Seeing through the Smoke:

Measuring Impacts of Improved Cookstove Interventions on Technology Adoption and Environmental and Health Outcomes

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Jessica Jaslow Lewis

Department of Environmental Science and Policy
Duke University

Date:____________________
Approved:

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Subhrendu K. Pattanayak, Supervisor

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Joel N. Meyer

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Marc A. Jeuland

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Jill Baumgartner

Dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy in the
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ABSTRACT

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Abstract

Traditional cooking using biomass is associated with adverse health consequences, local environmental degradation, and regional climate change. Improved cookstoves (liquefied petroleum gas (LPG), biogas, electric, efficient biomass) are heralded as a solution, but their adoption and use remains low. In the first chapter, I report on a series of pilot programs that utilized the marketing principles of promotion, product, price and place to increase stove sales in rural India. We found that when given a choice between products, households strongly preferred an electric stove over improved biomass-burning options. Households clearly identified price as a significant barrier to adoption, while provision of discounts (e.g., rebates given if households used the stove) or payments in installments were related to higher purchase. Collectively, these pilots point to the importance of continued and extensive testing of messages, pricing models, and responses to different stove types prior to scale-up. Thus, boosting adoption will require more than a one-size-fits-all approach.

In the second and third chapters, I analyze the impact of intense improved stove use on social, environmental, and health outcomes in rural India—first in a sample of biogas stove users in Odisha, India, and next with households in the Himalayan state of Uttarakhand. In both settings, improved cookstove use was associated with reduced firewood consumption, substantial time savings for primary cooks, and significant reduction in exposure to particulate matter and polycyclic aromatic hydrocarbons in household air. I find that ICS users in Odisha spend less time in the hospital with acute respiratory infection and reduced diastolic blood pressure, but detected no relationship with other health measurements.

In the third chapter, I also find significant reduction in exposure to personal air pollution for improved cookstove users. Furthermore, using temperature sensors as objective stove use monitors for all stoves and heaters, I find that households underreport the use of improved and traditional stoves.

These papers provide encouraging evidence of the potential for adoption of clean stoves and a suite of benefits from clean stove use; however they also suggest that in order to achieve WHO-recommended levels of air pollution additional policies may be needed.

Dedication

This dissertation is dedicated to the hundreds of households in India who opened their hearts, homes and hearths to me and our research group. It is only because of your generosity and kindness that the research presented herein was possible, and you have my most profound gratitude. From you, I absorbed many lessons beyond the findings reported here, and the time I spent in your villages and households has given me some of my most powerful memories.

I also dedicate this dissertation to my loving parents, Jancy L. Jaslow and Donald B. Lewis, who empowered me to reach this point and taught me the most important lessons.

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1. Piloting improved cookstoves in India[1]

Despite the potential of improved cookstoves (ICS) to reduce the adverse environmental and health impacts of solid fuel use, their adoption and use remains low. Social marketing – with its focus on the marketing mix of *promotion*, *product*, *price*, and *place* - offers a useful way to understand household behaviors and design campaigns to change biomass fuel use. We report on a series of pilots across three Indian states that use different combinations of the marketing mix. We find sales varying from 0 to 60%. Behavior change promotion that combined door-to-door personalized demonstrations with information pamphlets was effective. When given a choice amongst products, households strongly preferred an electric stove over improved biomass-burning options. Among different stove attributes, reduced cooking time was considered most valuable by those adopting a new stove. Households clearly identified price as a significant barrier to adoption, while provision of discounts (e.g., rebates given if households used the stove) or payments in installments were related to higher purchase. Place-based factors such as remoteness and NGO operations significantly affected the ability to supply and convince households to buy and use ICS. Collectively, these pilots point to the importance of continued and extensive testing of messages, pricing models, and

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[1] This chapter is derived in part from an article published in the Journal of Health Communication on April 8, 2015, available online: http://dx.doi.org/10.1080/10810730.2014.994243

responses to different stove types prior to scale-up. Thus, we caution that a one-size-fits-all approach will be unlikely to boost ICS adoption.

1.1. Why and how should we think about promoting improved cookstoves?

Almost half the world relies on solid biomass fuel for cooking purposes (Bonjour et al. 2013); in India this proportion reaches almost 70%, and 90% in rural areas (Venkataraman et al. 2010). Biomass burning – especially in inefficient traditional stoves – releases high concentrations of particulate matter (PM) and other household air pollutants (HAP) that are harmful to health (Smith et al., 2014). The use of solid fuels negatively impacts households' well-being in other ways, because time spent gathering fuel and cooking is diverted from other productive activities (Pattanayak et al., 2004). Burning biomass also harms the environment by contributing to unsustainable harvesting of fuelwood (Bensch & Peters, 2013; Pattanayak et al., 2004), regional air pollution (Rehman et al., 2011), and black carbon emissions (Bond et al., 2013).

One potential solution to this complex set of problems is use of cleaner-burning stoves, known as improved cookstoves (ICS) (Anenberg et al., 2013). Compared to traditional stoves, ICS burn less fuel and decrease time spent cooking. They also emit less smoke and improve air quality, and therefore potentially improve the health of children and cooks (e.g., Pant et al., 2014). Thus, a diverse set of interests have coalesced into a global community that is motivated towards dissemination of ICS (Simon et al., 2014). There is limited empirical evidence, however, of programs that have achieved the desired behavior change - ICS adoption and use – let alone the postulated environmental and health benefits of ICS (e.g., Lewis & Pattanayak, 2012; Hanna et al., 2012).

How should we move beyond these low levels of adoption and use of ICS? We argue that stove intervention programs can be viewed through a social marketing lens, specifically the 4Ps of the "marketing mix": ***promotion***, ***product***, ***price*** and ***place*** (Borden, 1964; Lee & Kotler, 2011). This perspective has previously been successfully applied in the environmental health domain, for example in the use of social mobilization, subsidies and on-site provision to promote household latrine use in rural India (Pattanayak et al. 2009). Recently, Evans et al. (2014) show how it can be used to promote water, sanitation and hygiene products and services and change behaviors. As such, social marketing is one of the tools in the behavior change communication (BCC) toolkit (Devine, 2009). These ideas behind social marketing are also consistent with a more conventional economic argument that households will adopt new products such as improved stoves if interventions change household constraints through promotion campaigns that pay attention to consumer preferences for product attributes and price discounts (Pattanayak & Pfaff, 2009).

We apply the social marketing lens to consider elements of a *behavior change communication* campaign to encourage household purchase and use of ICS, although we give equal attention to the non-communication aspects of social marketing such as price and place. To statistically test if a particular behavior change campaign would work in the field, ideally we conduct a large *n* quantitative study in the field and address the many complexities inherent in the causal chain. However, a logical precursor to large evaluations is the careful design and piloting of intervention strategies – for example, the testing of different attributes and combinations of the marketing mix – using smaller samples, case studies, qualitative appraisals or semi-quantitative approaches (Arriagada et al., 2009; Vreugdenhil et al., 2010). Such mixed-methods or iterative field research approaches are especially critical when the questions are relatively clear, but understanding of the socio-economic-institutional context for the behaviors in question is lacking (Kanbur 2003). They also allow better interpretation and contextualization of results from large *n* evaluations.

On the basis of a thorough literature review, focus groups (see Bhojvaid et al., 2014), and previous quantitative surveys in communities in our study regions (see Jeuland et al., 2014), we field tested different combinations of social marketing intervention features in 8 pilot villages in rural India. These pilots sought to build on previous findings that argue in particular that (a) promotion/communication alone may be insufficient to affect behavior change (Barnes 2014; Jin et al., 2006; Pattanayak et al., 2009); and (b) limited focus on the design and/or sale of specific products (*e.g.*, ICS prototypes that achieve emissions reduction targets) may not lead to long-term gains. Rather, behavioral outcomes (i.e., sustained ICS use and generation of benefits), which themselves moderate environmental and health impacts, define the success of social marketing campaigns (Lefebvre 2011).

India is a pertinent location for testing ideas for accelerating ICS dissemination because it has high-level policy directives related to ICS that nonetheless face great implementation challenges. For example, the country's National Biomass Cookstoves Initiative seeks to provide 160 million ICS to households currently using solid biomass fuel, a goal that is at least as ambitious as the Global Alliance for Clean Cookstoves (GACC) global target (Venkataraman et al., 2010). Households in our study area however appear to have very limited understanding of the adverse impacts of traditional cooking practices, strong entrenched preferences for traditional stoves, and somewhat limited but highly variable willingness to pay for ICS attributes (Jeuland et al., 2014). ICS adoption studies from India also find that awareness of health benefits alone is often insufficient to motivate ICS adoption (Thurber et al. 2013; Thurber et al. 2014).

Our pilot program was designed around variation in four dimensions: location and institutional context (*place*), ICS technology (*product*), the information and demonstration strategies (*promotion*) and the price and payment plans (*price*). It was conducted in cooperation with 3 non-governmental organizations (NGOs) each of which focused in one of three biophysically and socio-politically different rural settings of India, namely Uttar Pradesh, Odisha, and Uttarakhand. We explored demand for three different ICS technologies, two of which burn solid fuels more efficiently (natural and forced-draft stoves), and one that runs on electricity. Information and demonstrations were provided at community or individual household levels with varying intensity. Finally, the pilots varied in allowing households to pay for stoves over time or upfront, and in delivery of price discounts.

Our results offer a set of lessons on household behavior change related to adoption and use of ICS. First, successful BCC campaigns directly engaged households while providing information and conducting personalized demonstrations. Second, we must test diverse ICS products to identify an appropriate and desirable model for the cultural setting. Third, price is a significant barrier, but offering households the possibility of paying in installments might enable cash-strapped households. Fourth, understanding context – road and transport infrastructure, supply chains and local micro-institutions - is paramount for penetrating into remote, rural locations.

1.2. Can social marketing help us understand the challenges of disseminating ICS?

Despite the promise of ICS, adoption and use rates remain low in much of the world, including in India (Bhojvaid et al., 2014). Some have contended that stoves are a "push" rather than a "pull" product (unlike a technology like cell phones), suggesting that innovative methods are required for delivering stoves to households and convincing households of their utility (Shell Foundation, 2013). Others have categorized the challenges into demand and supply side factors (Lewis & Pattanayak, 2012; Rehfuess et al., 2014). Here we discuss if the low rates can be understood using a social marketing framework.

1.2.1. Information, education, communication

There is a small but growing literature in economics that shows how information, education and communication can influence the adoption and use of environmental health technologies such as taps, toilets, bednets and ICS (Pattanayak & Pfaff, 2009). The underlying premise is that poor households who would most benefit from such technologies may not know or are unable to learn about their benefits (Opar et al., 2006; Madajewicz et al., 2007). Information provision may also help overcome household reluctance to invest in new and costly goods like ICS technologies if these reduce the perceived riskiness of these investments (Conley & Udry 2010; Hazra et al. 2014).

This evidence is partly corroborated by the ICS practitioner literature that suggests that BCC, promotion, user demonstrations, and social networks can lead to more consistent behavior change (Dalberg Advisors, 2012; Ramirez et al., 2012; Shell Foundation, 2013). Health communication and or behavior change communication (BCC) that combines rational appeals (such as to decrease fuelwood use) with emotional messaging (such as improving health and improving household livelihood) would thus appear to be an important component of ICS dissemination campaigns.

1.2.2. Types and attributes of stoves

ICS such as liquefied petroleum gas (LPG) and electric stoves have long been available in developing countries, yet the supply of electricity and LPG fuels is not always dependable. Other improved stove technologies, most notably a variety of more efficient biomass stoves, are therefore being developed to reduce the health and environmental harms caused by traditional stoves. Unfortunately, the challenges of appropriate technology persist because a health-protective emission level is likely only possible with the cleanest of stoves such as gas, electric or advanced combustion (Simon et al. 2014). Furthermore, there is often a disconnect between the ICS that may be most accepted by users (e.g. similar to their traditional stoves in design and fuel type) and those that can meet efficiency and manufacturing standards (Beyene & Koch, 2012; Jeuland et al., 2014; Shell Foundation, 2013). Thus, it is imperative to test different stoves before scaling up, as documented in several recent field programs (Derby et al. 2014; Singh 2014).

1.2.3. Stove price and payment collection

Prices are usually set by market forces of demand (reflecting willingness to pay, WTP) and supply (reflecting opportunity costs of resources), with the market clearing price reflecting the equality of WTP and marginal cost. On the supply side, the market for most ICS is currently too thin to have confidence that stove prices represent marginal costs that are relevant for scaled up promotion programs. There is a small literature on household demand and WTP for ICS. Miller and Mobarak (2011) find very low WTP for two types of ICS. Jeuland et al. (2014) use stated preference methods to measure WTP for specific attributes of ICS such as reductions in smoke and fuelwood. They find that average demand for stove attributes in rural Indian communities may reach levels comparable to some cheaper natural draft ICS options, but that this average masks considerable heterogeneity across households. Cost would thus seem to be an important barrier to adoption, particularly by the poor.

Three other features of ICS use make it hard to decide how market price does and or should influence household demand. First, many of the impacts of ICS adoption and use may be external to households (Pattanayak & Pfaff, 2009; Jeuland & Pattanayak, 2012). This raises the case for subsidizing stove purchase. Yet programs providing ICS to households at highly subsidized rates or free of charge (as is often done in field studies) have faced their own problems, particularly with regards to achieving sustained use (Adrianzen 2010; Hanna et al., 2012). This suggests that household preferences - encompassing cultural or aesthetic preferences – and ICS proponents' expectations may not be fully aligned (Mitchell et al., 2010; Ruiz-Mercado et al., 2013).

Second, programs might want to change how they collect payments because poor rural households typically face serious credit and liquidity constraints (Adler 2010; Pant et al. 2014). Finally, programs that allow households to spread payments over time may increase ICS adoption because households may heavily discount the long-term benefits of ICS, or suffer from self-control problems (Beltramo et al., 2015).

