasonably large sample size, such selective trials can identify the effects of a treatment conditional on the participants' valuation of that treatment. Assuming that valuation is a predictor of participants' effort in use of stoves, a selective trial approach to stoves could effectively tease apart to what extent user effort is responsible for outcomes, versus stove efficacy.

As has been demonstrated, remote sensing can complement measures of stove performance and immediate outcomes. Stove usage monitors offer a readily accessible tool, although more work needs to be done before they can be easily interpreted. Cross-validation of a subset of stove usage monitors against observed stove use would allow for richer data interpretation than presented in the Ghana study—possible even allowing inferences of fuel use. Future research should also focus on improving signal-processing methods. One promising approach is principal component analysis, a statistical method that can conceivably identify and separate out idiosyncratic and common patterns of readings across many stoves (see Appendix E for a brief exploration). The result of such methods should be to quantify and provide rich descriptions of several of the separable components to stove uptake: adoption, usage, and substitution..

For the fourth element, maintenance, some amount of longitudinal follow-up is critical. Even a "light touch" of brief field observation and incidental interviews can illuminate the ex-

25 This is effectively stratification; randomization should occur within subgroups, rather than across them, to ensure a balanced set of treatment and control groups.

26 "Willingness to pay" may also mean "willingness to wait/spend time" in the case of cash-poor or credit-constrained populations.

tent to which stove uptake has proceeded (or not) over time. Rates of dis-adoption can similarly be quantified.

Finally, qualitative methods should have a substantial role in evaluation to increase the rate of learning in stove evaluations. The results from these efforts are likely to provide meaningful feedback on improved stove deployment and fill in gaps in description and inference that necessarily attend quantitative data. Contextual factors that affect behavior are sometimes revealed to researchers unexpectedly, either through informal conversations with participants or attention to details during implementation. Rather than treat such activity as incidental to quantitative methods, qualitative efforts should be intentional and developed with some detail. For example, structured observation of a random subsample of participants, such as through a time-activity survey, may be able to inform the particular constraints on cooks, household decision-making, and a variety of other behavioral and contextual factors. Similarly, interviewing a subsample of participants with open-ended questions about a list of contextual factors (such as are mentioned in Section 2.3.3), can aid interpretation of results without requiring extensive resources.

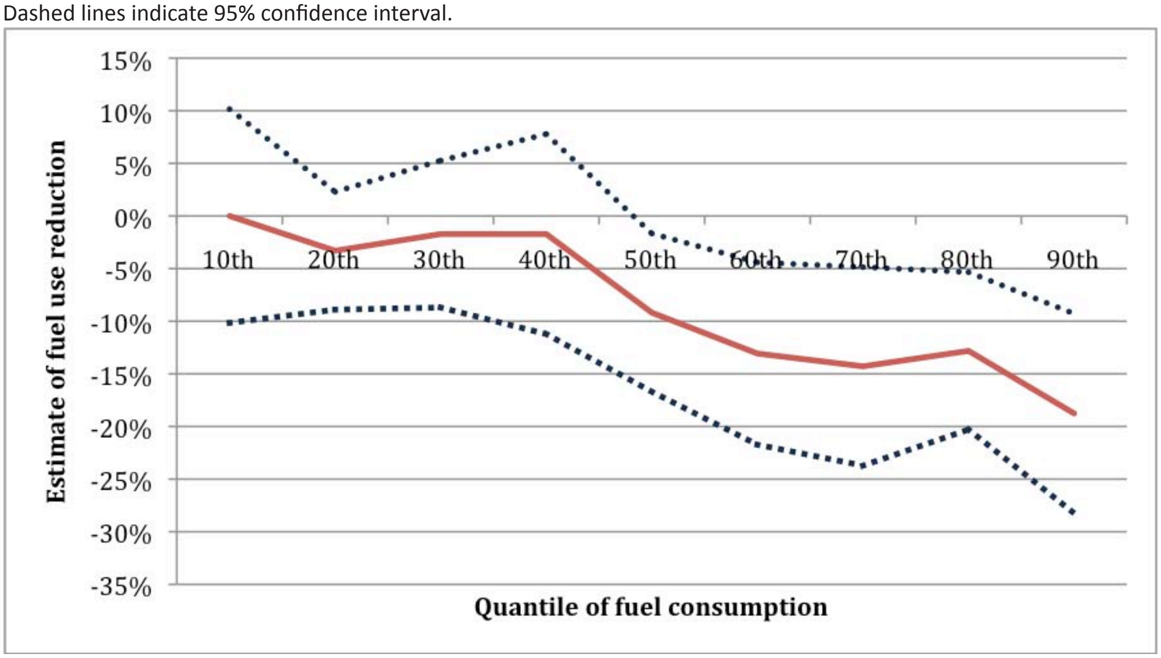
A brief note on data analysis

The structure of a randomized control trial allows for the revelation of average treatment effects through simple mean comparison tests between groups (i.e. t-tests). This is because the random assignment mechanism, when combined with a large enough sample size, will create two groups that do not differ systematically on observable characteristics (and therefore, presumably do not differ on unobservables as well), and the effect of a new stove can thus be considered entirely exogenous.

The use of mean comparison tests, however, is not appropriate for groups that differ systematically, which generally occurs when assignment is non-random. When the only people with improved stoves are those that want them—that is, self-selection—the measured impacts of the stoves are confounded by other systematic difference among the groups. Unfortunately, this has no stopped evaluations from using it. Mueller et al. (2009) show that the better health of improved stove users in China was partly due to their divergent socioeconomic characteristics, which affected stove uptake decisions to begin with. Similarly, the Ugastoves Project,

Figure 3.4 | Parameter estimate of fuel use reductions, by fuel consumption decile

Dashed lines indicate 95% confidence interval.



which is receiving carbon credits, quantified its fuel use reductions through a comparison of pre- and post-intervention averages of fuel use. However, their methods suggest systematic differences between pre- and post-intervention cooking exogenous to the new stove. The lack of a control group does not allow for a meaningful comparison of time trends.

A solution to this problem is to use parametric or semi-parametric methods to examine the effect of improved stoves when controlling for confounding covariates. In the case of the Ugastoves evaluation, a simple linear regression approach that takes into account the level of baseline consumption dramatically decreases the estimate of improved stove fuel reductions (see Appendix C). Similarly, Mueller et al. (2009) use nearest neighbor matching to produce an estimate of improved stove impacts in China that account for differences due to socioeconomic status. While it is beyond the scope of this paper to offer a deep introduction to such methods, Ravallion (2007) offers a useful discussion for practitioners and Deaton (2009) provides a handy summary of problems in these methods.

Such methods, moreover, can move beyond simple means and reveal the distribution of measured effects of stoves. In Figure 3.4, I apply the semi-parametric method of simultaneous quantile regression to the data from my Ghana 2009 study to show how the estimate of fuel use reduction varies with relative level of fuel consumption. This particular analysis reveals that the average fuel use reduction is almost entirely due to the reductions in fuel use from "highly consumptive" cooks. Cooks whose fuel consumption was below the median did not show significant differences in fuel use, whereas those above the median did.

This heterogeneity of experience should give us pause. While averages are important for policy purposes, cooks will individually experience an effect on fuel use below or above the average, and these experiences will inform behavior change associated with stove uptake.

Concluding thoughts

The prevailing understanding is that there is a direct path between improved stoves and desired impacts. Yet this metaphor is an inaccurate depiction of the world. We would better be served with a more ecological understanding; between improved stoves and impact is behavior change, influenced by the multiple interactions between stoves, cooks, and context. Similarly, rather than approach improved stoves in technology-led, engineering-economic terms, stove project implementers would improve rates of stove uptake by approaching stoves in more human- and systems-oriented terms. The multifaceted Patsari stove deployment program serves as an intriguing example of this shift "from cookstoves to cooking systems" (Masera at el., 2005); the program pursues technology innovation and market development, a cookstove dissemination package, support to micro-enterprise development, monitoring and evaluation, and outreach activities as an integrated effort. Notably, it is also subsidized.

The increasing emphasis on mass-market approaches to stoves presents an interesting question. Market mechanisms may create robust supply chains for stoves that lower unit costs, and cooks' purchase of stoves serves as a strong indicator of stove uptake. Such efforts may dovetail with recent work on innovative financial contracts for stove purchase and combined microfinance efforts (Levine, 2011). Carbon financing of improved stoves may also offer a new source of capital to entrepreneurs and subsidies to unit costs that increase unit sales. It remains to be seen whether such approaches can create and meet consumer demand for improved stoves on a wide scale. Of more interest, though, is whether the sale of an artifact will in fact "save lives, empower women, improve livelihoods, and combat climate change." If stoves remain posited narrowly as a technical problem, it is unclear that changing the mechanism of dissemination will fix it.

Understanding and measuring behavior change in biomass stoves will not unlock secrets to scaling up stove projects—those efforts will meet their challenges regardless. However, in refocusing from measuring impacts to also illuminating causal pathways, we can better understand the targeting, timing, communication, and structuring of biomass stove deployments. We can also better anticipate what a limited budget might be able to accomplish. Most of all, we can engage with and learn from developing country cooks to better meet them where they are and help them take a step forward, rather than demand a leap.

> It is possible to make very significant progress against the biggest problem in the world through the accumulation of a set of small steps, each well thought out, carefully tested, and judiciously implemented… These changes will be incremental, but they will sustain and build on themselves. They can be the start of a quiet revolution.
>
> —Abhit Banerjee and Esther Duflo

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Stoves as physically complex artifacts | A

Given the variation in cooking practices, fuels, and contexts, no single stove can hope to satisfy all situations well—or even more than a few select applications. Table 6.1 illustrates 48 models of improved stoves recently tested by McCarty et al. (2010).