1.2.4. Local context

In social marketing, place refers to the distribution channels and outlets through which tangible products are made available to consumers (Evans et al., 2014). For example, Pattanayak et al. (2009) argue that bringing masons and materials to households so that they could have an improved toilet next to their house radically alters sanitation options in remote rural villages. A similar challenge exists for ICS because of the remoteness of target markets. Local infrastructure (e.g., roads and the supply chain for alternative fuels) often remains underdeveloped in such locations, making transport of bulky products like ICS to remote rural regions difficult (Shell Foundation, 2013).

It has been hypothesized that the failure of previous ICS dissemination programs stemmed from insufficient attention to developing stable and accessible supply, though most evidence on this question is anecdotal (Bruce et al., 2006; Ezzati & Kammen, 2002; Shrimali et al., 2011). Therefore, there is growing recognition that ICS supply chains remain insufficient; experiences in India with clean stoves and fuels are no exception (Dalberg Advisors, 2012; Martin et al., 2011; Rehfuess et al., 2010). In contrast to the failure in India, strong government supply chain strengthening is hailed as a critical component of China's National Improved Stove Program (Smith et al., 1993). Thus, it is no surprise that the GACC prioritizes the strengthening of ICS supply chains (GACC, 2011).

In remote settings such as ours, micro-institutions such as effective NGOs, creditors, and retailers can also be vital for delivering environmental health technologies (Pattanayak et al., 2009; Pattanayak et al., 2010). When locals are unsure about a new and costly technology, NGOs can also serve as a major channel for trust and social capital (e.g., Krishna 2007). More generally, micro-institutions connect households to local collective action, determine flows of external support, and link local populations to national and international interventions (Agrawal & Perrin, 2009).

1.3 Designing the pilots

Eight pilots were conducted in rural villages in three states in succession, UP (3 villages), Orissa (2), and Uttarakhand (3). These pilots tested various aspects of the marketing mix related to 1) behavior change communication, 2) stove types, 3) purchase options (payment plan and risk-free trials) and use incentives, and 4) access and institutional delivery. The specific configuration of features that were tested were identified on the basis of literature reviews and extensive data collection from focus group discussions (March 2012) and a large cross-sectional survey (June-August 2012), both of which took place in communities in UP and Uttarakhand similar to those where we conducted these pilots; those results are reported elsewhere (Bhojvaid et al., 2013; Jeuland et al., 2014). Collectively, these data collection activities provided valuable information on consumer perceptions and impressions of traditional and improved cookstoves, and on prevailing cooking behaviors.

The pilots were implemented over a four month period (March – August 2013) with iterative updates to the design based on lessons learned from earlier pilots. For example, drawing on experiences in the first two sites that revealed the importance of prior institutional presence in a target community, pilots in Uttarakhand were only implemented in villages where the partner NGO had previously worked.

All households in the pilot villages were given the opportunity to purchase a stove. Additionally, in each pilot village, approximately 25 (UP and Odisha) or 15 (Uttarakhand) households were randomly selected for interview.[2] Households were selected by dividing the total number of households in the village by the desired sample size and sampling every nth household. Those who refused to participate or could not be located on the day of the pilot visits were replaced with a neighboring household. We implemented this procedure for random selection of survey households in order to obtain a representative picture of the adoption process that is most relevant for efforts to scale-up ICS promotion, rather than simply talking to those households most interested in demonstrations, stoves, or visits from outsiders. The survey was used to collect information on household characteristics (demographics and socio-economic status), perceptions of traditional and the offered improved stoves, cooking behaviors, as well as to gather real-time feedback on the effectiveness of the intervention program.

1.3.1. Promotion: Behavior change communication

Among the households participating in our initial data collection activities in UP and Uttarakhand, we found that a minority (39%) were aware of stoves that produce less smoke than traditional ones, and that only 41% believed that some fuels produce less

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[2] Actual sample sizes were slightly different (Pilot A, B, C, D, E: 25 households, Pilot F: 16, Pilot G: 15, Pilot H: 14) due to households not being at home during repeated visits or enumerator error.

smoke than others when burned (Jeuland et al., 2014). Most of these households knew about LPG stoves but had very limited exposure to other improved cooking technologies. Additionally, among households that were aware of adverse health effects from traditional cooking (68%), only 14% believed adopting a clean stove could help alleviate those effects. Knowledge and belief that improved stoves could also ameliorate environmental outcomes such as forest preservation and protection of regional air quality was even lower. Finally, upon discussion of ICS and their features and benefits with households, we observed that the weight placed on ICS benefits was influenced by prior exposure to technological products and experience with similar NGO environmental interventions (Bhojvaid et al., 2013).

To address these knowledge gaps and the need for additional education around the benefits of ICS, we piloted different promotional and social marketing campaigns. All pilots contained messaging around three key features: 1) time savings from reduced time spent cooking and gathering wood, 2) fuel savings, and 3) health benefits. During our preparatory work, nearly all households who knew of improved stoves had identified the first two as important benefits, while the latter was primarily mentioned by women who were the primary cooks in their particular households (Bhojvaid et al., 2013). The messages were included in various combinations of promotional materials and messages as part of the BCC strategy explained below.

Informational pamphlets were used in each pilot to compare various attributes of traditional and improved stoves, although the specific content of the pamphlet varied by pilot location. The pamphlets contained both Hindi text and visual icons for illiterate households. The promotional material compared the stoves on the basis of their differential fuel requirements, cooking times, smoke emissions, and prices. For example, in Pilot F (Figure 1), the fuel requirement of the natural draft stove is shown as 70% of the traditional stove requirement with written percentages, as well as a photo of a woman carrying a smaller pile of wood and symbols representing proportionately less wood; the electric coil stove is shown with a crossed out symbol for wood. In pilots where an electric stove was offered, households were informed about the anticipated impact of the electric stove on their monthly electricity bill.

उन्नत चूल्हा अपने घर ले जाइये। अपने परिवार और जगंल को बचाइये।

	अंगीठी	उन्नत चूल्हा ग्रीनवे	उन्नत चूल्हा जी–कोईल
चूल्हे			
ईंधन की जरूरत	100% खर्च	70 % खर्च	
समय की बचत			
धुआं और सेहत	100%	65 % कम	
हल्का करंट			कभी कभी* हल्का सा करंट लग सकता है। * गीले नंगे पाव; बरसात या अर्थिगं की समस्या।
दाम	0	1300 रुपए	900 रुपए महीने का बिजली का बिल बढ़ेगा : 2 महीने 1 घन्टा रोज = रु 260 2 महीने 2 घन्टे रोज = रु 525
किश्त	0	675 रुपए की 2 किश्त हर 2 हफ्ते बाद	470 रुपए की 2 किश्त हर 2 हफ्ते बाद

कम ईंधन। कम समय। कम धुआँ। स्वस्थ परिवार।

Figure 1: Promotional pamphlet in Hindi for Pilots F & G showing the traditional stove, natural draft stove, and an electric stove

Table 1: Promotional pamphlet for Pilots F & G showing the traditional stove, natural draft stove, and an electric stove (English translation)

BUY AN IMPROVED STOVE. SAVE YOUR FAMILY AND YOUR FORESTS.

STOVES TYPES	**Traditional 'angithi' stove**	**Improved Wood Stove**	**Improved Electric Stove**
FUEL REQUIREMENT	Most firewood use (100%)	Compared to traditional stove, uses 70% of the firewood	Uses electricity. Does not use firewood
COOKING TIME REQUIREMENT	Takes the most time to cook	Takes less time (compared to traditional stoves)	Takes the least time (compared to traditional stove)
SMOKE AND POLLUTION	Most smoke released (100%)	Less smoke (65% compared to traditional stove)	No smoke
ELECTRICAL FEATURES	None	None	As with all electrical products in rural India, use care. Ground your outlets and, during rainy season, wear rubber soled shoes.
PRICE OF STOVE	0 Rs.	1300 Rs.	900 Rs. Monthly electricity bill will increase with use of the electric stove. For example, daily 1 hour stove use will lead to a bill of approx. Rs. 260 over two months and daily 2 hour stove use will lead to a 2 month bill of approx. Rs.525
INSTALLMENTS	0	675 Rs. in 2 installments bi-weekly	470 Rs. in 2 installments monthly

Less fuel. Less time. Less smoke. Healthy family.

Household visits were included in all pilots. During the household visits, the stove sales staff talked at length through the benefits of the ICS depicted in the promotional pamphlet. Health communication included a discussion of the adverse impacts of smoke inhalation for respiratory health and eye problems, particularly for the cook and nearby children. BCC also included description of general livelihood benefits, such as the ability to carry the biomass stoves to cook in different locations in or outside the house. Visits at each household ranged from fifteen minutes (in the basic variety detailed below) to one hour (in the more intense option below). The sales staff pointed to the informational sheet (which was left with the household) as they described the benefits of the stove.

We attempted three levels of intensity for our BCC strategy. At the most basic level ("Basic"), households received informational pamphlets and private stove demonstrations during single-day visits conducted by trained ICS sales teams. Also, to allow users to become more familiar with the ICS, a few demonstration stoves were left overnight in some of the target communities (only in the UP pilots) prior to taking final orders. This was conducted in Pilots A and B in UP.

At a more intensive level ("Basic Plus"), an extended promotional campaign was conducted over a week. This included hanging informational posters throughout the targeted community, delivering flyers to every household in advance of ICS demonstrations, and multiple community demonstrations during which ICS benefits were described at length. Sales teams collected names of interested households and returned the following day to complete sales. If randomly selected households had not seen the demonstration, they were given a private one. This strategy was used in Pilots C (UP), D, and E (Odisha).

At the most intensive level (“Intensive”), used in Pilots E, F and G (Uttarakhand), households were also given an opportunity to purchase the stove after the demonstration (see Table 2).

The “messengers”, or sales staff, differed by region. In UP, young men, some of whom already sold energy products, were trained in ICS sales. An experienced stove salesman from the stove manufacturer also helped with the demonstrations for Pilot C. In Odisha, NGO village workers accompanied and provided support to a team of experienced male ICS salespeople from a local sales organization. The most extensive recruiting and training of male and female stove sales staff was conducted in Uttarakhand.

1.3.2. Product: Stove type

Households were found during preparatory work to have varying preferences for ICS features and fuel requirements, but only had substantial experience with LPG (which was owned by about 20% of households in our preparatory survey) (Jeuland et al., 2014). We therefore offered three distinct stove technologies in our pilots, which were not available in these locations but were manufactured and could be purchased in India. We did not attempt to test emissions or modify the designs of these improved stoves in the field. Instead, the stoves – a natural draft biomass ICS, a forced draft biomass ICS and an electric coil stove – were selected to offer varying characteristics (relative emissions and fuel requirements, prices, and operation and maintenance costs). We only selected stoves that are on the list of “approved” ICS published by the Indian

Ministry for New and Renewable Energy (MNRE),[3] or, in the case of the electric stove, that had zero household emissions (MNRE does not test electric stoves). And while the preparatory focus groups had indicated that women would prefer a double pot stove that would reduce the time required for cooking (Bhojvaid et al., 2014), no double pot stove that passed the government criteria for smoke and fuel reductions existed in the market at the time of the study.

The forced draft ICS (the TERI SPT-0610, sold for Rs. 2700) has a thermal efficiency of 37%, CO emissions of 2.25 g/MJ_d, and total particulate matter emissions of 147.40 mg/MJ_d (MNRE 2014), and gains efficiency because it uses a fan powered by a battery. This stove requires wood to be chopped into small pieces and inserted from the top. The natural draft ICS (Greenway Smart Stove) has a thermal efficiency of 24%, CO emissions of 3.0 g/MJ_d, and total particulate matter emissions of 315.38 mg/MJ_d (MNRE 2014); it was sold for Rs. 1300. Wood is inserted into the front of this stove. Finally, the electric stove uses a heated coil and emits zero household air pollution; it cost households Rs. 900 and was only piloted only in Uttarakhand. In some pilot villages, households were only offered a single stove, while in others, households had a choice of purchasing one or more different types. Ultimately, piloting several ICS also allowed us to observe the penetration of their supply and distribution networks.

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[3] For list of approved ICS, see http://mnre.gov.in/file-manager/UserFiles/improvedbiomass_cookstoves_manu.htm

1.3.3. Pricing and payment plan

The natural draft and electric stoves were sold at the manufacturer's suggested retail price (MSRP), whereas the more expensive forced draft stove was partially discounted (the MSRP is 4000). All three come with a one year warranty provided through the retailer, which covers the buyer in the event of serious defects in the ICS (the warranty only covered the coil element in the electric stove). In pilots where the electric stove was offered, households were informed about the anticipated impact of the electric stove on their monthly electricity bill (Figure 1).

The stoves described above have costs equivalent to about 25-77% of monthly expenditures among households in our sample (Rs. 3500 (US $60) on average across all pilots). They therefore represent significant investment decisions, and we expected based on our preparatory surveys that many potential purchasers – especially the poor and women – would have difficulty producing the cash required to pay for an ICS upfront even if they wanted it (Jeuland et al., 2014). These survey data also strongly suggested that liquidity constraints would be an important obstacle to stove purchase; access to credit was limited to 34% of households (ranging from 9% in UP to 64% in Uttarakhand), and a minority of households were members of microfinance or credit groups (ranging from 9% in UP to 62% in Uttarakhand). To address liquidity constraints, we therefore piloted several plans that allowed households to pay for the stove in installments (Pilots B – H). Participation in these installment plans was optional; any household could still choose to purchase a stove with a single upfront payment. The number of installments varied from 3-4 depending on the pilot, the fee associated with the installment plans was equivalent to 2% of total stove cost added on to each installment, and the interval between payments varied from 2-3 weeks.

Households might also be wary of paying a large amount for a product with which they had limited experience. To tackle the problem of investment risk in a new and unknown technology, we also piloted an optional return policy (Pilot G), which allowed households to return a stove at any time if they were unsatisfied with it. In such cases, the household would forfeit any payments already made towards the purchase of the stove, but would not be responsible for additional installment payments not yet provided.