The relationship between stove design, fuel use, and emissions is complex. Fuel efficiency and smoke mitigation are often a tradeoff in design; moreover, traditional three-stone fires appear to perform better than some improved stoves on either goal (Smith, 1989). Physical conformations and materials vary substantially among improved stove designs, and even substantially divergent designs may produce comparable performance in a laboratory setting. The 2009 observations of a *New Yorker* journalist, writing about stove designers at the Aprovecho Research Center in the United States, warrant repeating:

> Building a stove is simple. Building a good stove is hard. Building a good, cheap stove can drive an engineer crazy. The devices at Aprovecho looked straightforward enough. Most were about the size and shape of a stockpot, with a cylindrical combustion chamber and a cooking grate on top. You stuck some twigs in the chamber, set them on fire, and put your pot on the grate-nothing to it. Yet one stove used a pound of wood to boil a gallon of water, and another used two. **Fire is a fickle, nonlinear thing, and seems to be affected by every millimetre of a stove's design-the size of the opening, the shape and material of the chamber, the thickness of the grate-each variable amplifying the next and being amplified in turn, in a complex series of feedback loops. "You've heard of the butterfly effect?" one engineer told me. "Well, these stoves are full of butterflies."** (emphasis added)

The Aprovecho Research Center, which has studied and tested biomass stove designs since 1976, offers a set of ten design principles for wood-burning stoves intended as "technical best practices" (Bryden et al., 2005); while each of the principles are based on evidence from prior testing and are certainly useful, they very much remain principles—without more specific indications of the relative importance of each principle to performance or how design tradeoffs might be managed. That said, Aprovecho does favor a particular stove design: the StoveTec Wood Stove (see Item 20 in Table 6.1), which is currently being marketed worldwide. Recent field tests of this design show it to be comparable to several other competing designs in both fuel use and emissions (Pennise et al., 2010).

Even when stoves are well-designed, they are prone to modification. Again, from the *New Yorker*:

> Too many stoves start out as marvels of efficiency, they said, and are gradually modified into obsolescence. Once the engineer is gone, the local builder may widen the stove's mouth so it can burn larger sticks, only to draw in too much cold air. Or he'll make the stove out of denser bricks, not realizing that the air pockets in the clay are its best insulation. The better the stove, the tighter its tolerances, the easier it is to ruin.

Combined with recent, well-funded initiatives to deploy stoves at immense scale—notably the Global Alliance for Clean Cookstoves' plans to support 100 million stoves by 2020[27] and the Indian government's National Biomass Cookstoves Initiative—nearly all stove projects now seek to deploy mass-manufactured stoves, rather than those produced by artisans or built by cooks themselves.

Table 6.1 | Examples of current stoves (from McCarty et al., 2010)

27 See http://cleancookstoves.org/blog/the-impact-and-the-solution/

Perspectives on behavior change in household energy | B

(from Wilson and Dowlatabadi, 2007)

Main features	Conventional economics	Behavioral economics	Technology diffusion	Social psychology	Sociology
	Section 3		Section 4	Section 5	Section 6
Decision model	Utility-maximization based on fixed and consistent preferences	Widely varying decision heuristics and context-dependent preferences	Attitude-based evaluation of technologies and the consequences of adoption	Interacting psychological and contextual variables	Sociotechnical construction of demand
Decision scale	Individual	Individual	Individual/social	Individual/social	Social
Main research methods	Quantitative (observed behavior)	Quantitative (controlled experiments)	Quantitative and qualitative (surveys, interviews, observed behavior)	Quantitative and qualitative (surveys, observed behavior)	Qualitative (interviews, observation)
Main dependent variables	Preferences between decision outcomes	Preferences between decision outcomes	Rate of diffusion	Self-reports of behavior and/or energy use	Observed or self-reported behavior
Main independent variables	Costs and benefits of outcomes and their respective weightings	Aspects of the decision frame, context, and elicitation method, as well as outcomes	Adopter role in social networks, communication channels, technology attributes, and leadership of adopter	Values, attitudes, norms, sociodemographics, economic incentives, skills, capabilities, and resources	Social, cultural and technical determinants of energy demand embedded in routine behavior
Empirical basis in energy use	Extensive	Very little	Some	Extensive	Some
Implications for interventions to reduce residential energy use	Provide information about benefits and incentives to improve cost-benefit ratio and improve cognitive capacity to assess net benefits/utility	Pay attention to framing and reference points for decisions, influence heuristic selection by emphasizing associations or emotive attributes, control choice sets and default options	Segment target population, exploit communication channels through social networks and use change agents, identify stage of decision process in target groups and use appropriate change mechanisms, ensure desired technology or behavior has key attributes	Influence attitudes only if external conditions are weak, use multiple interventions with due attention to interaction effects, identify and target barriers, design salient and personally relevant information, values provide a disposition for long-term change	Work toward long-term sociotechnical regime change, exploit opportunities of transition, recognize the social role of routine or habitual behavior, manage expectations
Timescales for interventions	Short term	Short term	Short to medium term	Short to medium term	Long term

C | Case Study of Efficient Cooking with Ugastoves

The project entitled "Efficient Cooking with Ugastoves,"[28] which began in Kampala, Uganda, in 2005 and was officially registered with Gold Standard in March 2009, is the first and only stove project that has received carbon offsets to date. It is instructive, therefore, to examine the project design document (PDD) and other related verification documents to understand how this project addresses components of behavior change.

The Ugastoves PDD describes both a baseline methodology for calculating expected carbon offsets and a verification protocol to ensure that these offsets are produced over time. The verification protocol states that Ugastoves will keep sales records, which will measure stove adoption, as well as carry out a biannual kitchen test (KT) and a quarterly kitchen survey (KS), which will measure stove usage and performance. Ugastoves states that it will hire a third-party with the capacity to undertake this data collection; the PDD lists the local partner third-party and the foreign partners in the US and UK who will provide training and oversight to the local third-party. While costs are not listed, it is likely that the hiring and training of data collectors is a non-trivial component of the overall program budget.

The Ugastoves PDD indicates that project developers conducted a KT in 2006 and a KS in 2007. The KT involved 68 cooks and looked at overall household charcoal use three days prior to installation of a Ugastove and then three days post installation, with no secondary stoves or fuels allowed. The developer computed the difference in fuel use pre- and post-installation using a simple t-test and used the lower bound of a 90% confidence interval to determine a conservative estimate of fuel savings per day per stove; this number has then been extrapolated out to determine average annual fuel use reductions per stove.

This method raises concern. First and foremost is that the fuel use reduction is considered in a circumstance where a cook has been directed to stop using secondary stoves or fuels; yet, the use of multiple stoves and/or fuels may be common. Second, the fuel use reduction is measured immediately post-installation—thereby not capturing usage patterns that may develop and stabilize over the weeks following installation. Third, there is a distinct likelihood of a Hawthorne effect; the recipients of the stoves likely understood the object of the foreign researchers and may have been more conscious of their fuel use than normal.

A closer look at the 2006 KT data shows further issues.[29] There are a wide range of fuel uses, with some households

28 See https://gs1.apx.com/mymodule/ProjectDoc/EditProjectDoc.asp?id1=447

29 The 2008 analysis by Oxford statistician TJ Heaton entitled "Statistical Analysis of Fuel Consumption on Charcoal Ugastoves 2006" is available at https://gs1.apx.com/mymodule/ProjectDoc/Project_ViewFile.asp?FileID=1692&IDKEY=k0e98hfalksuf098fnsdalfkjfoijmn4309JLKJFjlaksjfla9o2333268

at 1 kg/day and others at 10 kg/day; notes in the statistical analysis state that the high variance may be due to the commercial cooking activities of some households. This raises immediate questions about what accounts for differences among households; it is possible that some cooks who cooked for commercial purposes pre-installation did not carry out commercial activities on the post-installation days, and such a phenomenon would grossly exaggerate fuel savings.

Indeed, the observations with the highest fuel use show the most dramatic reductions; when comparing the top ten percent of fuel users to the rest, the difference in relative fuel reductions is significant (56% vs. 21%, t = -2.09). A regression of relative fuel reduction on the pre-installation fuel consumption (specified below) shows that fuel reductions increase linearly with baseline consumption.

$$PctReduction_i = \underset{(0.061)}{0.044} + \underset{(0.015)}{0.059}\ PretestFuelUse_i$$

Therefore, the average difference specified by the project developer uses an inadequate method and is a likely overstatement of fuel reductions.[30] More careful attention to actual behavior—such as the impact and timing of commercial activity—would probably have had significant downward effects on the measured stove efficiency.

The 2007 KS attempts to address some of these issues. The project developer surveyed 104 people who had purchased a Ugastove in the preceding 6 months. They found that 60% of surveyed individuals used other conventional stoves in addition to the Ugastove, and that 42% of households used secondary fuels (gas, electricity, paraffin) on these stoves. Households were asked to report how average daily use of stoves had changed upon adoption of the Ugastove. To account for multiple fuel use, the project developer devised a rough heuristic that such fuels account for 10% of all fuel use, calculating that all savings should be adjusted downward by 6%.[31] To account for the multiple stove use, the project developer devises another rough heuristic[32] that Ugastoves account for 80% of charcoal use, calculating then that all stove savings should be adjusted downward by 12%.

While the KS random sample may be representative of Ugastove purchasers, it did not include participants in the 2006 KT. It is unclear if the sample of stove users from 2006 is representative of Ugastove users generally. The KS also found that optimally sized stoves were not being used, given cost constraints:

> "The survey found that some users of the small stoves cook for larger than expected number of people (ie medium rather small families), taking longer hours, cooking more times a day than is common with the medium stove. They said they bought the small stove not because they have a small family but because it is cheaper."

The KS also revealed variance in cooking behavior over time, both by season and by day of week. No adjustment was recommended in light of this information.