The benefits of adopting an ICS can only be realized if their use is sustained over time, and adjustment or learning costs may discourage uptake (Jeuland & Pattanayak, 2012; Ruiz-Mercado et al. 2011). Thus, to incentivize both adoption and short-term learning about these technologies, we included rebates in some of the pilot villages (Pilots A, C, D, F, G). These rebates were only delivered if the household continued to use its purchased ICS over the entire installment collection period. During this period, household stove use (for all stoves owned) was recorded by the sales teams every 2-3 weeks (via household self-reports with verification of signs of stove use by enumerators) in conjunction with the visits to collect installments. During each visit that households were found to be using their purchased stove, they received a Rs. 50-100 rebate that would count against the payment of the installment that was due (depending on the pilot).

1.3.4 Place: Context, institution and access

We conducted our pilots in 3 Indian states that differed in extent of economic development and market access. The sites were selected to allow for variation in the presence and nature of local NGOs and infrastructure, and therefore in the geography and connectivity of the sites (Table 2).

Table 2. Summary of pilot intervention features

Pilot	Product			Pricing Plan				Place			Promotion: Social marketing/ BCC[4]	Total Sales (sales in random sample)	% HH Purchase (% purchase in random sample)
	Forced Draft	Natural Draft	Electric	Full upfront payment	Installments	Rebates conditional on use	Optional stove return	State	NGO	Near Highway?			
A	✓	✓		✓		✓		Uttar Pradesh (UP)			Basic	0 (0)	0 % (0%)
B	✓	✓			✓				✓		Basic	2 (2)	8% (8%)
C		✓			✓	✓			✓		Basic Plus	3 (0)	1% (0%)
D		✓			✓	✓		Odisha	✓		Basic Plus	14 (6)	23% (46%)
E		✓			✓					✓	Basic Plus	4 (1)	4% (8%)
F		✓	✓		✓	✓		Uttarakhand	✓		Intensive	19 (6)	40% (38%)
G		✓	✓		✓		✓		✓		Intensive	17 (9)	31% (60%)
H		✓			✓	✓			✓		Intensive	2 (2)	7 % (14%)

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[4] Basic: Pamphlets and household demonstration; Basic Plus: pamphlets (in advance), village posters, community and household demonstration; Intensive: new pamphlets and extended household visit (in advance), community and household demonstration

The pilots required development of a new supply network for ICS because there were no retailers located near our study sites. Indian regulation prohibits shipments across state boundaries by organizations without a tax-identification number (TIN) such as NGOs (compared to registered businesses that have TINs). In addition, although the three ICS are sold with a one year manufacturers' warranty, it is usually not practical for a household to act on this warranty because it would have to travel 1-2 days to reach the retailer. Finally, local suppliers were unwilling to order large numbers of ICS without a payment guarantee, which could not be provided in advance. Thus, our NGO partners collaborated with local wholesalers to order and transport ICS to our sites, purchasing 20-50 ICS at a time to minimize financial risks.[5]

Given these challenges, it was thus critical to partner with NGOs who were among a small number of micro-institutions working or interested in working to disseminate clean energy products (and ICS) in our pilot regions. These NGO partners had varying degrees of knowledge of and relationships with local communities, all of which affected the supply chain in our pilots. Our UP partner was a research organization headquartered in New Delhi and working in policy research, rural livelihoods, energy needs and sustainable development. Pilot villages (A-C) were chosen to vary according to the NGO's prior presence in the community from a set of villages

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[5] In UP, this problem was somewhat reduced; a small network of energy entrepreneurs were beginning to sell ICS but only had the capital to stock a few stoves at a time.

situated near to this organization's local office and accessible by paved roads. Our Odisha NGO partner was headquartered in a rural setting; they focus on water, sanitation, education, livelihood and energy programs throughout the state. Pilot locations there (one from a tribal area (D) relatively near to the NGO office; the other from farther away near a highway (E)) were selected from villages where this partner had previously worked. Finally, in Uttarakhand, we worked with a rural NGO whose programs emphasize improved livelihoods, health, education, and natural resource management across several districts. The UK pilot villages (F through H) consisted of dispersed and isolated communities located in the Himalayan foothills where our partner had also previously worked; the intensity of NGO livelihood programs was greater in pilots F and G than pilot H.

Given the fact that no point of sale existed for these ICS in the study areas prior to these programs, the improved stove sales offer was delivered by the sales teams at the dwelling of all randomly selected households. In some pilots (C-H), households were also able to purchase the stove at community demonstrations.

Differences in connectivity, geography, and the local economy of our pilot sites also translated into a range of different fuel and stove use situations; this was intentional given our objective. Prior to our pilots, though virtually all households owned traditional stoves, rates of ICS (LPG, biogas or kerosene) ownership varied widely (Table 3); they were greatest in Uttarakhand (>60% of households owned improved stoves in two pilot villages), but much lower in UP (9%) and Odisha (0% in D and 25% in E). Rates were slightly lower for LPG. Average time spent gathering traditional fuels also varied by pilot location: households in Uttarakhand and UP spent the most time (all village averages were over 12 hours per week) compared to 5 hours per week or less in Odisha. Households in Uttarakhand did not pay for traditional fuels, unlike households in UP and Odisha. Conversely, Uttarakhand and Odisha households spent the most money on clean fuels.

With respect to household characteristics, Uttarakhand households were much more likely to be in the open or general caste designation, and were wealthier and more educated than their counterparts in UP or Odisha. Average electricity supply in the UP communities was much lower (ranging from 0 to 10 hours per day) than in those in Odisha (0 to 21) and Uttarakhand (15 to 22). Uttarakhand and Odisha villages were more remote compared to UP villages. The fraction of households that have taken out a loan was far higher in Uttarakhand than in the other states where pilots were conducted.

Table 3. Characteristics of pilot villages, by Village (Pilots C – H)

Household Characteristics		Uttar Pradesh	Odisha		Uttarakhand			Full Sample
		C	D	E	F	G	H	
Household Characteristics	Total # hh	23	25	24	16	15	14	117
	BPL	48%	56%	29%	81%	80%	50%	55%
	Open/general caste	4%	0%	0%	75%	93%	93%	34%
	Household size	6.1	5.0	4.7	6.7	6.3	6.0	5.7
	% female headed household	13%	8%	13%	6%	20%	7%	11%
	Head of household years of education	5.3	3.4	6.9	8.1	5.0	6.8	5.7
	Head cook years of education	1.4	1.9	4.9	5.8	2.9	6.7	3.6
	SHG membership	9%	44%	71%	69%	53%	64%	50%
	# hrs electricity	5.0	20.0	17.5	19.6	20.1	20.9	16.6
	Avg monthly expenditures	3,370	1,776	2,492	5,250	3,900	6,143	3,506
	% latrine access	9%	96%	92%	100%	93%	100%	79%
	% fuelwood used for heat	100%	96%	54%	94%	100%	100%	89%
	% with savings	52%	48%	63%	31%	40%	86%	53%
	% taken out a loan	9%	20%	17%	69%	73%	50%	34%
Stove/Fuel Use	% trad stove ownership	100%	96%	96%	94%	100%	100%	97%
	% Imp stove ownership (LPG, biogas or kerosene)	9%	0%	29%	75%	27%	79%	31%
	% LPG stove ownership	9%	0%	25%	60%	27%	64%	26%
	Avg time spent gathering fuel (all trad fuels) in hrs/week	16.3	5.2	3.7	20.1	23.7	12.1	12.3
	Avg Rs spent on trad fuels per week	43.7	0.0	29.0	0.0	0.0	0.0	14.5
	Av Rs spent on clean fuels per week	11.1	0.0	107.2	237.8	62.2	145.1	82.0
Preferences for Stove Attributes	ICS Top 2 Attribute - Reduced Smoke	74%	40%	0%	38%	7%	57%	42%
	ICS Top 2 Attribute - Cooking time	11%	47%	1%	56%	67%	14%	42%
	ICS Top 2 Attribute - Fuel requirement	21%	93%	1%	44%	40%	64%	54%
	ICS Bottom 2 Attribute - Cost	42%	100%	95%	33%	33%	77%	63%
	ICS Bottom 2 Attribute - Maintenance	0%	10%	0%	75%	0%	15%	14%

Several differences are also notable at the level of individual pilot villages. The Pilot C village, for example, stands out for the very low percentage of households in open or general caste categories, few years of education for primary cooks, low latrine coverage, and low access to credit compared to the other villages. This village also has the greatest percentage of households that value the reduced smoke from ICS. Pilot E (Odisha) had the highest SHG membership, the lowest percentage of households that use fuelwood for heat, and the lowest time spent gathering traditional fuels. In the Pilot F village (Uttarakhand) education levels were higher; this village also had fairly high baseline ownership of improved stoves and spending on clean fuels. Approximately 20% of the households in the Pilot G village (Uttarakhand) had female heads, which stands out from the other villages; households in this village spend the most time gathering wood and also expressed the lowest preference for reduced smoke from ICS. Pilot H (Uttarakhand) had substantially higher average monthly expenditures than any of the other villages, as well as noticeably greater access to savings and credit. This village also had by far the highest baseline level of improved stove ownership.

1.4. Pilot findings

Stove sales varied widely in these pilot programs; within the random sample of households selected for targeted demonstrations and surveys, sales varied from 0 (Pilot A, Uttar Pradesh) to 60% (Pilot G, Uttarakhand; Table 4 & Figure 3). Across all pilots, 18% of randomly selected survey households (26 out of 146 households) purchased an ICS. Stove sales varied substantially by state. In UP, Odisha, and Uttarakhand villages, 3%, 27%, and 38% of randomly selected households purchased ICS, with one household purchasing two stoves in Uttarakhand. The total rate and numbers of stoves sold to any households in these three states were 2% in UP, 11% in Odisha, and 29% in Uttarakhand. While our design precludes us from conducting rigorous causal analysis or controlling for village-level differences, we present t-tests results for differences in means that suggest some noteworthy differences between households that bought and those that did not (Table 4). Overall, households that adopted ICS were significantly more likely to have access to a latrine (27%, p-value 0.00), own cellphones (22%, p-value 0.00), and to have taken out a loan (36%, p-value 0.00) than non-purchasers.

Table 4. Test for differences in means between purchases and non-purchasers for randomly selected households (Pilots C – H). *** p<0.01, ** p<0.05, * p<0.1

	Variable	Purchasers (n=24)	Non-purchasers (n=93)	P-value
Promo-tion	HH received pamphlet	92%	76%	0.036**
	HH attended demonstration	88%	73%	0.084*
Household Characteristics	% female headed household	13%	11%	0.817
	Head of household years of education	5.6	5.8	0.912
	Head cook years of education	3.2	3.8	0.5
	BPL	71%	51%	0.061*
	Open/general caste	63%	27%	0.002***
	SHG	67%	45%	0.053*
	% latrine access	100%	73%	0.000***
	% with cellphone	91%	69%	0.004***
	% with cattle	88%	74%	0.108
	% with savings	46%	55%	0.435
	% taken out a loan	63%	27%	0.002***
	% fuelwood used for heat	96%	87%	0.109
	Household Size	6.5	5.5	0.118
	Number of cooks in household	2.1	1.8	0.302
	Avg monthly expenditures	3563	3491	0.86
	# hrs electricity	20	16	0.000***
Stove/Fuel Use	% trad stove ownership	100%	97%	0.0836*
	% Imp stove ownership	29%	31%	0.849
	% LPG stove ownership	17%	28%	0.256
	Avg Rs spent on trad fuels per week	3	18	0.008***
	Avg Rs spent on clean fuels per week	68	85	0.592
	Avg Rs spent on LPG per week	133	91	0.447
	Avg time spent gathering fuel (all trad fuels) in hrs/week	16	11	0.062*
Prefer-ences	ICS Top 2 Attribute - Reduced Smoke	9%	53%	0.000***
	ICS Top 2 Attribute - Cooking time	66%	33%	0.007***
	ICS Top 2 Attribute - Fuel requirement	62%	53%	0.447

1.4.1. Promotion

In Uttarakhand, only 7% (3 of 45) randomly selected households indicated they had heard of ICS prior to observing a stove demonstration. After the demonstrations, households indicated that the ICS attributes they found most desirable were amount of fuel required (54%), reduced smoke emissions (42%) and reduced time spent cooking (42%) (Table 2 & Figure 2). This is in keeping with consumer aspirations that emerged from prior work (FGD and baseline) in assessing community needs with regard to ICS. These stove attributes were explicitly highlighted in the information campaign, suggesting that the informational materials and stove demonstrations likely influenced households’ thinking about the ICS. The vast majority (63%) of randomly selected households cited cost as the least desirable aspect of the ICS. Purchasers were significantly more likely to value a reduction in cooking time, whereas non-purchasers were much less likely to value smoke reduction (p-value 0.000). Purchasers may have also highly valued smoke reduction, but it fell below their desire for reduced cooking time and fuel requirement. Purchasers spent on average 5 more hours collecting fuel than non-purchasers, and though they spent less money on fuel, the numbers of households paying for fuel and amounts involved were very small (Table 4).