Because Ugastove sells its improved stoves, purchase equates with initial technology adoption. The PDD states that there are two methods to track stove usage over time: a KS will be performed quarterly on a sample of 25 HHs who bought stoves in current or previous quarter, and a KT (sample unspecified) will be performed biannually. Such methods are a significant step toward understanding technology adoption and use, and it will be interesting to see what kind of numbers come out of it. However, the 2009 third-party verification report,[33] a necessary requirement for

30 It does not escape notice that the use of a one-sided 90% confidence interval is particularly lax given stated concern for "conservative lower bound estimates;" calculation of a two-sided 95% confidence interval shows the lower bound to be 0.39 kg/day, less than half the reported figured used to calculate GHG emissions reductions.

31 "The survey found that secondary fuels were used only for light tasks such as warming food, boiling milk and making tea. The indication was very clear that these fuels contributed only 5%, up to 10% at most, of total fuel use."

32 "The survey indication was therefore that TS fuel consumption comprises less than 20% of total consumption in a conservative assessment."

33 See https://gs1.apx.com/mymodule/ProjectDoc/Project_ViewFile.asp?FileID=1691&IDKEY=d097809fdslkjf09rndasfufd098asodfjlkduf09nm23mrn8702331889

receiving carbon offsets, states that the last KS was in 2008; the project developer replies that the Gold Standard methodological requirements only compel such ongoing quarterly surveys once the project has been registered.

The main takeaway from the preceding analysis is that Ugastoves has applied for and received carbon offsets covering stoves sold over the period 2007 – 2009, gleaning its insights on behavior change from a small-sample KT in 2006 and a KS in 2007. The behavior change criteria are as follows:

- Technology adoption: stoves purchase proves initial adoption; ongoing KS expected to verify cTechnology use: the manner in which cooks use stoves contributes to their revealed efficiencies; it is still unclear what kind of efficiency should be expected overall.
- Technology substitution: KS determines multiple stove and fuel use; however, no quantification in KS, and KT method specifically does not allow quantification of this.
- Technology maintenance: no data yet on whether customers replace stoves (estimated three-year life is yet unproven); ongoing KS expected to verify replacement.

There are, therefore, striking concerns over the quantification, verification, and permanence of offsets derived from this project. Registries, including CDM, lack the resources and capacity to critically review projects in a manner as above. Furthermore, third-party verifiers are paid by the project developer; thus, there are disincentives for third-party verifiers to sustain objections and critical views of methods, as project developers can just hire a less careful third-party verifier.

The 2009 randomized-control trial of improved cookstoves in rural Ghana

D

The improved stove

The improved cookstove model we evaluated was designed by a consultant at the Ghanaian Council on Scientific and Industrial Research to increase fuel efficiency and reduce emissions by producing more complete combustion of solid fuels and venting smoke away from the user. To improve combustion efficiency, the stove used a metal grate suspended above the ground to allow air to vent through the burning biomass. To vent smoke away from the user, the stove included a chimney and walls that fully enveloped cook pots, thereby enclosing the combustion chamber and forcing air to draft through the chimney.

The stove was largely built from locally gathered materials (see Figure 9.1). The Ghanaian Council of Scientific and Industrial Research reported that August 2008 water-boiling tests of the improved stove design found significant reductions in fuel wood use. Also in August 2008, Plan Ghana pilot tested the improved stove in the village of Kupulima, in our study region. Their results reportedly indicated high rates of adoption and sizeable reductions in fuel wood use.

The measurements of the improved stoves that women built show a strong adherence to demonstrated design dimensions (see Figure 9.2).

Study System: Location, Study Population, and Cookstoves

Geography

The Sissala West district in the Upper West region of Ghana (see Figure 9.4) is a semi-arid region that receives rains from May through August. It is substantially less developed than other parts of Ghana; for example, it has almost no paved roads.

Population

A significant majority of households depend on subsistence farming. Literacy rates are extremely low among people over the age of 30. People in the Sissala West district identify primarily by ethno-linguistic group and secondarily by religion. The villages nearer to Tumu (Gorima, Jitong, and Kandia) are ethnic Sissali. Settlement in these villages is centralized and consists of 60 to 120 households; farm plots are spread over the surrounding environment. The villages near Hamale (Buo, Kaa, Kankanduale, Liero, and Foliteng) are mostly ethnic Dagaare, with a substantial ethnic Sissali minority in some villages; many ethnic Sissali in these communities are bilingual. Settlement in these villages is highly dispersed and consists of 50 to 300 households; farm plots are interspersed among the settlements. Men commonly have multiple wives, and each wife cares for a household (children,

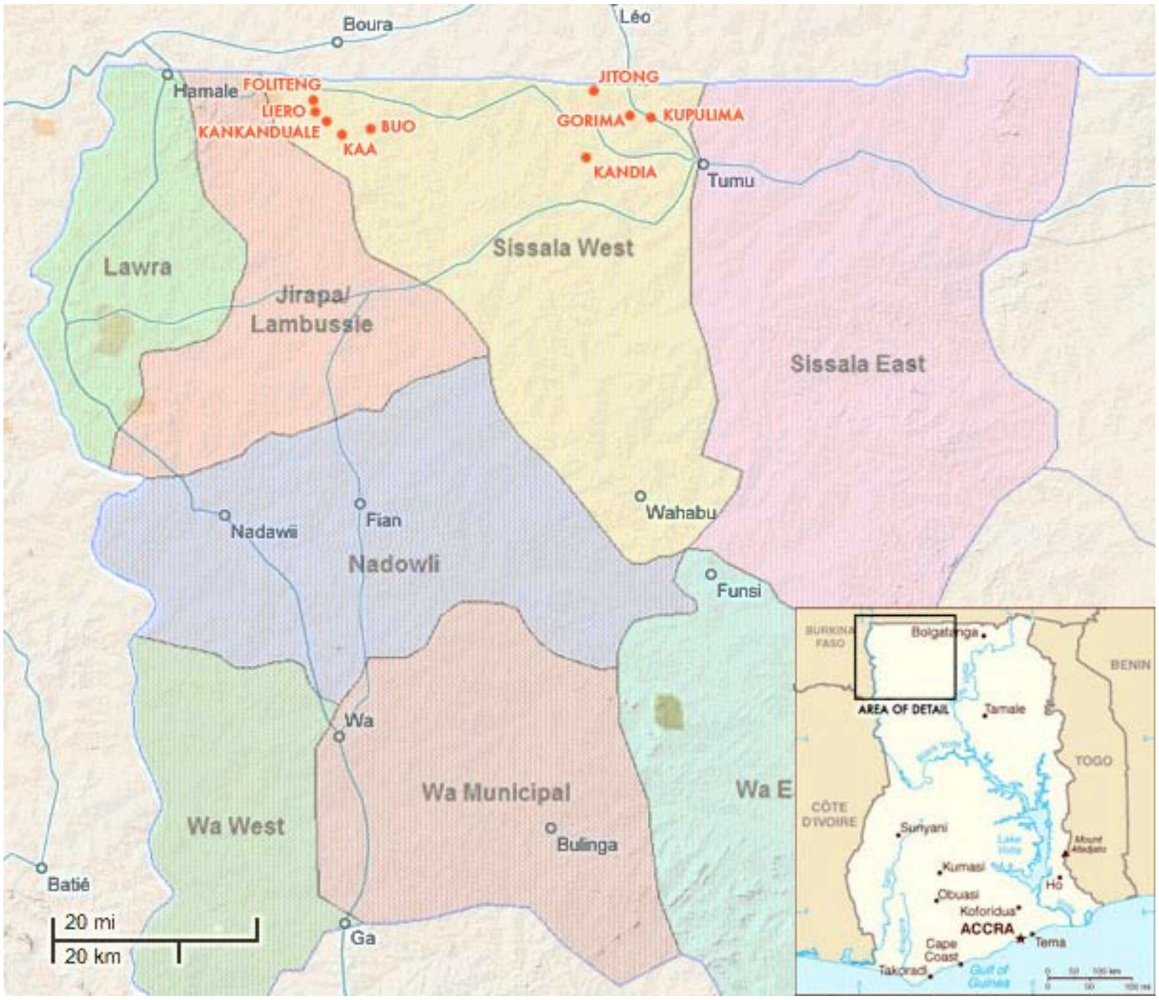
Figure 9.1 | The improved cookstove deployed in Sissala West (indoor installation featured at left; outdoor installation featured at right)

Participants first produced bricks by mixing finely ground cow dung and termite mound "clay" with water and kneading the result into a consistent aggregate; they then put this aggregate in molds to produce bricks. Participants also sculpted the aggregate by hand to produce stove walls and the mortar that went between bricks. The intervention team provided a metal grate and iron rebar. The metal grate was suspended off the ground by spanning a brick base, allowing airflow through the wood that would be burned on it. The rebar was wedged between stove walls to allow cook pots to sit above the fire while recessed into the stove opening. Stove dimensions, along with observed dimensions of built stoves, are listed in Table 9.2. Video of the construction process is available online at http://www.youtube.com/watch?v=gA2a3_VmJKI. Dot marks conventional placement of stove usage monitor.

Table 9.2 | Dimensions of built improved stoves (in cm)

	Ideal	Mean	Std. Dev.	Min	Max
Fire grate to ground	12	12.06	1.07	9.8	17
Fire grate to top of bars	11	11.45	2.03	6	16.9
Fire grate to top of chimney	100-150	126.35	2.02	52	332
Height of walls	min. 10	14.04	2.68	7.9	25
Air intake diameter	20	17.90	2.70	9	27
Wood intake diameter	14	15.42	2.25	10	22
Chimney inlet diameter	8	8.91	1.83	4	15
Wall thickness	7	8.58	1.56	5	18

Figure 9.4 | Map of study sites



children-in-law, elderly family members, etc).[34] All wives usually live in the same multiple-household compound together; compounds typically range from 2 to 8 households.

Geographical Distribution of Cookstove Type and Cooking Practices

Traditional cookstove designs were fairly homogeneous within villages and varied across villages. For example, Gorima, Jitong, and Kandia had largely U-shaped stoves, Kaa had largely three-stone stoves, and Liero had largely L-shaped stoves (see Figure 9.5 for examples). Households report only cooking with fuel wood and occasional agricultural residues; charcoal, when produced, is reportedly always intended for sale. Cooking practices appear to vary by ethnic group. For example, Dagaare women often cook several days' *tisert* (boiled maize flour) in one cooking session using very large pots; this *tisert* is then consumed over the following several days. This practice is reportedly uncommon in Sissali communities.

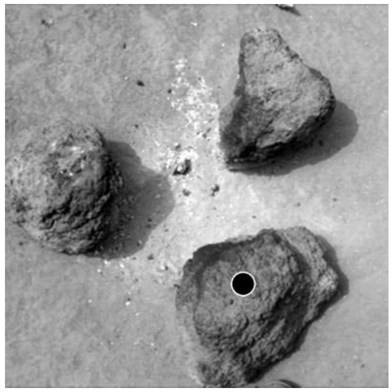
Geographical Fuel Access (see Figure 9.6*)*

The villages closer to Hamale have sparse tree cover nearby, and fuel wood collection in one village competes with fuel wood collection in neighboring villages (Kaa is a notable exception). Households in these villages do not report selling fuel wood or fuel wood products. Some households

34 The term "household" does not translate well in either of the local languages used during this study. We clarified that by "household" we meant a group of people who eat together regularly and/or who sleep under the same roof together.

Table 9.5 | Examples of traditional stoves in Sissala West

Dots indicate convention for placement of stove usage monitors



in these villages reported buying fuel wood and charcoal from the local market. The villages closer to Tumu have more access to fuel wood, as tree cover near each village is denser and neighboring villages are far enough apart that fuel wood collection zones do not overlap. Villagers near primary roads close to the major market of Tumu reported sales of fuel wood and charcoal as the largest non-transfer source of cash income. No households in these villages reported buying fuel wood or charcoal.

Study design

Recruitment

Plan Ghana sited the project in the Sissala West district of the Upper West region in Ghana. Plan Ghana presented a sampling frame of 20 villages that were at least 15 km from the electrical grid as of December 2008 and had ongoing relationships with Plan Ghana. We chose 8 of the 20 villages for our randomized trial with an eye to variation in ethno-linguistic and geographic context: three villages (Gorima, Jitong, Kandia) are situated near the town of Tumu and primarily Sissali, and five villages (Foliteng, Liero, Kankanduale, Kaa, and Buo) are situated near the town of Hamale and primarily Dagaare. We tested protocols and recruited women trainers in the pilot village of Kupulima. The study ran from February to May 2009.

In February 2009 we presented the stove program at village meetings. We recruited women to attend the meeting by contacting the chief and other local leaders in each village and requesting them to notify the rest of the village. Once a group of women assembled, we explained the intent of the study and eligibility for participation. Eligibility was restricted to one woman per household, and to the women most frequently responsible for cooking. Following a question and answer session, we enrolled volunteers. Translators on our team read out an informed consent letter and explained that only one group would receive stove materials at first, and the second group would receive stove materials approximately one month later.

Training

Approximately two weeks after the first village meetings, women from our pilot village who were experienced in building the new stoves trained participants in stove construction. The trainings occurred over two separate days. On the first day, trainers taught participants to use brick molds we distributed. We recruited several members in each village, mostly women but some men, to act as group leaders, responsible for organizing and motivating women to make bricks and build their stoves. There was then a gap of roughly two weeks so women could make bricks. On the second day, trainers showed participants to build the stoves using the bricks they had made along with the iron grate and rebar we provided.

Figure 9.6 | Village layouts and local woodsheds

The villages of Gorima, Kandia, Kaa, and Jitong (top photograph) all have clustered settlements and reasonably ample woodsheds. The villages of Foliteng, Kankanduale, Buo, and Liero (bottom photograph) all have dispersed settlements and are nearly denuded. Images from Google Maps, July 2010.

At the end of the second training day, we used a lottery to randomly assign participants to control and treatment groups. We divided lottery tickets such that participants had a 55% chance of drawing treatment group status; participants drew tickets without replacement. The treatment group received materials to build their stoves immediately, and the control group was told they would receive their stove materials in one month.

Stove building

In the two weeks following randomization, (most of) the treatment group of each village built their improved stoves, assisting each other on an *ad hoc* basis and motivated by their group leaders. Our staff oversaw improved stove construction and measured the dimensions of each improved stove, directing participants to rebuild their stoves if construction was of particularly poor quality. Our staff also demonstrated the construction of proper chimneys to participants, as well as adding a ventilation hole to each indoor kitchen to provide a proper outlet for chimneys.

Between three and four weeks following random assignment, experienced women from Kupulima village demonstrated fuel-efficient cooking on an improved stove in each village. Both treatment and control group members attended the demonstrations.

Randomization Check, Pipeline, and Attrition

The random assignment process resulted in 402 treatment group participants and 366 control group participants. Adherence to randomization was fairly high: 331 treatment households (82%) built an improved cookstove, while 33 controls (9%) procured the metal grate on their own and built an improved cookstove during our study period. Our analysis is based on the randomized intention-to-treat, not on adherence to the randomization; thus, our results are not biased by self-selection among those who did or did not build a stove.

The treatments and controls are similar on baseline characteristics (see Table 9.10). A probit regression of treatment status on baseline characteristics shows no joint significance.

Significant attrition occurred during the course of the study (see Table 9.7). Of the 768 study participants, 572 (74%) completed the controlled cooking test, 539 (70%) provided CO tube readings, and 498 (64%) completed the survey. Data collection rates for the cooking test and CO tube readings were similar for treatments and controls. Owing to difficulty in locating households for follow-up, only 53% of treatments completed the survey, versus 73% controls (see Table 9.8). Attrition was largley due to participants' absence from the villages on days that we scheduled intervention activities and data collection, owing to weddings, funerals, and market days. We used a number of our surveyed characteristics in a probit regression to predict attrition; results showed no statistically significant predictors of attrition.

We placed SUMs on a subsample of study participants' households, covering 295 stoves in 114 treatment households and 159 stoves in 77 control households. There were more treatment households covered primarily because field staff identified study participants more readily when an improved stove was present. High heat destroyed 28% of the SUMs, leaving data from 217 (74%) of the SUMs on treatment household stoves and 108 (68%) of the SUMs on control stoves. Attrition was comparable for improved and traditional stoves (see Table 9.9).

Summary Statistics

The household survey shows no systematic difference in study groups other than number of stoves (see Table 9.10). The sample is fairly evenly split between those who speak Dagaare (56%) and those who speak Sissali (44%), and these proportions remain the same across treatment and control groups. Polygamy is common: 43% of respondents are married to a man with more than one wife. Average household size is 6.4 people. Participants in the study are poor. While respondents may under-report of cash income, the

Table 9.7 | Pipeline by study component

Survey	Y	Y	Y		Y				
CO tube	Y	Y		Y		Y			
Cooking test	Y		Y	Y			Y		
									Totals
Treatment	193	2	12	94	24	0	5	72	402
Control	208	1	18	40	40	1	2	56	366
Total	401	3	30	134	64	1	7	128	768
% Treatment	48%	67%	40%	70%	38%	0%	71%	56%	52%

Table 9.8 | Participation rates

	Participation, by study component				Participation rate, by study component		
	Treatments	**Controls**	**Total**	**% Treatment**	**Treatments**	**Controls**	**Total**
Survey	231	267	498	46%	57%	73%	65%
CO tube	289	250	539	54%	72%	68%	70%
Cooking test	304	268	572	53%	76%	73%	74%

Table 9.9 | Attrition in stove usage monitors

	Placed		Missing		Captured		Attrition	
Sensor by stove rank	**Treatment**	**Control**	**Treatment**	**Control**	**Treatment**	**Control**	**Treatment**	**Control**
First	112	77	34	25	78	52	30%	32%
Second	100	55	27	18	73	37	27%	33%
Third	63	19	13	5	50	14	21%	26%
Fourth	18	5	1	1	17	4	6%	20%
TOTAL	*293*	*156*	*75*	*49*	*218*	*107*	26%	31%

median respondent reports 8 GHS ($5.60) of cash income per month. Only 10% of both women and their husbands report any formal schooling, and of those with schooling, only half proceeded beyond primary education. Only 4% of respondents report owning a television, although 25% have a cell phone and 85% have a flashlight or other form of electric light.

76% of households have two or more wood-burning stoves. The mean among controls is 1.9 wood-burning stoves. Many participants also employ a charcoal-based stove that utilizes embers from other stoves, primarily for the purpose of heating water or soup in smaller pots; we have not included these stoves in any figures. Nearly all participants cook with wood that the household gathers.

Data Collection Methods

We measured adoption and use of the improved cookstove using remote sensing techniques. We also measured stove performance in fuel wood use and changes in carbon monoxide exposure among women that use the improved cookstoves.

Stove Usage Monitors (SUMs)

We installed stove usage monitors (SUMs) a few weeks after construction of the improved stoves. Modeled on the work of Mercado et al. (2008), we employed Thermochron 1921G iButtons, a programmable digital temperature sensor and memory enclosed in a 16mm thick stainless steel case, capable of measuring temperatures between -40°C

Table 9.10 | Summary statistics from the household survey

Includes mean-comparison test statistics and proportion test statistics

* = p<0.1 ** = p<0.05 *** = p<0.01

	Treatment (stdev)	Control (stdev)	Difference (z-stat / t-stat)	
Number of members in household	6.3	6.5	0.2	
	(2)	(2.6)	(0.71)	
Number of wives husband has	1.7	1.7	0	
	(0.9)	(0.9)	(0.27)	
Primary language Dagaare (vs. Sissali)	0.56	0.58	0.02	
			(0.31)	
HH Std Adult Equivalents (1=man, 0.7=woman, 0.5=child under 16)	4.6	4.5	0.1	
	(1.6)	(1.9)	(0.11)	
Number of overall stoves	2.3	1.9	0.4	***
	(0.7)	(0.6)	(7.28)	
Number of traditional stoves	1.4	1.9	0.5	***
	(0.7)	(0.6)	(7.77)	
Share of traditional stoves outdoors	0.64	0.59	0.05	
	(0.43)	(0.36)	(1.44)	
Pct that buy wood	0.03	0.03	0	
	(0.17)	(0.17)	(0.03)	
Pct that sell wood	0.05	0.05	0	
	(0.22)	(0.21)	(0.36)	
Pct that sell charcoal	0.06	0.04	0.02	
	(0.23)	(0.19)	(1.01)	
n	225	263		

and 85°C at user-specified intervals. We programmed the SUMs to measure temperature every 15 minutes, and SUMs operated for three weeks before being recovered.