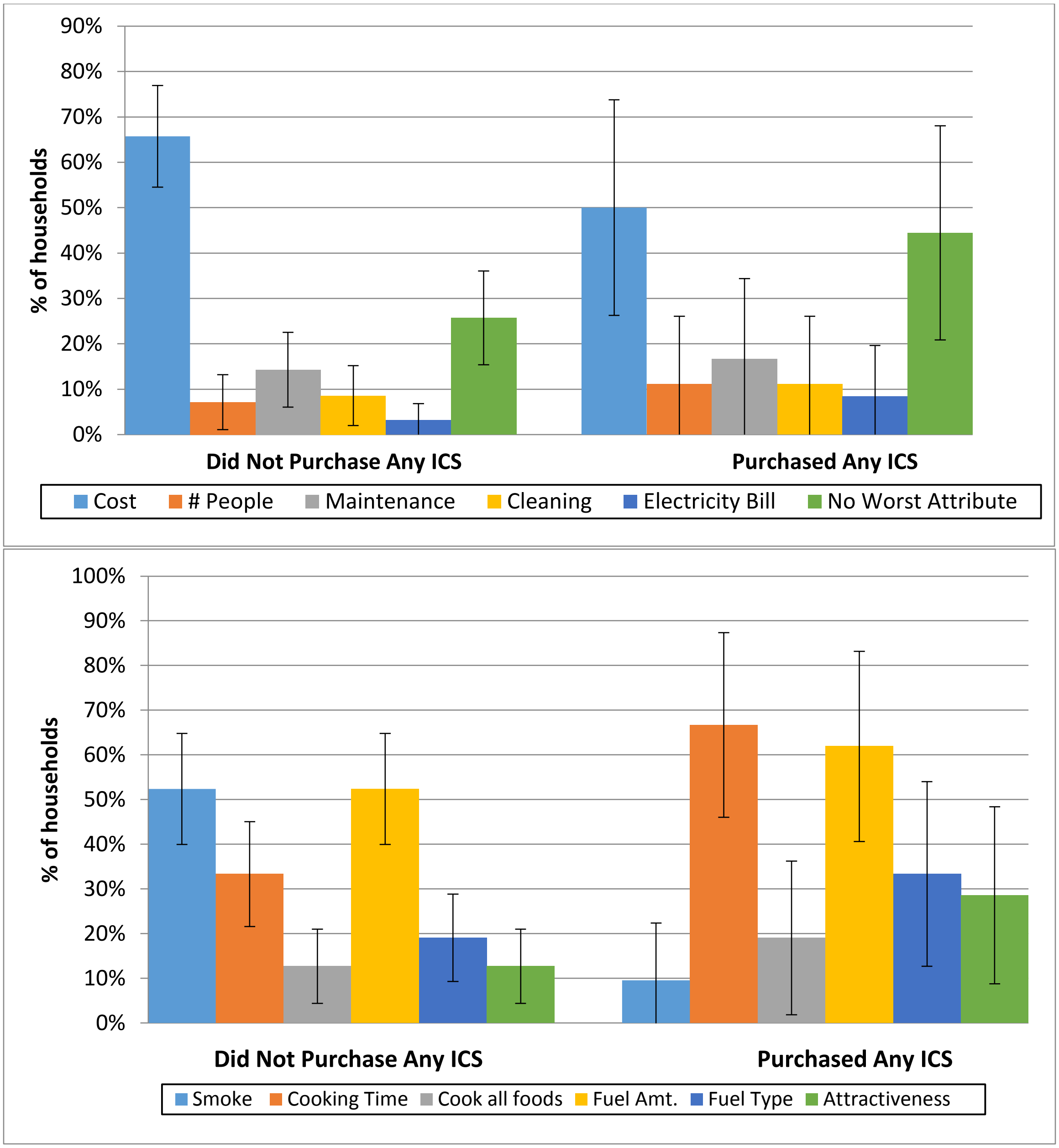

Figure 2: Two attributes considered best (top figure; n=84) and worst (bottom figure; n=88) about the improved stove(s) by randomly selected households (Pilots C – H) on average (with 95% confidence intervals).

As shown in Table 3, the BCC campaign appears to have influenced sales. Purchasers were 15% (p-value 0.08) more likely to have attended a demonstration and 16% more likely to have remembered receiving a pamphlet (p-value 0.03). Stove sales were also greatest in the villages with more intense marketing: in villages with the basic BCC campaign (A and B), only 4% of survey households purchased stoves, compared to 38% in villages with more extensive social marketing (C through H) (Figure 3).

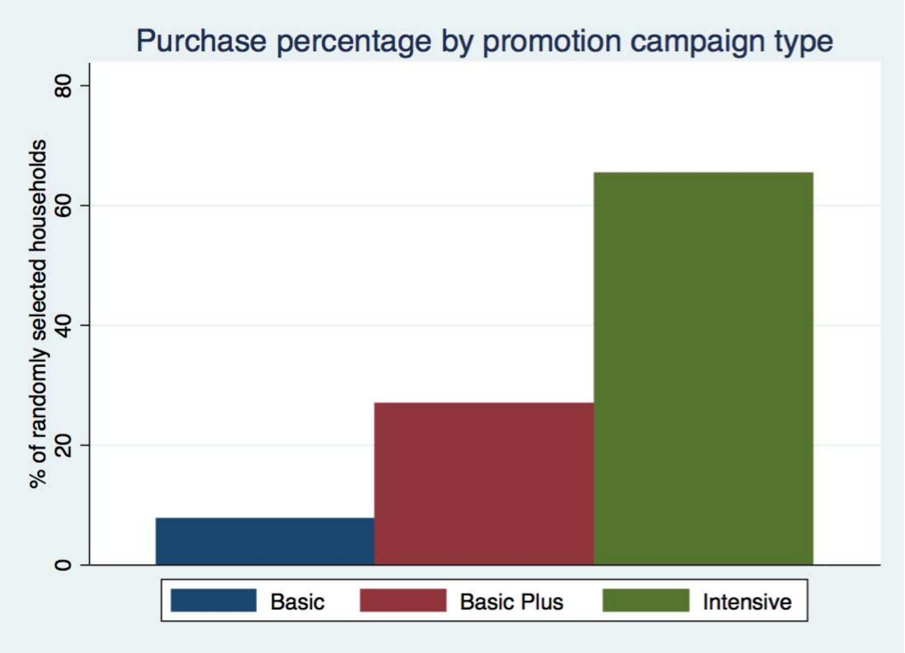

Figure 3: Purchases among randomly selected households grouped by intensity of promotion campaign

1.4.2. Product

When households were given a choice between the natural and forced draft biomass ICS (Pilots A and B), households that purchased ICS strictly preferred the more expensive forced draft stove. Also, nearly all households selected the electric ICS when given the choice between the latter and the natural draft stove (Pilots F and G). In villages where both the electric and natural draft stove were offered, 45% (14) of randomly selected households purchased the electric stove, only 3% (1) purchased the natural draft stove, and 3% (1) purchased both types. In contrast, when only offered the natural draft, households did make purchases: 3 such stoves were purchased in Pilot C (though none by survey households); 46% (6) of randomly selected households purchased in D; 8% (1) in E; and 14% (2) in H. These results suggest that households may be less interested in the natural draft stove when they observe it alongside other ICS. More critically, it shows that households have heterogenous preferences, and suggest that giving multiple stove choices may increase adoption.

Results from the pilots indicate that once households purchased an ICS, the stove was used regularly. In Pilots F and H, stove use was monitored every two weeks for one month after initial purchase, while in Pilot D use was recorded over eight visits for two months. All households reported using the purchased stove during all visits, with the exception of one household on the second monitoring visit and one household on the sixth monitoring visit. Enumerator observations for signs of use (e.g. presence of ash or food residue) confirmed these household reports. Even so, households also continued to use traditional stoves. On average, households reported approximately equal time of stove use for ICS and traditional stoves (Figure 4). This pattern is consistent regardless of the type of stove purchased, although electric stove buyers generally reported greater use.

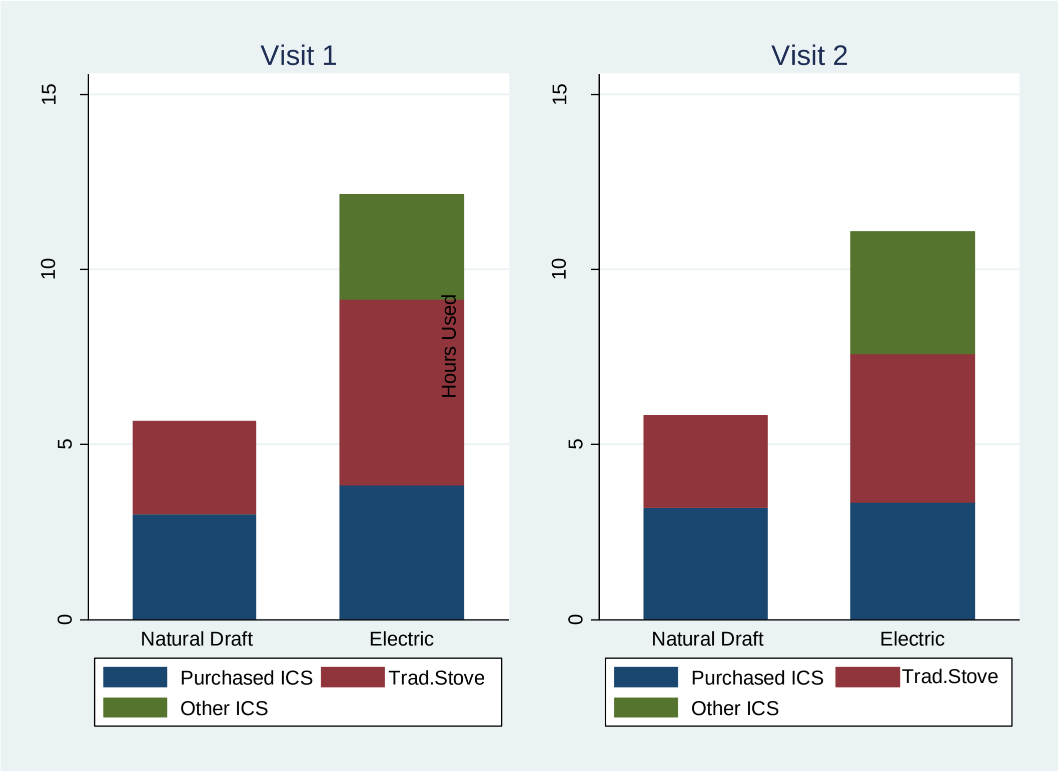

**Figure 4: Stove use in the past 24 hours checked at visit 1 (2 weeks after purchase) and visit 2 (one month after purchase)
(Visit 1 & 2, n=35; data from Pilots D - H)[6]**

1.4.3. Price

Responses under different payment schemes were also different (Figure 5). Where rebates alone were offered (Pilot A), no households purchased stoves. In pilots where the installment plan was offered alone (Pilots B and E), purchase rates were 8%

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[6] If households responded that both traditional and ICS were used the time was divided between the two stoves

(Pilot B) and 8% (Pilot E) to randomly selected households. Where rebates were added to the installment plan, adoption rates were 0% (Pilot C), 46% (Pilot D), 8% (Pilot E), and 38% (Pilot F) for adoption in randomly selected household. Finally, where the stove return option was instead added to the installment plan, the greatest sales rate was achieved: 60% (Pilot G) of randomly selected households made purchases, and no households chose to return their stove.

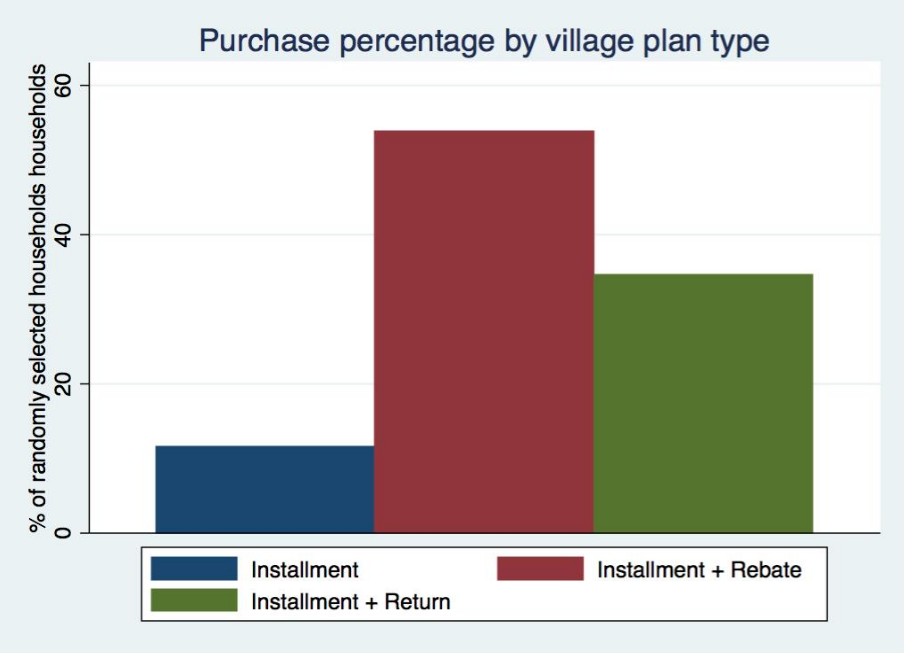

Figure 5: Purchases among randomly selected households grouped by payment plan in the village; (n=26 purchasers) across all pilots

Almost all households that had the opportunity to pay in installments took advantage of this option, with only 8% of survey households electing to pay full price (and 33% households overall), whereas the rest utilized the installment plan. In Uttarakhand, of the 15 randomly selected households that opted for the installment plan, installment payments were recovered from 87%. Installments were recovered from all households in UP.

We also note that the timing of the pilot programs relative to the harvest season may have translated into households having different amounts of cash on hand in different pilots. Some of the difference in sales between UP, on the one hand, and Odisha and Uttarakhand, on the other, may have been due to the fact that programs in the former location preceded the harvest, which is the major source of income for rural households in these pilot communities.

Although households responded in the survey that cost was the most negative attribute they perceived about the improved cookstoves, we observed that households preferred the more expensive forced draft stove over the biomass stove, suggesting that other factors such as modernity and novelty also play an important role in consumer interactions with these technologies. Nonetheless, the majority of these households still proved unwilling to purchase the more expensive stove they preferred.