Due to limitations on the number of SUMs in our possession, we placed stove usage monitors on stoves in four villages. At households chosen, we placed a SUM in each stove the respondent reported using in the prior month. In two villages we placed SUMs one week after improved stove construction; in the other two, we placed SUMs five weeks after improved stove construction.

We used conventions for the placement of SUMs on each stove type (see Table 9.3 and Table 9.5). For three-stone fires, we buried SUMs approximately two centimeters below the largest of the three stones and instructed households not to relocate the stove during our study. For other stoves, we carved a shallow depression into the wall of each stove and sealed in a SUM using clay.

Controlled Cooking Test

Roughly five weeks following stove construction we carried out controlled cooking tests in each village. We asked participants to cook the common meal of a pot of *tisert* (boiled maize flour) and a pot of stew, cooking pots sequentially on the same stove. We gave participants a bag of maize flour (700-900 grams), but only if they presented an equal amount at the outset of the cooking test, thereby ensuring each participant would make a full pot of *tisert* to match realistic cooking conditions. We instructed treatment group participants to cook with improved stoves and control group participants to cook on their primary traditional stove. Prior to cooking, we weighed the total flour, the cooking pots, and an estimate of how much water participants planned to use. Following cooking, we weighed the *tisert*, the stew, and any leftover flour.

We also instructed the participants to present the amount of wood they considered necessary for cooking the *tisert* meal. We weighed this wood prior to cooking and weighed remaining wood following cooking. To calculate wood use during the cooking test, we subtracted the weight of the remaining wood from the weight of the wood respondents presented prior to cooking.[35]

Carbon monoxide tubes

We measured exposure to carbon monoxide during the cooking test with Gastec 1DL Carbon Monoxide Passive Diffusion Tubes (hereafter referred to as CO tubes). Using the principles of gas diffusion and colorimetric reaction, the CO tubes measure the time-weighted average concentrations of carbon monoxide between 0.4 and 400 ppm. While the CO tubes directly measure exposure to carbon monoxide, they also proxy for exposure to particulate matter (Smith, 2010; Northcross, 2010). Fischer and Koshland (2007) find that 1-hour CO tube exposures correlate moderately with both 1-hour and 24-hour exposures to PM2.5, and research by Northcross (2010) shows that time-weighted CO tube readings correlate highly to time-weighted exposure to $PM_{2.5}$.

After weighing participants' cooking materials during the cooking test, we attached the CO tubes to the lapels of the participants' shirts with the exposed end facing down and unobstructed to ambient airflow, and we recorded the time. Once the participants finished cooking and returned to the weighing station, we noted the time and removed the CO tubes. These CO tubes were immediately sealed with duct tape and kept in an airtight bag until they could be digitally photographed in controlled fluorescent lighting conditions, usually within 48 hours. CO tubes of identical manufacturing specifications were photographed in batches with an unexposed reference tube in each image.

Each tube has a reactive strip bounded by non-reactive layers. A longer length of the reactive strip darkened in tubes exposed to more carbon monoxide. The tubes also had 7 rings dividing the tube into six discrete bands, where each band represented a range of parts per million per hour (ppm-hr): 0-10, 10-30, 30-50, 50-100, 100-150, 150-200.

We worked with three separate batches of CO tubes, which were manufactured to different specifications. We categorized exposure by the highest discrete band of the reactive strip that darkened. To determine the highest darkened band, we converted the digital photographs to black and white and compared the brightness of pixels inside the reactive strip with adjacent pixels in the adjacent non-reactive layers (see Table 9.11). We repeated this comparison at the midpoint of the 6 discrete bands as well as just after the final ppm-hr marking (which we coded as 200-400 ppm-hr) and midway between the final marking and the very end of the reactive strip (which we coded as "over 400 ppm-hr"). We coded the reactive portion of a band as "darkened" if its RGB values were 10 or more units greater than the adjacent non-reactive portion's RGB values; RGB values range from 0 (pure black) to 255 (pure white).

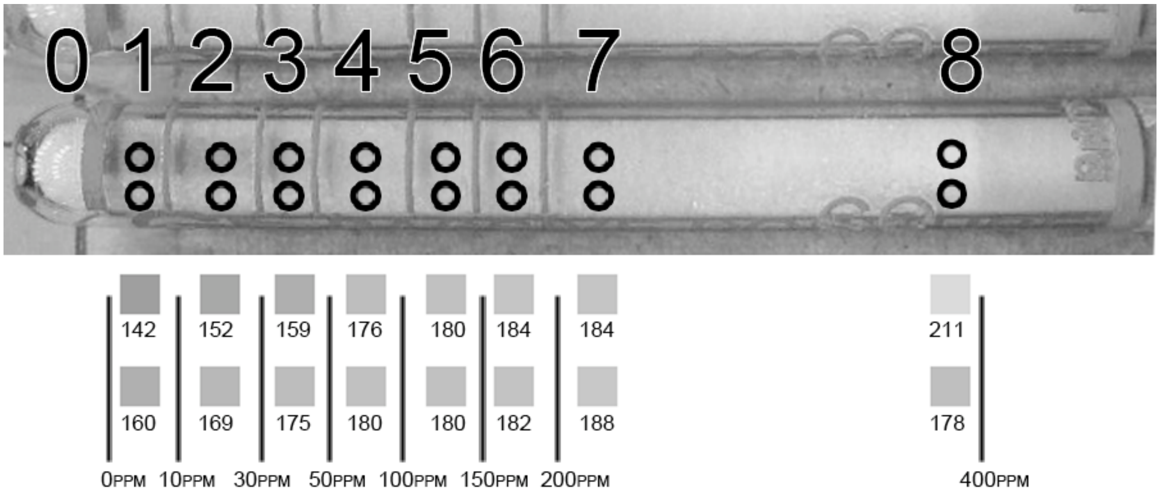
Household survey

Roughly eight weeks after randomization we surveyed both control and treatment group participants on self-reported recent cooking activity, frequency and duration of wood collection, perceptions of the improved cookstove, and socio-economic status. The survey also asked participants about their symptoms related to exposure to smoke when cooking (sore eyes, and so forth) and about a variety of respiratory ailments they or their children suffer from (cough, runny nose, and so forth).

35 We also weighed remaining coals and ash. For the purpose of our analysis, we consider coals as "burned," although they are often placed in small metal containers for keeping pots of food warm.

Table 9.11 | Measurement of pixel values inside and outside of CO tube reactive strip

We converted digital images from RGB color to black and white using the “desaturate” function of Adobe Photoshop CS3 software. We read RGB unit values by using the Photoshop Navigator information pane while scrolling the cursor to a midpoint in each band. Results were robust to using other thresholds ranging from 2 to 15 RGB unit values. In this example, band 3 is the highest band with a more than 10 “RGB” unit value difference (as measured by Adobe Photoshop CS3 software) between the reactive and non-reactive parts of the CO tube. We code this reading as 30-50 ppm.



Follow-up stove usage observations

Field staff returned to three villages eight months following program implementation. Field staff completed walkthroughs of the villages to observe the conditions of the improved stoves and determine whether or not stoves evidenced recent use—determined affirmatively if the stoves were observed in use, warm to the touch, or contained significant amounts of ash.

Findings

We first present findings on outcomes from the controlled cooking test and household survey. We then present the usage of traditional and improved cookstoves observed from stove usage monitors and eight-month follow-up.

Fuel use during the controlled cooking test

During the controlled cooking test, treatments and controls cooked indoors in equal proportions and cooked the same weight of food on average (see Table 9.12). Treatment group participants brought less fuel wood to the controlled cooking test than controls. Treatments also had slightly longer duration CO tube exposure than controls.

We were interested in whether the potentially endogenous covariates of outdoor cooking and the weight of the pot full of cooked *tisert* affected our results. To control for covariates we ran the following linear regression:

(1) $$\text{Fuel use} = \beta_0 + \beta_1 \text{ treatment group status} + \beta_2 \text{ outside location} + \beta_3 \text{ cooked tisert weight} + \beta_4 \text{ education day attendance} + \beta_5 \text{ education day attendance x treatment} + \partial \text{ village} + \varepsilon$$

Results (Table 9.13, col. 2) were similar to simple group mean comparisons (col. 1); treatment group members used 12% less fuel wood. Inclusion of village fixed effects does not alter this result. Attendance at the cooking training session has no correlation with fuel wood use in the cooking test (col. 3). However, it is possible that the non-random nature of attendance at the training session obscured its measurable impact.

In column 4 we shift from intention-to-treat to a treatment-on-the-treated analysis. We instrument for whether the cooking test was on an improved stove using treatment status as an instrument and conduct two-stage least squares. As expected, results show slightly higher fuel savings (14%) when we focus solely on participants who built an improved stove. Inclusion of other covariates and village fixed effects does not affect this finding (col. 5).

Interestingly, the treatment group also brought 15% less wood to be weighted at the start of the cooking test, a statistically significant difference ($P < 0.001$). This appears to indicate learning-by-doing among cooks with the improved stove. However, it is also possible that treatment group participants wished to demonstrate fuel-efficiency behavior when being observed closely—that is, a Hawthorne effect.