1.4.4. Place

Consistent with the challenges we faced in procuring stoves, households told us that ICS technologies were not locally available in or near these villages. In supplying stoves to these communities, we frequently experienced significant delays in procurement and transport of several weeks to months. Routes to some villages in Uttarkhand in particular were inaccessible to vehicles of any kind and it was necessary to carry stoves to households. ICS adopters also appeared satisfied with their purchases; no households sought to return stoves after purchase. Nonetheless, 31% of households in pilots featuring the electric ICS listed stove maintenance as one of their main concerns about ICS purchase, compared to very few households expressing this concern in the biomass-stove only pilots. Given the lack of a realistic warranty scheme, maintenance concerns were reported to our NGO partners, who in turn organized the return of non-functional ICS to the retail partners and bore the coordination costs for repairs.

We are unable to separate the role of specific NGO characteristics from contextual variables across states, because partner organization is perfectly correlated with state. Despite greater remoteness and other supply chain problem in the Orissa and Uttarakhand sites, ICS sales were higher in these regions. As discussed in the next section, we attribute this to two interrelated place-based features of UP: the socio-political climate and the rootedness of the community-based organizations with whom we partnered. Three pilots have markedly higher sales among randomly selected households: G (Uttarakhand), in which 60% purchased a stove, and D (Odisha), with 46%, and F (Uttarakhand), with 38%.

1.5. How promotion, product, price and place attributes influence ICS adoption

We conducted eight ICS promotion pilots across three states in India to both (a) highlight some of the challenges related to ICS promotion, and (b) design a behavior change communication strategy. Following the social marketing mix of the 4 Ps (promotion, product, price and place), our pilots tested various levels and designs based around:

- Behavior change communication strategies for ICS promotion and sales team composition;
- Stove type;
- Stove payment plans, rebate incentives, and risk-free trials; and
- Geographical context, access, and local institutional environments

Overall, approximately 18% of a randomly selected group of households (26 out of 146 households) purchased an ICS at the full retail price, although the most successful pilot (G) had an adoption rate reaching 60% (Figure 3). While our small *n* design limits any definitive endorsements, we believe the pilots offer several lessons relevant to ICS promotion efforts.

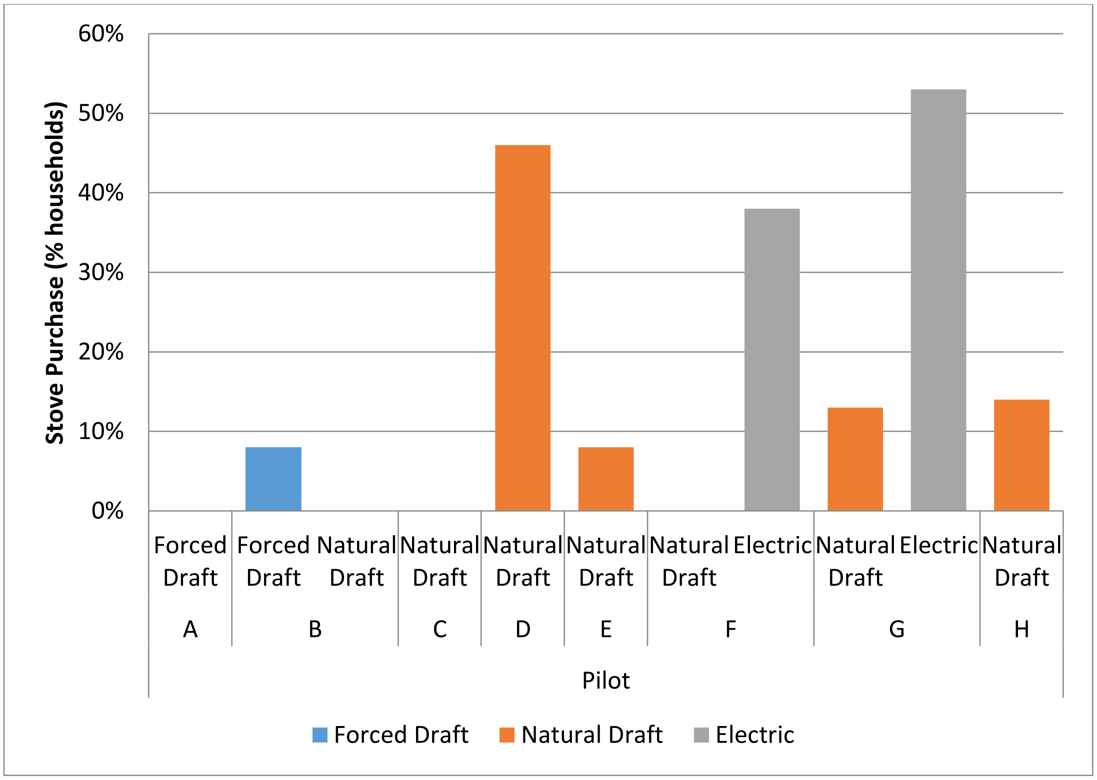

Figure 6: Stove purchase by randomly selected households[7]

1.5.1. Promotion

Much has already been written about the role of promotion for behavior change (e.g., Pattanayak et al. 2009; Shell Foundation, 2013; Thurber et al. 2014); we therefore limit our discussion to a few important observations. First, as indicated in previous surveys and through interviews in these specific pilot communities, potential beneficiaries have little knowledge of ICS benefits (Bhojvaid et al., 2014; Jeuland et al., 2014). Given this low baseline awareness, a combination of promotional efforts are likely to be crucial for increasing purchase and use of ICS. The promotional efforts in the pilots

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[7] One household in Pilot G that purchased an electric stove also purchased a natural draft stove.

focused on discussing the merits of ICS in terms of reduced wood use, cooking times, and health benefits because households identified these to be key features. In addition, significantly more households that purchased an ICS reported receiving one of our informational brochures and explanations, or witnessed an ICS demonstration (as part of the BCC campaign). Finally, our pilots show sales that increase with the intensity of the promotional campaign.

1.5.2. Product

Second, these small-scale promotion efforts reveal the importance of the ICS technology itself and the impact of presenting households with multiple stove options. Different combinations of three stove types were offered to households in the pilots. Sales of the electric stoves were greatest (45% in randomly selected households; 34% overall), followed by the natural draft biomass stove (9%; 4% and the forced draft biomass stove (4%; 4%). Somewhat unexpectedly, the electric stove clearly emerged as the most attractive option when it was offered to households (in pilots F and G), both in terms of interest and purchase. In fact, attempts were not made to market this product prior to the Uttarakhand pilots, mainly because we initially thought that the cost and lack of reliable electricity supply to rural Indian villages would preclude the use of this ICS. It is clear that potential beneficiaries thought differently, however, perhaps because they did receive electricity for roughly 20 hours per day on average. Therefore, future

ICS promotion efforts should consider the potential of electric stoves even where electrification rates are low and supplies are not fully reliable.

Impressions of the relative value of ICS compared to traditional cooking technologies varied considerably across sites. In Uttar Pradesh, households expressed limited interest in either ICS (these pilots involved the biomass stoves). These households' curiosity about the forced draft stove was greatest, but that stove was ultimately judged to be too expensive by most, even when these were given the opportunity to purchase it in installments. These households expressed concern about the time required to chop wood into small pieces for this stove. In addition, households observing demonstrations of this stove generally responded negatively to the natural draft stove, which was deemed to be an inferior technology by comparison. Interestingly, when the natural draft was the only stove offered (Pilots C, D, E, G), households did express interest in it, particularly in Odisha, where the sales team that was employed had the most prior experience marketing it. The effects of product comparisons on consumer choice have been the subject of extensive prior research in the field of marketing (Heath & Chatterjee, 1995; Choplin & Hummel, 2005).

Impressions of ICS also varied across households within specific pilot villages, variation that highlights the importance of acknowledging heterogeneity in consumer preferences (Jeuland et al., 2013). Households that value the time savings from an ICS were much more likely to adopt than households who valued smoke reduction. Also, adopters generally had higher asset ownership (cellphones), which may indicate that their budget constraints are somewhat looser than non-purchasers.

We found that all households whose use was monitored during collection of installment payments (admittedly a short time horizon) continued to use the stove throughout this period of follow-up. Even so, none of these households ever completely stopped using their traditional stoves. Households therefore appear to see advantages in having multiple stoves, either because they allow for more efficient cooking or because some are better tailored to specific cooking needs. This could be due to household preference for cooking bread on the traditional stove, the need to cook multiple dishes simultaneously, or as back-up in the event of electricity of fuelwood supply problems. Significant challenges remain if the goal is to induce a complete switch to ICS technologies, and future studies should include long-term follow up to monitor sustained use.

1.5.3. Price

Cost was clearly not the only factor influencing household purchase decisions: when given the choice between a more expensive forced draft or less expensive natural draft stoves, households strictly preferred the more expensive (but more novel) forced draft stove. The pilots also provide evidence that liquidity constraints are a significant barrier to adoption, and that installment payment schemes may help overcome it. This finding is consistent with recent evidence from Uganda that offering a lower risk, rentto-own experience leads to higher initial adoption rates (Beltramo et al., 2015). The majority of households reported that cost was the single most important negative attribute of the ICS options, and the varying degree to which households had cash on hand (perhaps related to the timing of the pilots relative to the harvest season) may have played a role in their adoption decisions. Only 8% of the survey households that purchased ICS in the pilot programs in installments paid the full price upfront, with all others opting for the installment plan. In the only village where no installment plan was offered, no households purchased an ICS. We offered rebates to incentivize ICS use, and the resulting positive health and environmental externalities. By comparing sales in Pilot D and E, we see that offering rebates seems to promote demand. For both the installment and rebate results, we caution that there were likely other factors contributing to the sales differential.

1.5.4. Place

We experienced a variety of challenges in obtaining stoves for dissemination to rural areas that reveal real gaps in the supply chain for such technologies. The lack of existing ICS markets and supply networks outside of large urban centers in India implies that any scaled-up stove dissemination programs targeted to rural households will face major obstacles. The lack of ICS distribution networks also presents problems for stove maintenance, since finding retailers to honor manufacturer warranties or facilitate stove repairs will be difficult. Proper maintenance of ICS is crucial for delivering benefits, but without support from a local supply chain it may be difficult for households to maintain stoves, particularly electric ones. To a large extent, there was an enthusiasm gap in Pilots A-C (compared to the other 5 pilots), potentially because of a variety of socio-political and cultural factors in the Indo-Gangetic plains of UP that make them different from communities in the Uttarakhand mountains and coastal Orissa.

To some extent the capacity of implementing NGOs helped us overcome some of the formidable place-based barriers. Given low baseline awareness of ICS and lack of a local supply chain, it was crucial for local NGOs to have a strong grassroots presence that engendered trust. For example, the NGO in UP was primarily a research organization, without a substantive community presence and little or no experience in social marketing. The opposite was true in Orissa and Uttarakhand, where NGOs had long been working intimately with communities in their respective areas. We attribute much of the greater success in these villages to the role played by these micro-institutions. Critically, these institutions provided capable management of local field logistics and were also viewed by households as a trustworthy source of information.

1.6. Conclusion

Use of biomass fuels impacts household health, local forests, and global climate. Despite the potential of ICS to reduce these adverse environment and health impacts, their adoption and use remains low. Social marketing – with its focus on the marketing mix of *promotion*, *product*, *price*, and *place* - offers a potentially useful way to understand household behaviors and design campaigns to address biomass fuel use. We report on a series of pilots across three Indian states where we varied this marketing mix. We find ICS sales ranging from 0 to 60%. Behavior change promotion that combined door-to-door personalized demonstrations with information pamphlets was effective. When given a choice amongst products, households strongly preferred an electric stove over improved biomass-burning options. Time savings emerged as particularly critical: ICS purchasers spent significantly more time gathering traditional fuels than non-purchasers, and adopters considered reduced cooking time most valuable among different stove attributes. Households clearly identified price as a significant barrier to adoption, while provision of discounts or payments in installment payments boosted demand. Place based factors such as remoteness and NGO operations significantly affected the ability to supply and convince households to buy and use ICS. Collectively, these pilots point to the importance of continued and extensive testing of messages, pricing models, and responses to different stove types prior to scale-up.

2. Biogas stoves reduce firewood use, household air pollution, and hospital visits in Odisha, India

2.1 Introduction

Forty percent of the global population relies on solid fuel such as wood and dung for cooking (IEA 2012). Inefficient combustion of solid fuel in household stoves results in very high emissions of particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and short lived climate forcers (Ramanathan and Carmichael 2008). In homes, these high pollutant levels combined with poor or no ventilation in cooking areas result in high exposure. It is estimated that household air pollution (HAP) represents the fourth overall global risk factor to health, responsible for 4.3 million deaths in 2012, much of which is concentrated in south Asia (Forouzanfar et al. 2015; Lim et al. 2012; Smith et al. 2014). Furthermore, traditional cooking forces households to spend more time and effort collecting fuel (Pattanayak et al., 2004); this deforestation in turn degrades local forests (Bailis et al. 2015).

Exposure to high levels of particulate air pollution has long known to be associated with many adverse human health consequences (Dockery et al. 1993). HAP exposure is strongly associated with acute lower respiratory infections (ALRI) in children (Dherani et al. 2008; Po et al. 2011) and significantly reduced lung function with increased rates of both chronic obstructive pulmonary disease (COPD) and chronic bronchitis in adults (Smith et al. 2014; Zhou et al. 2014). However, field evidence of associations between HAP exposure and pulmonary function (e.g., Rinne et al. 2006) is mixed, particularly in India (Hanna et al. 2012; Sukhsohale et al. 2013). These divergent findings could be due to use of multiple stoves and fuels in some settings, the fact that chronic health outcomes may take many years to be reversed, or because the reduction in exposure achieved is insufficient to improve health.

The vast majority of current evidence on PM exposure and cardiovascular disease (CVD) is derived from developed countries and links PM exposure with CVD, including myocardial infarction, stroke, and cardiovascular mortality (Brook et al. 2010). Growing evidence from developing countries supports an association between HAP exposure and elevated blood pressure (BP) (Alexander et al. 2014; Baumgartner et al. 2011) as well as biomarkers suggesting increased risk of CVD including systemic inflammation and oxidative stress (Dutta et al. 2012; Yamamoto et al. 2014).