Survey measures of fuel use and fuel collection activity

Treatment group participants report spending about the same time collecting wood per week as do control group participants (see Table 9.14). This equality arises from two offsetting small effects: Treatments spend about 10% more time per trip to collect wood but collect wood about 10% less often. It is highly plausible these effects are just sampling error.

Exposure to Carbon Monoxide

We present the histogram of CO exposure for treatments and controls in Figure 9.15. On average, treatments and controls showed statistically indistinguishable mean exposures to hourly CO. At the same time, the treatments wore the CO tubes slightly longer than controls (89 min vs. 80 min, $P < 0.1$).

Given the censored nature of high exposure, we ran a tobit regression to examine exposure to carbon monoxide. We use the following regression specification:

$$\text{(2)} \quad \text{band}_i = \beta_0 + \beta_1 \text{exposure}_i + \beta_2 \text{treatment}_i + \beta_3 \text{outside}_i + \beta_4 \text{treatment x outside}_i + \varepsilon_i$$

with upper limit censoring at band 8 (i.e., 400+ ppm-hr).

Participants in the treatment group do not register significantly different exposure to carbon monoxide than participants in the control group during the controlled cooking test (see Table 9.16, col. 1). In column 2 we adjust for whether the cook was outdoors – an endogenous factor – and find that cooking outdoors lowered CO exposure by over one band for controls. Given that the average one-band decrease represents as much as a 50% change in ppm-hours, the decrease experienced by controls cooking outdoors is substantial. The coefficient on the interaction term *treatment* □ *outside* is large but not precisely estimated.

Due to the ordinal nature of the dependent variable, we also ran an ordinal logistic regression using the same specification (see Table 9.17). A Wald test shows the proportional odds/parallel-lines assumption of the model is valid ($X^2(21, N = 458) = 34.73$, $p = .0302$). Again, treatment group status has no effect on the propensity for higher bands of exposure. Outside cooking halves the propensity for higher exposure,[36] as compared to indoor cooking—a finding in line with the preceding tobit regression analysis.

Self-reported recent health

Table 9.18 shows self-reported recent health from the household survey. Control group participants reported experiencing irritated eyes following cooking over twice as many days as treatment group participants reported for the preceding week. Differences were almost as large for symptoms of headache and bad cough or sore throat. Similarly, control group participants averaged a larger number of respiratory symptoms from the previous week (sore throat, bad cough, difficulty breathing, chest pain, excessive mucus) than treatments. Over the five symptoms we surveyed, 34% of controls reported at least one symptom in the previous week versus 17% of treatments ($P < 0.01$). In contrast, there was no dif-

36 The conversion of a logit coefficient to odds ratio takes the form exp(ß). In this case, exp(-0.71) = 0.5, signifying that the probability of a given band of exposure for those cooking outside is ½ the probability for those cooking inside.

Table 9.12 | Summary statistics from the controlled cooking test

Given the familiarity of participants with the commonly cooked meal of tisert, most participants selected an appropriate amount of wood for the task. Thus, we dropped observations (25 treatment, 28 control) where we recorded that the cooks used less than one third of the wood they had presented, as such data were likely due to measurement error. Inclusion decreases the magnitude of observed differences between groups but does not alter subsequent statistical significance of subsequent finding

* = p<0.1 ** = p<0.05 *** = p<0.01

	Treatment (stdev)	**Control (stdev)**	**Difference (z-stat or t-stat)**
Fuel wood use (grams)	1434	1621	187**
	(519)	(705)	(3.53)
Proportion of participants cooking outdoors	0.43	0.48	0.05
			(1.04)
Initial fuel wood presented at cooking test (grams)	2366	2758	392**
	(671)	(954)	(5.46)
Weight of pot & cooked tisert (grams)	6679	6576	103
	(1542)	(1713)	(0.72)
Carbon monoxide tube exposure band (1 to 8, coding described in the text)	5.2	5.2	0
	(2.7)	(2.6)	(0.17)
Minutes wearing carbon monoxide tubes	89	80	9*
	(27)	(65)	(1.91)
n	278	239	

Table 9.13 | Fuel wood use during the controlled cooking test

* = p<0.1 ** = p<0.05 *** = p<0.01

	Fuel wood use (grams)									
	1		**2**		**3**		**4**		**5**	
Treatment group	-187	***	-196	***	-187	**				
	(54)		(53)		(89)					
Used an improved stove (instrumented with Treatment group)							-218	***	-215	**
							(63)		(102)	
Cooked outdoors during CCT			56		52				41	
			(53)		(53)				(53)	
Weight of pot & cooked tisert (grams)			0.087	***	0.088	***			0.090	***
			(0.016)		(0.016)				(0.016)	
Attended stove use educational session					-41				-40	
					(80)				(79)	
Education × Treatment					-8				-13	
					(110)				(108)	
Constant	1621		1021	***	1042	***	1634		1049	***
	(39)		(115)		(122)		(42)		(122)	
n	517		517		517		517		517	
R^2	0.02		0.08		0.08		0.02		0.08	

Table 9.14 | Self-reported wood collection activity

* = p<0.1 ** = p<0.05 *** = p<0.01

Pearson chi-square for median-comparison test: + = z<0.1 ++ = z<0.05 +++= z<0.01

	Treatment	**Control**	**Difference (t-stat / z-stat)**	
Number of days of wood collection in past week				
Mean	1.73	2.02	0.29	**
SD	(1.27)	(1.47)	(2.24)	
Median	2	2	0	++
Duration of most recent wood collection (min)				
Mean	183	165	18	*
SD	(87)	(96)	(1.85)	
Median	180	180	0	++
Number of days of wood collection in past week × duration of most recent wood collection (min)				
Mean	349	358	9	
SD	(328)	(386)	(0.24)	
Median	240	240	0	
Number of days since most recent wood collection				
Mean	6.25	5.30	0.95	*
SD	(5.74)	(5.00)	(1.95)	
Median	5	4	1	++
Number of days wood collected lasts "in general"				
Mean	11.27	9.77	1.50	*
SD	(9.21)	(10.00)	(1.71)	
Median	7	7	0	++
n	227	255		

Table 9.15 | Histogram of exposure to carbon monoxide during controlled cooking test

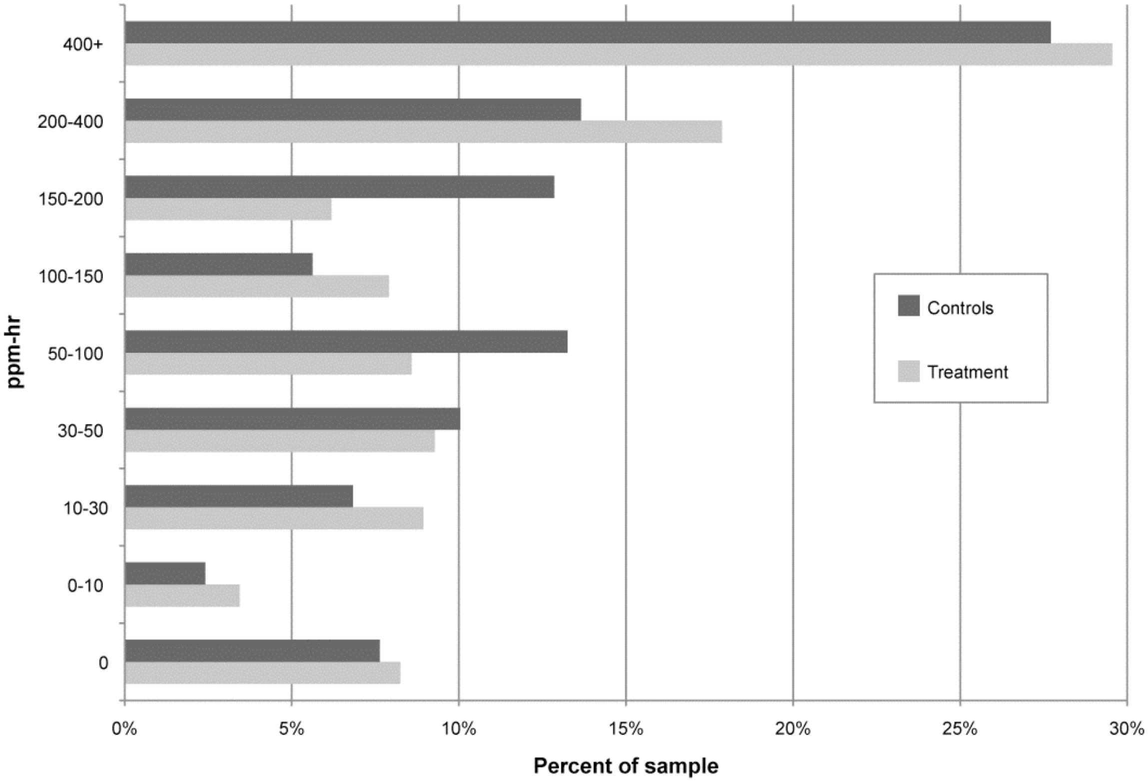


Table 9.16 | Tobit regression analysis of treatment status effect on CO exposure band

Used a pixel difference threshold between strip recording CO exposure and adjacent portion of CO tube of 10 RGB unit values (where pure black = 0, pure white = 255). Uncertain readings, in which value differences did not decrease steadily, were removed from sample (27% of controls vs. 25% of treatments, difference n.s.) These findings are robust when the pixel difference threshold is varied from 2 to 15 RGB units, although the magnitude of the effect of outdoor location decreases as the difference threshold decreases

* = p<0.1 ** = p<0.05 *** = p<0.01

	1		2	
Treatment group	0.016		-0.414	
	(0.337)		(0.460)	
Minutes of CO tube exposure	0.006	*	0.005	
	(0.003)		(0.003)	
Cooked outdoors during CCT			-1.356	***
			(0.499)	
Treatment * Outdoors			0.793	
			(0.676)	
Constant	5.380	***	6.212	***
	(0.364)		(0.471)	
Standard error of regression	3.455		3.433	
n	458		458	
n censored (upper limit)	137		137	

Table 9.17 | Ordinal logistic regression analysis of treatment on CO exposure band

* = p<0.1 ** = p<0.05 *** = p<0.01

	Band of CO tube exposure			
	1		**2**	
Treatment group	0.02		-0.22	
	(0.17)		(0.23)	
Minutes of CO tube exposure	0.003	*	0.002	
	(0.001)		(0.001)	
Cooked outdoors during cooking test			-0.71	***
			(0.25)	
Treatment * Outdoors			0.41	
			(0.34)	
n	458		458	

Table 9.18 | Self-reported recent health

* = p<0.1 ** = p<0.05 *** = p<0.01

	Treatment (stdev)	**Control (stdev)**	**Difference (z-stat / t-stat)**
Number of days in previous week respondent reported problem following cooking			
Irritated eyes	1.0	2.7	1.7***
	(2.1)	(2.6)	(7.63)
Headache	1.0	2.2	1.2***
	(2.0)	(2.4)	(5.75)
A bad cough or sore throat	0.7	1.6	0.9***
	(1.6)	(2.4)	(4.91)
Self-reported respiratory symptoms in previous week (1 = yes)			
Sore throat outside of cooking	0.10	0.19	0.09***
	(0.02)	(0.02)	(2.75)
Bad cough outside of cooking	0.16	0.27	0.11***
	(0.02)	(0.03)	(3.13)
Difficulty breathing	0.12	0.27	0.15***
	(0.02)	(0.03)	(4.32)
Chest pain	0.18	0.31	0.13***
	(0.03)	(0.03)	(3.35)
Excessive mucus	0.13	0.19	0.06
	(0.02)	(0.03)	(1.71)
Number of above symptoms (out of 5)	0.68	1.22	0.54***
	(1.29)	(1.63)	(4.00)
Report sick child in previous week (1 = yes)	0.21	0.24	0.03
	(0.03)	(0.03)	(0.82)
N	225	255	

ference in the proportion of control and treatment groups reporting children becoming sick in the preceding week.

Self-reported recent use of the improved stove does not show any significant relationship to self-reported recent health. Similarly, self-reported recent health measures do not exhibit a relationship with CO tube readings observed during the controlled cooking test.

Stove Usage

Improved stoves may have precipitated a movement of some cooking activity indoors; 58% of improved stoves were built indoors, substantially more frequently than traditional stoves, 38% of which were observed indoors.

Also, there is evidence that improved stoves may have displaced some traditional stoves. In the household survey following the intervention, treatment group participants reported using an average of 1.4 traditional stoves, whereas control group participants reported using an average of 1.9 traditional stoves. Given that treatment group participants report using an average of 2.3 stoves overall—improved plus traditional—this suggests that treatment group participants ceased using an average of 0.4 traditional stoves per household.

Difficulties in working with SUMs

Households reporting more stoves had higher attrition than those reporting fewer stoves. 48 compliant treatment households and 38 compliant control households had all their reported stoves successfully monitored by SUMs over the monitoring period. Participants reporting more stoves had more opportunity to damage a SUM; as expected, households with overheated SUMs reported an average of 2.5 stoves, a bit above those with no overheated SUM (2.2, $P < .05$). Therefore, the fully monitored households tend to have fewer stoves than do households with incomplete surviving SUMs. Self-reported characteristics of recent stove usage do not systematically affect likelihood of SUM overheating.

Adoption of the improved stove appears to be reasonably high. Eight of the 78 improved stoves monitored were used two or fewer times over the three-week monitoring period, representing a lack of adoption. The 70 improved stoves that were used more than two times over the monitoring period registered temperatures in excess of 50°C on average 60% of the days in the monitoring period. During this time, these improved stoves show an average of 185 minutes (and median of 136 minutes) over 50°C per day. In contrast, at both control and treatment homes, the typical traditional stove registered temperatures in excess of 50°C on average 74% of days monitored (difference $P < 0.01$).

If we assume SUMs overheated at random, then we can multiply SUM readings on individual stoves by the mean number of stoves to estimate household-level usage. Control homes average almost 11 stove-hours per day over 50°C across all traditional stoves (see Table9.19); this number is greater than total time cooking because most control homes have multiple stoves and sometimes heated two or more stoves at once. Treatment homes used their traditional stoves a total of about 7 stove-hours a day on average and their improved stoves about 2½ hours per day. Thus, being in a treatment home reduced use of traditional stoves ($P < .05$), but did not necessarily reduce overall stove use (10.72 hours total for controls, 9.59 hours for treatments, difference not statistically significant).

The subset of fully-covered households (i.e., those with no SUM attrition) tell a different story. For reasons we do not fully understand, treatment households do not show a reduction in the number of traditional stoves that we see in the survey (treatments have 1.65 traditional stoves and controls have 1.71, difference not significant). Such treatment households also show no reduction in minutes per day they use their traditional stoves compared to controls.

In short, there is some, but not always consistent, evidence that the new cookstoves reduced usage of the traditional stoves.

Table9.19 | Usage of improved and traditional stoves (minutes over 50˚C)

9 control-group improved stoves (due to non-compliance) not included in table. Inclusion does not significantly alter full control group averages and comparisons to treatment group.

All surviving SUMs	Treatment			Control
	Traditional	Improved	All	Traditional
Hours of stove usage per home	7.1	2.5	9.6	10.7
n homes	103	103	103	48
n SUMs	139	69	208	95
Only households with 100% coverage by SUMs	**Treatment**			**Control**
	Traditional	Improved	All	Traditional
Hours of stove usage per home	9.2	2.6	11.8	8.6
n homes	48	48	48	38
n SUMs	79	44	123	65

Table 9.20 | Field observations of improved stoves in three villages after 8 months

		Broken (not in use)		Appear in use		Unclear if in use	
	Observed	N	%	N	%	N	%
Gorima	53	10	19%	32	60%	11	21%
Kandia	81	12	15%	41	51%	28	34%
Jitong	88	35	40%	35	40%	18	20%

Participants commonly employ multiple stoves. Of the 23 completely monitored control group participants reporting two stoves, the median first-ranked stove accounts for 52% of time over 50˚C. The improved stove was heated a smaller share of time than traditional stoves. Of the 15 completely monitored treatment group participants reporting two stoves, on average the improved stove accounts for 36% of time over 50˚C; of the 22 completely monitored treatment group participants reporting three stoves, the improved stove represents only 25% of time over 50˚C. Multiple stoves register temperatures over 50˚C about a third of the time when at least one stove is in use, suggesting that simultaneous use of multiple stoves is common.

Besides temperatures over 50° C, we examined several methods for translating SUM readings into indicators of stove usage, including an increase in temperature of over 5° C in one hour, and a reduction in temperature of over 3° C in one hour. Results remained robust to the measure we used.

Eight month follow-up observations of stove usage

Approximately half of improved stoves appear to remain in regular use eight months after implementation (Table 9.20).

Discussion

Stove Adoption and Usage

Our stove usage monitors showed that on average improved stoves were used at least half of all days in the three-week monitoring period, indicating continuing use past construction. In addition, treatment group participants reported fewer traditional stoves in regular use than controls, suggesting some displacement of traditional stoves. At the same time, many treatment participants continued to use one or more traditional stoves. On average, traditional stoves were also used more often and for longer periods than improved stoves. The net result is that treatment and control households do not register significantly different durations of overall stove activity, and there was mixed evidence for decline in use of traditional stoves among treatments. Also, usage of the improved stoves appears to have declined over time;

by the eighth month following construction, perhaps 50% of improved stoves remained in use.

Our estimated stove usage is only a rough approximation for multiple reasons: different stove models had different placement of the usage monitors; stoves vary in how well they conduct heat to the SUM; many of the SUMs over-heated, leading to non-random attrition; and we are unsure if SUM readings on indoor stoves are comparable to readings on outdoor stoves.

The non-random survival of SUMs may introduce negative bias. Recall that almost a third of stove usage monitors were either destroyed by heat or misplaced. For example, surviving SUMs will under-state average usage if, as is likely, SUMs overheated more often when placed on stoves that were used more intensively. In addition, improved stoves' walls were thin compared to traditional stoves; the decreased thermal mass means improved stoves were likely to heat and cool faster than traditional stoves—and so therefore might record less usage than traditional stoves. Furthermore, because rarely-used stoves presumably are less likely to overheat SUMs, the rate of non-adoption (10%) is likely to be overstated.

Although SUMs provide real-time objective monitoring, our results remain less than conclusive. The lack of standardized placement of temperature sensors, the variation in thermal mass, and the partial coverage of households due to sensor attrition all add error to the stove usage measures. In addition, cooks use multiple stoves and stoves are used by multiple cooks, making it difficult to measure who is cooking where. For example, 25 of the 31 participants identifying only a single stove for SUM placement report multiple stoves in the survey. Furthermore, some participants reporting only a single stove show very little time over 50°C on that stove, suggesting some degree of misreporting of number of stoves and/or inaccurate monitoring of stove activity.

Regardless of these concerns, it is clear adoption of a new stove does not imply the household uses the new stove, and adopting or using a new stove does not always directly reduce usage of an old stove. Furthermore, even if new stoves are used and substitute for old stoves, some measure may fall into disuse from breakage. To accurately assess the impact of improved stove programs, future evaluations must focus on all four, separable behaviors associated with new technology uptake: adoption, usage, substitution, and upkeep.

Indoor air pollution

Based on the CO tube measures, improved stoves do not by themselves reduce exposure to smoke. Cooking outdoors produces a significant decrease in exposure to smoke for controls; the same, however, cannot be said for treatments. Treatments had far better self-reported recent health than controls, despite the lack of measured reductions in CO exposure. Self-reported health also does not bear a relationship with CO tube measures. It is unclear what is behind the divergence. We emphasized health concerns as a rationale for the improved stove; it is possible that members of the treatment group responded with "courtesy bias" during the survey by giving encouraging responses on self-reported health.