Another class of pollutants released by household fuel combustion that is particularly harmful to health is the polycyclic aromatic hydrocarbons (PAHs), which are associated with increased risk of cancer, heart disease, as well as other reproductive, neurologic, and developmental health consequences (Kim et al. 2013; WHO and IARC 2010). Water soluble organic carbon (WSOC) is highly correlated to oxidative potential of particulate matter (Biswas et al. 2009; Zhang et al. 2008) and particulate water soluble organic nitrogen (WSON) increases potential mutagenicity (Tokiwa et al. 1981).

Although there is strong evidence for the adverse impact of HAP on health (Smith et al. 2014), the current state of knowledge in this area is not detailed and additional work in diverse field settings that includes the most appropriate exposure assessment and health measurements is critical (Rodes and Thornburg 2012). Health impacts may be different across developing countries because of very different background health, pollution levels and preventive behaviors.

Improved cookstoves (ICS) provide an opportunity to alleviate the negative impacts on both health and the environment by increasing combustion efficiency, requiring less fuel, and reducing cooking time. Published evidence also suggests that use of an improved stove (with a chimney) can reduce PAH exposure (Li et al. 2011; Riojas-Rodriguez et al. 2011; Torres-Dosal et al. 2008).

However, numerous challenges remain for widespread ICS adoption (Lewis and Pattanayak 2012) and for identifying clearly beneficial interventions (Jeuland and Pattanayak 2012). For example, stoves that reduce PM emissions in laboratory settings (Jetter et al. 2012) may not achieve the same results in the field (Roden et al. 2009), and in order to provide substantial health benefits the WHO calls for HAP $PM_{2.5}$ (particles with diameter less than 2.5 microns) levels to be reduced to the interim target 1 level of 35 $\mu g/m^3$ (Bruce et al. 2015; WHO 2006). Furthermore, household choices regarding ICS (e.g., correct or exclusive use) may undermine the potential benefits (Jeuland et al. 2015a; Pattanayak and Pfaff 2009). Additionally, reliance on observational data is problematic; for example, households with a history of respiratory illness may more likely purchase ICS, which further complicates inferences about health impacts (Mueller et al. 2011).

Most of the cleanest household energy fuels (liquid petroleum gas (LPG), electric, ethanol) (WHO 2014) are not readily available or affordable in regions with high HAP such as many parts of India. Biogas, a clean and renewable energy source, has potential for providing clean energy in rural regions where these other clean fuels are not widely available. Biogas refers to methane produced by the breakdown of organic matter from buffalo and cow dung. Biogas plants break down dung through anaerobic digestion and the released gas is piped to a gas-burning stove in the household where it is used for cooking (ISAT & GTZ 1999a). Thus, biogas stoves have many potential benefits, including: 1) reduction in fecal-borne and parasitic diseases through the removal of openly defecated animal dung; 2) reduction in household air pollution; 3) reduction in time spent and amount of firewood collected; 4) reduction in emission of methane, a potent climate forcer; 5) generation of high quality fertilizer (Bond and Templeton 2011; Chen et al. 2010; de Alwis 2002; ISAT & GTZ 1999b; Jian 2009). However, biogas plants can face operational and structural challenges, requiring regular maintenance (Surendra et al. 2014).

Despite the potential of this technology and its availability in India since the 1980s, relatively few field based studies have examined the effectiveness of biogas as an improved cooking fuel (Semple et al. 2014). A few evaluations have demonstrated reduced fuelwood consumption with biogas stove use (Bedi et al. 2015; Xiaohua and Jingfei 2005). However, very few studies have assessed PM levels in biogas households;

although there is suggestive evidence of large reductions of PM in comparison to solid fuel users (Wang et al. 2010). To our knowledge, only one study has directly measured the association between use of a biogas stove and health, finding unclear impacts using a sample of 62 households in Kenya (Dohoo et al. 2012).

Our aim was to challenge this knowledge gap by measuring the environment and health impacts of biogas and LPG in Odisha, India. We tested the hypothesis that families with ICS will reduce cooking time and firewood usage, lower the levels of household air pollution, and substantiate reduced illnesses of household members.

2.2 Methods

First, we describe the study location and sample composition. Second, we summarize the main forms of data collection (details on data collection and processing for analysis are reported in Appendix A). Finally, we summarize the primary strategy for analyzing these data.

2.1.1 Study Location and Sample

We conducted our study in Odisha - one of India's poorest states, in which more than 85% of households rely on solid fuels as their primary cooking fuel (Census of India 2011b). The study was approved by the Institutional Review Boards at Duke University and the Asian Institute of Public Health, Bhubaneswar, India. Our sample size comprised 105 rural households (46 in Jajpur district; 59 in Angul district) that had been previously surveyed in December 2011-January 2012. Whenever possible, the interview was conducted directly with the head of the household with input from the primary cook.

We stratified the sample by the presence of "major industrial areas/zones" (as identified by the Odisha State Pollution Control Board) at the administrative block (sub-district unit) level in order to examine the impact of outdoor air pollution.[1] Three villages were located in these industrial regions (1 in Jajpur; 2 in Angul); 6 villages were non-industrial (3 per district) (Figure 14). The Odisha Renewable Energy Development Agency (OREDA) previously had installed household biogas plants in this region between Feburary 2008 and December 2010. To ensure that our sample contained households who received biogas plants, the villages with the greatest number of biogas plants installed by OREDA were selected to ensure a sufficient sample of biogas users.

The sample was deliberately designed to include households with different types of ICS (including functional and non-functional biogas plants) and traditional stoves. Within each village, approximately twelve households were selected by counting every fifth house starting in the village center until desired categories of stove ownership were satisfied: 6 households with a biogas plant (3 with a working plant, 3 with a currently dysfunctional plant), 3 households with another type of ICS (LPG or electric), and 3 households with only a traditional mud stove.

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[1] In Jajpur, the industrial zone Chandikhol/Barchana contains a stone crushing and a coke oven plant. In Angul, the Talcher industrial zone includes a thermal power plant (running on 7,000 tons coal per day), an ash pond that feeds into a river, and coal washeries (OSPCB 2011).

Survey. Households were surveyed to collect data on socioeconomic characteristics, time spent gathering firewood, stove and fuel use, disease incidence, duration and costs of hospitalization because of last episode of cold/cough (including user feeds, medicines, transportation, lodging, meals, and other expenses).

Fuel use. First, we weighed the amount of fuel households anticipated using for the next 24 hours, including wood, twigs, dung cakes and crop residue. Second, we weighed the amount of fuel remaining 24 hours later. The difference between the two weights is the fuel consumed (kilograms) over the 24 hour monitoring period.

$PM_{2.5}$. We measured $PM_{2.5}$ in three ways: first, in all households, we suspended filters near the stove for 24 hours. Personal Exposure Monitors (PEMs; BGI Incorporated, Waltham, MA) with 37 mm 2.0 μm pore size Teflon filters (Pall Corporation, Port Washington, NY) were used for 24 hours in all households to measure household air concentrations of fine particles less than 2.5 μm in diameter. These units were suspended two horizontal meters from the stove, towards the doorway out of the kitchen area (when applicable), and 1.5 vertical meters above the ground in the breathing zone. In households that cooked with more than one stove, the PEM was hung between the stoves.

Second, for a subset of households, we measured personal exposure directly using a portable device that was carried by the cook (MicroPEM v3.2, RTI International).

Third, we obtained one 24 measurement of outdoor $PM_{2.5}$ in each village. Additional details of the air pollution and health measurements are provided in Appendix A.

Other pollution. Household, personal, and outdoor Teflo filter samples were analyzed for 35 individual PAHs and the total PAH concentration for each filter sample (See Supporting Information for Method Details). Household, personal, and outdoor filter samples were also analyzed for water soluble organic carbon (WSOC) and nitrogen (WSON) concentrations.

Health. Blood pressure was measured using a manual mercury manometer for the primary and/or secondary cook. Hypertension was defined as systolic BP over 140 mmHg or diastolic BP over 90. We evaluated respiratory health using spirometry, a non-invasive physiological test of lung function that can be used to assess airway obstruction and chronic obstructive pulmonary disease (Smith-Sivertsen et al. 2009). Spirometry was assessed on the primary cook of each household or a secondary cook when possible if the primary cook was unavailable or refused. Height (centimeters) and weight (kilograms) were monitored and recorded for the same individuals.

2.1.2 Data Analysis

In order to better assess beneficial effects of ICS use, we define our ICS treatment as household use of any improved stove (biogas, LPG or electric) during the 24 hour monitoring period rather than stove ownership. First, we conducted chi-squared and t-tests to analyze for statistically significant differences in characteristics of households who do and do not use ICS. Next, as described below, we used multivariate regression analysis to examine associations between several outcomes and ICS use. All statistical analyses were performed in STATA 12 (Stata Corporation, College Station, TX, USA).

We estimate the following regression of each outcome (Y) on ICS, while controlling for covariates such as years of primary cook education, monthly household expenditure, household size (number of people in home), use of electricity for lighting, and outdoor PM pollution:

$$Y = \beta_0 + \beta_1 hh\, covar. + \varepsilon$$

We used OLS regression with robust standard errors for all models. Where measurements were available for both primary and secondary cooks in a household (e.g., health), both were used.

Fuelwood-ICS association. We estimated the association between ICS and fuelwood consumption in kilograms.

Pollution-ICS association. $PM_{2.5}$, PAH, WSOC and WSON levels were log transformed to improve data normality. First, we modeled the association between ICS and $PM_{2.5}$ concentration. PM values were trimmed at the 99% level, and the most extreme outlier (2,963 μg/m^3) was re-coded with the next highest value, 1,207 μg/m^3.

Second, we modeled the association between ICS and seven priority PAHs, identified by the USEPA as probable human carcinogens: chrysene, benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, dibenzo[a,h]anthracene and indeno(1,2,3-c,d)pyrene.

Third, we analyzed personal and household exposure for Spearman's and Kendall's correlations, and tested for equality with the Wilcoxon rank-sum test.

Health-ICS association. We analyzed the association between ICS and various health measures. These included 1) systolic and diastolic blood pressure; and 2) respiratory indices by spirometry for the forced expiratory volume 1 (FEV1), or the amount (in liters) of air expelled in the first one second of exhalation and forced vital capacity (FVC), the total amount of air expelled in liters. Normalized for sex and BMI, higher FEV1 and FVC values in general indicate better lung function. There is currently no reliable reference data for ethnic Indian populations (Quanjer et al. 2012); therefore, a reference population from Thailand (Dejsomritrutai et al. 2000) was used to calculate the predicted values based on participant's age, sex, height and weight. We also modeled associations with: 3) a dummy variable based upon whether the cook had had a respiratory complication (i.e., cold or cough) in the preceding month, and 4) the number of days any household members spent in the hospital due to the previous acute respiratory illness (ARI) episode. Odds ratios for hypertension, and chi squared tests for normal FEV1 percent predicted (>80) and normal FEV/FVC (>72) in ICS owners were calculated. FEV1 percent predicted is calculated as the actual FEV1 divided by the predicted FEV.

Only one cook reported use of tobacco, and was dropped from the analysis. All analyses were evaluated separately for all cooks, cooks <35 years old, and cooks ≥35 years old (there was a natural break in cook age at 35).

2.3 Results

First, we describe household characteristics of improved stove owners. Next, we present associations between biogas or other ICS use and (1) firewood consumption, (2) household air pollution, (3) personal air pollution, and (4) health.

2.3.1 Cohort Characteristics

All but two of the 105 households owned a traditional stove and many used it during the sampling period (68%). Many households (55%) owned at least one ICS (32% biogas, 30% LPG, 11% electric), with 15% owning multiple. However, only 34% of these households used an ICS during the monitoring period including: 24% biogas, 11% LPG, 1% electric (one household used two stoves). Households cooked an average of 3.3 meals per day.

Households that exclusively use traditional stoves are not significantly different from ICS households if we compare societal caste (overall only 15% are in the general caste), household headed by females (13%), household size (5.4 people), malaria infection (1 per household in the last three years), number of rooms in the house (4.4), recent receipt of a loan (one third of households), or electricity use for lighting (over 90% of households) (Table 5). However, ICS users were different from exclusive traditional stove users in important respects. Specifically, ICS users had a higher education level (e.g., household heads and primary cooks have about 3 more years of schooling) and are of higher socioeconomic status (e.g., higher income and private toilets). Thus, we controlled for education and expenditure in the impact analyses.