The indoor stoves were designed with a chimney to remove smoke. Perhaps for this reason, a higher share of the new stoves were placed indoors than was typical. However, moving indoors could offset any emissions reductions improved cookstoves might have. We observed many improved stoves emitted some amount of smoke, whether due to physical failures of the chimneys (cracking of mortar seal around bricks, chimney outlet too low to create strong vacuum effect), improper use of the improved cookstove (blocking the chimney inlet by pushing fuel wood too far into the stove), or unexpected cooking behavior (removing a pot from the fire for some time or use of a small pot that leaves a gap between the pot side and the wall where smoke escapes). The WHO (2006) also cites 26 ppm as the average limit for 1-hour exposure to carbon monoxide indoors; cooks using both stoves frequently exceeded this level.

We found no detectable decline in exposure to carbon monoxide among treatment group participants during the controlled cooking test. At the same time, women in the treatment group self-reported far fewer symptoms related to cooking (e.g., irritated eyes) and respiratory symptoms (e.g., runny nose and chest pain). This divergence may indicate that exposure to carbon monoxide is not a direct proxy for exposure to smoke, at least as reflected in the health of cooks. On the other hand, the findings of the survey may reflect a "courtesy bias" by participants, who have existing relationships with our partner Plan Ghana and might want to encourage future activities.

Fuel use

Treatment group participants achieved economically and statistically significant 12% reduction in fuel wood use during a controlled cooking test. This reduction is modest compared to claims for many improved stoves. However, we have greater reason to believe that our findings are precise. We assume that variance in fuel consumption between individuals is not different that variance within individuals (i.e., over time). The large number of observations in our study captures fuel consumption variance with sufficient power to detect an average reduction of 12%.

If the wood savings on the cook test generalized, we would expect treatment households to spend less time collecting wood. There was no decline in our measures of time spent per week gathering wood.

E | Principal component analysis of stove usage monitor data

Principal component analysis can potentially aid in signal processing across many stoves. Daily temperature changes and stove activity generally follow occur in regular, periodic fashion. Moreover, people often used their stoves at nearly the same times of day. These common patterns create an intrinsic spatial and temporal correlation—that is, they make it difficult to compare readings across many stoves and identify "signal" versus "noise."

Principal component analysis (PCA) takes advantage of these common patterns to decompose time series across many stoves to tease out idiosyncratic stove activity, as well as examine that activity systematically. For example, it is possible to examine patterns of activity within the several stoves of single households, as well as across stoves by type or location.

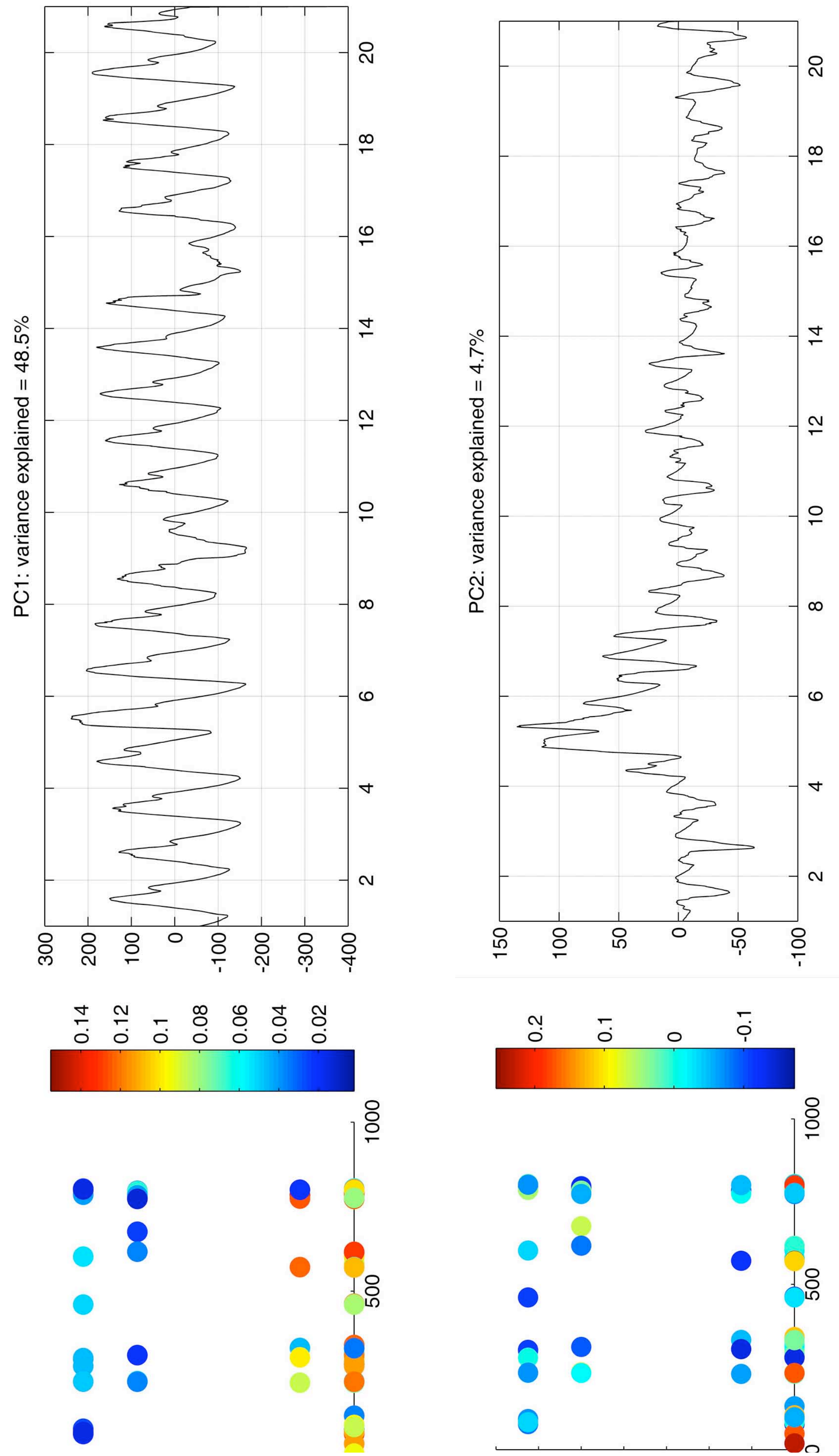
Each principal component of a spatiotemporal dataset is a spatial structure that explains the maximum amount of variance possible within the dataset when combined with its associated temporal structure. The temporal structure—the amplitude of the principal component—defines the variability that is shared by the locations. Each successive principal component then explains the maximum amount of variability that remains in the dataset after removing the contributions of the previous principal components. All the principal components are mutually orthogonal to each other—that is, they have zero correlation with each other and are thus "idiosyncratic." See Jolliffe (2002) for a complete explanation and discussion of PCA, including applications to time series.

While it is beyond the scope of this paper to carry out a full PCA, I seek to simply illustrate its promise. In Figure 0.1 below, I show the results from a PCA approach developed by Wagner et al. (2010) as applied to 20 days of temperature data from the stove usage monitors deployed in Gorima village as part of the 2009 Ghana stove study (see Appendix D). I have presented only the first two principal components, which together explain over 50% of the variance in signals. The time series chart at the right of each display represents the common signal, normalized around zero (i.e., not the actual temperature in °C). The chart of dots at the left of each display represents the "spatial" characteristics, with each dot representing a stove. In this case, we separated by owner, location, and type. Each vertical axis represents a single households' stoves. The upper two bands represent indoor stoves, while the lower two bands represent outdoor stoves. Within these bands, the upper stove represents improved stoves and the lower band represents traditional stoves. The coloration of each dot indicates the extent to which the principal component identified correlates with the actual signal at a given stove.

The top image shows the common signal that explains the most variance (48.5%) in temperature data across all stoves. This common pattern is very regular and periodic,

Figure 10.1 | Principal component analysis of SUM data

Data from Gorima village in the 2009 Ghana study. Day markings underneath the time series patterns signify time 00:00:00.



with the steady declines and minima coinciding with night and dawn, respectively. Intuitively, this pattern is likely to represent a common ambient temperature recorded at all stove usage monitors. We see by coloration of the dots at left that this common pattern is correlated with all stoves, though more strongly with outdoor stoves than indoor stoves—backing up our intuition. However, the common pattern is not entirely smooth and captures a small regular spike of activity that coincide with evenings. This may be due to the fact that most stoves at most evenings register activity. Finally, on day 15 there appears to be a break in the pattern; this pattern is common across stoves, suggesting a village-wide event—perhaps rain disrupting normal cooking activity, or a funeral/festival/other observance.

The bottom image shows the common pattern that explains the next most variance in temperature data across stoves (4.7%). Note that this signal is considered entirely orthogonal to the preceding common pattern—that is, it explains the maximal variance once the initial common pattern is accounted for. This signal also has a degree of periodicity and regularity with a repeating figure of two spikes that happen to coincide with morning and evening, potentially accounting for common periods of cooking activity. This activity is correlated positively only with some traditional stoves; for all improved stove, the correlation is zero or negative—which would imply that the common pattern is reflected in a mirror image fashion (i.e., stoves are disused at the same time that other stoves are used). On the evening of day 4 and leading into day 5, temperature data becomes more extreme, representing an anomaly that is difficult to interpret—perhaps some all night cooking on several stoves.

Note that these data reflect only a non-random subsample of stoves, as there was significant attrition of stove usage monitors during this period. More to the point, stoves that had more activity were probably more likely to end up burning their stove usage monitors—and thus, we may lack enough "signal" because these stoves are excluded from the analysis.

While there are no meaningful conclusions from this analysis, it is possible to conceive that PCA could be used in combination with other methods to identify idiosyncratic activity and derive a more granular observation of activity on a particular stove or set of stoves.

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