Table 5. Descriptive statistics of household characteristics for (a) full sample, (b) households that only use traditional stoves, (c) households that use any improved stove. Reported p-values are from two-sided t-tests for differences in means between (b) and (c) for continuous variables, or Pearson's chi squared tests for categorical variables (* p<0.01, ** p<0.05, * p<0.1).**

Household Characteristic	(a) Full Sample		(b) Use Only Traditional Stove		(c) Use Improved Cookstove		p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs	Mean (s.d.)	Obs	
General caste (ineligible for caste-based government assistance)	15% (0.36)	105	13% (0.34)	68	19% (0.4)	37	0.44
Female head of HH	13% (0.34)	105	16% (0.37)	68	8% (0.28)	37	0.25
Primary cook education (yrs)	8.5 (3.9)	92	7.5 (3.7)	57	10 (3.8)	35	<0.01***
Head of household education (yrs)	8 (3.8)	87	6.8 (3.5)	54	9.9 (3.5)	33	<0.01***
Household size (# ppl)	5.4 (2)	105	5.5 (1.9)	68	5.4 (2.1)	37	0.77
Animal fodder is cooked on stove	22% (0.42)	105	32% (0.47)	68	3% (0.16)	37	<0.01***
Trash is burned near household	42% (0.5)	105	44% (0.5)	68	38% (0.49)	37	0.53
Stove is vented	41% (0.49)	105	31% (0.47)	68	59% (0.5)	37	<0.01***
Stove is located outdoors	57% (0.5)	105	69% (0.47)	68	35% (0.48)	37	<0.01***
Fuel collection time (hrs/day)	2.4 (3.4)	105	2.9 (3.8)	68	1.4 (1.9)	37	0.03**
# stoves owned by HH	2.2 (1.1)	105	1.9 (0.9)	68	2.8 (1.1)	37	<0.01***
# people in household with malaria in past 3 yrs	0.9 (1.5)	105	1.1 (1.6)	68	0.7 (1.3)	37	0.23
Household uses toilet	46% (0.5)	105	29% (0.46)	68	76% (0.43)	37	<0.01***
# rooms	4.4 (1.9)	105	4.2 (1.7)	68	4.7 (2.3)	37	0.15
Monthly expenditure (log)	8.4 (0.7)	105	8.3 (0.6)	68	8.6 (0.8)	37	0.01**
HH has access to loans	33% (0.47)	105	26% (0.44)	68	46% (0.51)	37	0.04**
Loan was taken in past year	51% (0.5)	105	49% (0.5)	68	57% (0.5)	37	0.42
Electricity is main source of light	94% (0.23)	105	93% (0.26)	68	97% (0.16)	37	0.33
Payment for most recent ARI episode treatment (Rs.)	694.2 (3044.8)	105	953.9 (3749.4)	68	216.8 (506.5)	37	0.09

2.3.2 Fuelwood collection and consumption

ICS households saved substantial time in firewood collection. ICS users spent 1.4 hours per day on firewood collection compared to 2.9 hours per day by traditional stove users (Table 5). Compared to traditional stove users (5.2 kg), ICS use was associated with a substantially reduced fuelwood consumption of 0.5 kg (Table 6; Figure 7), with LPG or electric stove use associated with the greatest reduction (4.1 kg) and biogas with reduction of 3.8kg. These associations were supported by regression analysis (Table 8; Appendix A Table 16).

Table 6. Descriptive statistics of outcomes for (a) full sample, (b) households that only use traditional stoves, (c) households that use any improved stove. Reported p-values are from two-sided t-tests for differences in means between (b) and (c) for continuous variables, or Pearson's chi squared tests for categorical variables (* p<0.01, ** p<0.05, * p<0.1).**

Outcome Variable	(a) Full Sample		(b) Use Only Traditional Stove		(c) Use Improved Cookstove		p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs	Mean (s.d.)	Obs	
Environmental Outcomes							
Firewood consumed (kg)	3.5 (4.3)	105	5.2 (4.3)	68	0.5 (2.1)	37	<0.01***
Household $PM_{2.5}$ ($\mu g/m^3$)	299.1 (322.9)	99	409.9 (351.5)	62	113.9 (139.1)	37	<0.01***,[2]
Household total 35 PAH (ng/m^3)	689.0 (1109.8)	87	953.3 (1290.7)	56	211.6 (332.7)	31	<0.01***,[2]
Chrysene (ng/m^3)	44.5 (69.9)	87	62.1 (80.4)	56	12.5 (22.7)	31	<0.01***,[2]
Benz(a)anthracene (ng/m^3)	78.1 (110.6)	87	106.9 (123)	56	26 (54.6)	31	<0.01***,[2]
Benzo(a)pyrene (ng/m^3)	29.5 (42.6)	87	39.4 (48)	56	11.7 (21.7)	31	<0.01***,[2]
Benzo(b)fluoranthene (ng/m^3)	60 (86.4)	87	81.9 (96.2)	56	20.3 (43.9)	31	<0.01***,[2]
Dibenzo(a,h)anthracene (ng/m^3)	6 (10)	87	7.8 (11.5)	56	2.6 (5.4)	31	<0.01***,[2]
Idenopyrene (ng/m^3)	35.9 (52.8)	87	48.1 (58.8)	56	13.8 (29.8)	31	<0.01***,[2]
Personal $PM_{2.5}$ ($\mu g/m^3$)	124.3 (81.1)	16	114.5 (89.3)	11	79.9 (33.4)	5	0.30,[2]
Personal total 35 PAH (ng/m^3)	26.2 (21.6)	14	29.4 (23.5)	11	14.4 (3.4)	3	0.25,[2]
Water soluble organic carbon ($\mu g/m^3$)	104.7 (87.5)	65	121.2 (90.5)	50	50.0 (46.4)	15	<0.01***,[2]
Water soluble organic nitrogen ($\mu g/m^3$)	13.3 (11.3)	85	14.8 (11.4)	56	10.2 (10.5)	29	0.01**,[2]
Health Outcomes							
Height (cm)	150.6 (7.3)	115	149.4 (6.8)	76	152.8 (7.8)	39	0.01**
Weight (kg)	49.8 (11.1)	115	47.5 (9.9)	76	54.4 (11.9)	39	<0.01***
BMI	21.8 (3.7)	115	21.2 (3.5)	76	23.1 (3.8)	39	<0.01***
Pulse rate	86.1 (10.2)	113	87 (10.9)	74	84.3 (8.7)	39	0.17
Systolic blood pressure (mmHg)	123.3 (17.5)	113	123.6 (17)	74	122.8 (18.6)	39	0.82
Diastolic blood pressure (mmHg)	78.6 (10.2)	113	79 (10.2)	74	77.7 (10.3)	39	0.51
Hypertension	14% (0.35)	113	14% (0.34)	74	15% (0.37)	39	0.78
FEV1 % Predicted	106.8% (18.1)	32	113.3% (19)	19	97.4% (18.0)	13	0.01**
Normal FEV/FVC (>72)	100% (0)	32	100% (0)	19	100% (0)	13	-
Normal FEV1 (>80)	93.8% (24.5)	32	100% (0)	19	84.6% (38.6)	13	0.08
Cold/cough in past month	41% (0.49)	114	37% (0.49)	75	49% (0.51)	39	0.24
# days in hospital for last ARI episode	1.8 (3.6)	209	2.2 (4.3)	136	1 (1.4)	73	0.02**

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[2] Data are lognormally distributed, so significance is reported for t-tests using log-transformed data

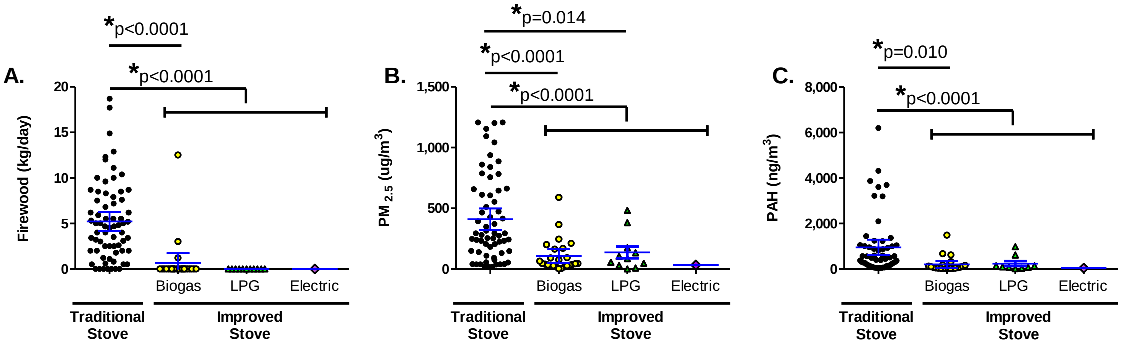

Figure 7. (a) Average firewood consumption by stove type (error bars shown at the 95% confidence interval); (b) Average household $PM_{2.5}$ concentrations by stove type (error bars shown at the 95% confidence interval) with WHO interim standard of 35 μg/m^3 shown.; (c) Average PAH concentrations by stove type (error bars shown at the 95% confidence interval).

2.3.3 ICS and Ambient air pollution

Household air sampling allowed us to analyze filters for $PM_{2.5}$ (99 filters) and PAH (87 filters). $PM_{2.5}$ level among ICS users was 114 μg/m^3 on average compared to 410 μg/m^3 among traditional stove users (p<0.01) (Fig.1, Table 6). This implies that ICS use is associated with a 72% reduction in $PM_{2.5}$; we confirm this significant finding with regression analyses (Table 8; Appendix A Table 17). Figure 7 clearly depicts the significantly lower levels of household $PM_{2.5}$ associated with biogas or LPG stoves use compared to traditional stoves. Additionally, we observed that ICS use was associated with lower levels of six high risk PAHs, total PAH and WSON (Fig.1, Table 6) and confirm this finding with regression analysis (Table 8; Appendix A Table 17). The highly significant association between the PAH and $PM_{2.5}$ levels suggests that measured particulate was derived from biomass combustion rather than dust.

To determine personal exposure level directly, we deployed personal monitors to a small subset of subjects. Resource constraints dictated that we could collect 16 personal $PM_{2.5}$ samples from primary cooks (11 traditional, 5 biogas). As shown by the accelerometer data, respondent compliance with wearing the monitor while awake ranged between 8% - 80% of the sampling period. Although household and personal $PM_{2.5}$ concentrations are positively correlated (Kendall's tau 0.17; Spearman's rho 0.23), the correlation was not statistically significant (p-value of 0.39 in both cases). Similarly, there was no significant correlation between the total PAH concentrations measured with the household and personal samplers for a single house (Kendall's tau 0.34, p-value 0.10; Spearman's rho 0.40, p-value 0.15). Given this small sample size, it is not surprising that we could not detect a statistically significant difference between the distribution of household and personal $PM_{2.5}$ or PAH measurements (Mann-Whitney test p-value 0.61 and 0.14, respectively). Real time peaks from a single personal sample were often dramatically higher than the reported averages (Appendix A Figure 15). All of this could imply that the household and personal measures are correlated but we are unable to detect that correlation in a small sample. The lack of correlation might explain why the signals on the differences between health outcomes of ICS users and non-users health impacts are diffuse (as discussed below).

We did not observe differences in measured outdoor ambient $PM_{2.5}$ concentrations (village-level, n=8) when comparing industrial and non-industrial regions, possibly because of a very small sample size. However, strikingly and as anticipated, measured outdoor $PM_{2.5}$ levels were much lower than household $PM_{2.5}$ concentrations.

To attempt to determine whether there was a relationship between stove use and outdoor environment, we stratified the population based on proximity to industry. We find a complex relationship between ambient (industry proximity as a proxy) and household air quality, and the moderating effect of ICS use. While there was no overall relationship between household air pollution and industry proximity, we find that traditional cookstoves users in industrial areas have significantly higher levels of household air pollution when compared to similar users in non-industrial areas including household $PM_{2.5}$ (592 $\mu g/m^3$ *vs* 329 $\mu g/m^3$) and total PAH (1585 ng/m^3 *vs* 700 ng/m^3) (Table 7). Interestingly, we do not see correspondingly higher levels of air pollution for ICS users in these areas compared with ICS users in non-industrial zones. However, we find that ICS use in industrial-areas was associated with significantly reduced levels of $PM_{2.5}$, PAH, WSOC, and WSON compared to *traditional* stove users in both industrial and non-industrial regions (Table 7). While ICS appear to be effective across the board, they have the greatest impact on $PM_{2.5}$ reduction in industrial areas (Table 17).

Table 7. Pollution levels for (a) full sample, (b) households located in industrial area, (c) households not located in industrial areas. Mean and standard deviation are reported in non-log transformed units; t-tests were conducted on log-transformed data for all pollution variables. Reported p-values are from two-sided t-tests for differences in means between (b) and (c) (* $p<0.01$, ** $p<0.05$, * $p<0.1$).**

Air Pollution Variables	(a) Full Sample		(b) Industrial Area			(c) Non-Industrial Area			p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs		
Household $PM_{2.5}$ ($\mu g/m^3$)	299.1 (322.9)	99	405.9 (385.6)	30		252.6 (282.1)	69		0.31
Only traditional stove users	409.6 (350.5)	62	592.0 (365.9)	19	] ***	329.0 (315.1)	43	] ***	0.01**
Only ICS users	113.9 (139.1)	37	84.4 (103.3)	11		126.3 (151.8)	26		0.42
Personal $PM_{2.5}$ ($\mu g/m^3$)	124.3 (81.1)	16	62.4 (32.9)	4		145.0 (82.6)	12		0.21
Only traditional stove users	144.5 (89.3)	11	66.7 (38.9)	3	]	173.7 (86.0))	8	]	0.29
Only ICS users	79.9 (33.4)	5	49.6 (.)	1		87.5 (33.3)	4		--
Household total PAH (ng/m^3)	689.0 (1109.8)	87	987.3 (1347.8)	27		554.8 (967.3)	60		0.17
Only traditional stove users	953.3 (1290.7)	56	1585.2 (1481.0)	16	] ***	700.5 (1130.0)	40	] ***	<0.01***
Only ICS users	211.6 (332.7)	31	117.6 (169.9)	11		263.2 (389.5)	20		0.36
Personal total PAH (ng/m^3)	26.2 (21.6)	14	14.1 (2.1)	4		31.0 (24.1)	10		0.12
Only traditional stove users	29.4 (23.5)	11	14.5 (2.4)	3	]	35.0 (25.6)	8	]	0.12
Only ICS users	14.4 (3.4)	3	12.9 (.)	1		15.1 (4.4)	2		--
Outdoor ambient $PM_{2.5}$ ($\mu g/m^3$)	81.6 (51.7)	8	117.3 (74.6)	2		69.7 (44.1)	6		0.52
Water soluble organic carbon ($\mu g/m^3$)	104.7 (87.5)	65	132.2 (101.2)	19		93.4 (79.6)	46		0.18
Only traditional stove users	121.2 (90.5)	50	107.6 (84.1)	34	] ***	149.9 (99.3)	16	] ***	0.09
Only ICS users	50.0 (46.4)	15	53.1 (47.9)	12		37.7 (46.7)	3		0.34
Water soluble organic nitrogen ($\mu g/m^3$)	13.3 (11.3)	85	15.9 (13.1)	25		12.2 (10.4)	60		0.09
Only traditional stove users	14.8 (11.4)	56	19.6 (14.8)	16	] **	12.9 (9.3)	40	] *	0.05*
Only ICS users	10.2 (10.5)	29	9.3 (5.0)	9		10.7 (12.3)	20		0.62

2.3.4 ICS and Health

Health parameters were evaluated based on survey and objective measurements. There were some differences between cooks using ICS and cooks using traditional stoves. On average, ICS cooks were taller (152cm vs 149cm), heavier (54.4kg vs 47.5kg), and had higher body mass index (BMI) (23.1 vs 21.2). This suggests that differences between the two different types of cooks might be susceptible to confounding. Overall, there is no association between stove use and blood pressure, pulse rate, or diagnosis of hypertension (Table 6), and the odds ratio for risk of hypertension is not significant: 1.16 (0.39-3.48), p-value 0.79, 0.79 (0.23-2.72), p-value 0.71 after adjusting for age, BMI and sex.

However, regression analysis that controls for observable differences in primary cook education, household expenditure, outdoor air pollution levels (village level), household size, and electricity access reveals associations between cookstove use and both systolic and diastolic blood pressure (Table 8). We find in younger aged cooks (less than 35 years of age) ICS use is associated with lower diastolic blood pressure. Among older cooks (i.e., subjects greater than 35 years of age), we find a significant positive relationship between both measures of blood pressure (diastolic and systolic) and high $PM_{2.5}$ levels (i.e., greater than 35 $\mu g/m^3$). We also find this positive association was also seen between diastolic blood pressure and WSON.

Table 8. Association between key environmental variables (ICS use, household PM 2.5 concentration, a binary indicator high household $PM_{2.5}$, and total household PAH concentration) and health outcomes from regression models stratified by age of cook.[1]

Environmental Variables	Health Variables					
	(1) Systolic BP	(2) Diastolic BP	(3) FEV1[2]	(4) FVC[2]	(5) Cold	(6) Hospital
Use of any improved stove						
All ages	-1.21	-3.12	-0.15	-0.13	0.77	-1.85
	(0.79)	(0.18)	(0.34)	(0.39)	(0.18)	(0.08)
<35	-3.38	-6.78**	0.47*	0.68	1.57	-1.65**
	(0.54)	(0.05)	(0.08)	(0.10)	(0.21)	(0.03)
≥35	-1.44	-3.19	0.00	-0.09	2.07	-2.02
	(0.85)	(0.37)	(0.99)	(0.71)	(0.06)	(0.22)
Household $PM_{2.5}$ (log μg/m3)						
All ages	1.93	1.83	-0.02	-0.07	-0.00	1.05
	(0.53)	(0.25)	(0.94)	(0.77)	(1.00)	(0.08)
<35	0.65	0.26	-	-	-0.31	0.77
	(0.81)	(0.90)	-	-	(0.57)	(0.09)
≥35	4.36	4.41	-0.34	-0.16	-0.12	1.32
	(0.47)	(0.17)	(0.67)	(0.85)	(0.88)	(0.31)
High $PM_{2.5}$ (>35 μg/m3)						
All ages	7.06*	4.72*	-0.07	-0.12	-0.72	0.34
	(0.09)	(0.06)	(0.71)	(0.58)	(0.22)	(0.51)
<35	-1.82	-1.27	-	-	-1.65	1.76***
	(0.68)	(0.73)	-	-	(0.23)	(0.00)
≥35	15.02**	10.00***	-0.62	-0.69	-0.69	-0.89
	(0.01)	(0.00)	(0.13)	(0.13)	(0.38)	(0.23)
Household PAH (log μg/m3)						
All ages	2.19	1.45	-0.02	-0.03	0.15	0.72***
	(0.24)	(0.12)	(0.79)	(0.73)	(0.55)	(0.01)
<35	2.35	1.12	-	-	0.60	0.72
	(0.23)	(0.41)	-	-	(0.28)	(0.10)
≥35	0.18	0.96	0.05	0.06	0.09	0.80*
	(0.95)	(0.49)	(0.32)	(0.49)	(0.81)	(0.06)
Household WSON (log μg/m3)						
All ages	15.02*	9.22**	-0.36	-0.51	-0.75	2.22*
	(0.08)	(0.01)	(0.33)	(0.18)	(0.45)	(0.05)
<35	11.06	3.83	-	-	-0.71	1.93
	(0.32)	(0.51)	-	-	(0.73)	(0.28)
≥35	20.60*	13.39**	-0.87	-0.99	-1.48	2.46
	(0.10)	(0.01)	(0.22)	(0.13)	(0.29)	(0.18)

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[1] Columns 1-2 report blood pressure; columns 3-4 observed lung function; column 5 binary incidence of cold/cough; column 6 number of days household members spent in the hospital for the last episode of ARI. BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R^2 reported). Incidence of cold/cough was modeled with logit (pseudo-R^2 reported). All analyses include controls for primary cook education, household expenditure, outdoor air pollution levels (village level), household size, and use of electricity as main source of lighting. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). Full regression results are reported in Appendix A.

[2] Regressions for FEV1 and FVC for middle aged were underspecified in some models.

We measured lung function by spirometry, and obtained measurements of sufficient quality from 32 primary cooks. All subjects had normal FEV_1/FVC ratios and only two ICS cooks had reduced FEV_1. Compared to the ICS cooks, we observed an increased % predicted FEV_1 in the traditional cookstove group (Table 6; 113% vs 97%). Regression analysis did not detect associations between spirometry values and ICS use.

We also assessed self-reported incidence of respiratory symptoms: 14% reported wheezing (6% reported at the time of sampling), 10% report waking with tightness in their chest (10% at time of sampling), 22% report shortness of breath after exertion (17% at time of sampling), 10% report shortness of breath at times other than after exertion (7% at time of sampling), 41% report experiencing a respiratory complication (cold or cough) in the past month before sampling; and 14% report sneezing or rhinorrhea even when they do not have a cold. We also collected data on household expenditures associated with hospitalization for ARI, which was more costly (e.g., approximately 700 rupees greater for exclusive traditional stove users) (Table 5). While ICS use was not associated with a reduction in cold or cough in the last month, ICS use was associated with reduced number of reported days in the hospital for respiratory infection (1.0 day *vs* 2.2 days; Table 6). Logistical regression analysis reveal for subjects less than 35 years of age a negative association between ICS use and hospitalizations for ARI. This relationship is supported by regression results showing a positive association between hospitalization and three measures of household air quality - $PM_{2.5}$ level of greater than 35 $\mu g/m^3$, PAH and WSON (Appendix A Table 21, Table 22, Table 23).

2.4 Discussion

Traditional cooking practices in the developing world can be harmful to the local environment and health. In this study, we helped improve the understanding of health impacts of biogas and LPG by implementing a direct examination of the potential benefits of established programs to promote a particularly promising improved cookstove – biogas - in a specific region of rural India. We observed in a comparison of households in both industrial and non-industrial locales that use of ICS was associated with time savings, reduced firewood consumption, lower levels of household air pollution, and some measures of health benefits.

In this cohort, ICS use was associated with a 90% reduction in average daily fuelwood consumption (5.2kg/d *vs* 0.5kg/d). This observation on fuelwood reduction is consistent with evidence from Rwanda (Bedi et al. 2015) and India (Programme Evaluation Organisation 2002). These reductions in fuelwood consumption could have important implications for regional deforestation resultant from harvesting trees as a source of fuel. Furthermore, ICS adoption is associated with a 48% reduction (2.9hr/d *vs* 1.4hr/d) in time spent collecting biomass fuel, which equates to approximately ten hours saved per week. While time savings is often touted as an ICS benefit, it is rarely supported by field evidence. It is reasonable that the fuelwood and time savings over the past 24 hours are not proportional; more households burned wood during the 24 hour monitoring period than collected it.

ICS use in our cohort was associated with much lower level of household $PM_{2.5}$ in households with ICS (approximately 300 μg/m^3 lower) than in those with only traditional stoves. Despite this reduction in air pollution, the average $PM_{2.5}$ level in homes that use ICS remained 114 μg/m^3, which is approximately three times above recommendations from the WHO interim target of 35 μg/m^3 (2006);– indeed only 16 households were below the WHO target level. This finding is consistent with previous reports that found large $PM_{2.5}$ and PM_{10} reductions in ICS households, although levels were above the WHO standard (Hasanudin et al. 2011; Wang et al. 2010), probably due to stove stacking**.** A major concern to be addressed for household environments is whether adoption of currently available ICS reduces household $PM_{2.5}$ air pollution to a level that is adequately protective for cardiovascular and respiratory health.

Exposure assessment is further complicated by robustly elevated background levels of ambient air pollution in many developing regions of the world. We stratified our population into either industrial or non-industrial regions and found higher average $PM_{2.5}$ (for traditional stove users only) for households in villages near industrial areas. These observations suggest a complicated interaction between indoor and outdoor environments, moderated by ICS use. In this context, monitoring levels of individual exposures directly and specific for indoor and outdoor environments are both now feasible in the field and may provide important insights. While limited by our very small sample size of personal average exposures, we did observe extremely high peak exposures in $PM_{2.5}$ of unrecognized significance associated with traditional cookstoves (Figure 15). Overall, these findings suggest that ICS use was associated with reduced levels of household level $PM_{2.5}$, although differences in outdoor environment add a layer of complexity.

As previewed above, the composition of $PM_{2.5}$ (PAHs and water soluble organic carbon / nitrogen) can provide evidence regarding whether the source of measured HAP is from cooking rather than ambient dust, and can signal potential risks for impacting health. In this study, we found that using ICS was associated with a 25% reduction in total PAHs when compared to households with only traditional stoves (Figure 3) and lower household PAH levels for seven high-risk PAHs (Table 8). The potential health benefit from this level of reduced PAH exposure remains unknown. For example, while previous work supports that stove interventions can reduce ambient PAH levels, the post-intervention level of urinary PAH can remain extraordinarily high (over 8-fold higher than US smokers who smoke more than 20 cigarettes per day)(Li et al. 2011). In addition to PAHs, we show that ICS use was associated with reductions in both WSOC and WSON, which suggests a potential decrease in oxidative stress and toxicity. Together, these findings support that use of ICSs is associated with lower ambient levels of PAHs, WSOC, and WSON.

Given the observational nature of this study, there are potential important confounders that could influence observed outcomes. Differences in cohort characteristics are accounted for through multivariate regression analysis, although we are unable to account for all underlying factors that may have influenced adoption decisions or health outcomes (Mueller et al. 2011). However, ICS owners and users 'stack', i.e., they owned multiple stoves and use clean and dirty stoves simultaneously (Masera et al. 2000). For example, only two households with an ICS exclusively used an ICS in our cohort. The majority of our cohort continues to intermittently use a traditional stove (98%), and is therefore unlikely to reduce exposures to WHO-advocated levels according to recent estimates that households would need to use traditional stoves for less than one hour per week (Johnson and Chiang 2015). Furthermore, ICS users were 30% less likely to use animal fodder as a source of biomass and are more likely to cook indoors.

Despite these complications and despite the small size of our observational study, we do observe statistically significantly reductions in household air pollution associated with ICS use. This reduction might explain why we find some associations between ICS and health outcomes. First, we see negative associations between ICS use and hospitalization (days and money spent) for respiratory infections. Second, the regression analysis shows the relationship between hospitalization and ICS use is particularly significant for subjects less than 35 years of age and for specific measures of air quality – e.g., high levels of $PM_{2.5}$ and PAH. Third, beyond respiratory illness, ICS use was associated with reduced systemic blood pressure in our cohort, similar to reports from China (Baumgartner et al. 2011) and Guatemala (McCracken et al. 2007).

Specifically, we observed that increased systolic and diastolic blood pressure is associated with (i) high $PM_{2.5}$ exposure, and (ii) elevated levels of water soluble organic nitrogen, especially in older (> 35 years) cooks. We speculate that the systemic effect is observed in older cooks compared to younger cooks because of potentially stiffer aged arteries and reduced ability to compensate for environmental stress. We also note that a single measurement of blood pressure was taken; repeated measurements may have resulted in differences such as lower BP (Schulze et al. 2000).

Nonetheless, while we observe improvements in some health measurements, they were modest in magnitude, and not all investigated outcomes showed improvement. For example, we did not observe consistent associations between either ICS use or exposure levels and acute measurements of lung function as measured by spirometry. There were several possible explanations for lack of effects, including the sensitivity and specificity of the spirometry measures, small sample size, time course considerations, the nature of the experimental design, and the shape of the dose-response curve. For example, decline in lung function requires prolonged reduction in exposure to impact disease progression (Rylance et al. 2013), whereas our cohort only adopted ICS in recent years, and we did not collect data on the number of years ICS were used. However, we know that plants were installed between February 2008 and December 2010, meaning that households used them for between 1 to at most 3 years before our survey in December 2011. This time course concern may apply to many health measurements, implying that future studies should span a longer period of time. Additionally, the field needs careful analysis of which markers of HAP-induced health problems are the most specific to HAP and the most sensitive to changes in exposure. Finally, it remains unclear if our cohort witnessed sufficient reductions in exposure to produce specific improvements in health. It has been argued that that the greatest reduction in health risk is expected to occur at low exposure levels (Smith et al. 2014), and it is likely that different health parameters will be improved at different levels of exposure. Nonetheless, our study demonstrates the feasibility of field measurements of environmental and health outcomes and supports findings that ICS use is associated with reductions in air pollution, respiratory infections and blood pressure.

2.5 Conclusion

Our findings from this direct observational study in rural India show that biogas and other improved stove users save time, consume less firewood, reduce household air pollution (measured by $PM_{2.5}$ or PAH), and have improved health (visit hospitals less frequently and improve systemic blood pressure). Prospective intervention studies with biogas that include the most appropriate measurements of socioeconomic, environmental, and health benefits that validate observations from this observational study could help inform future adoption interventions and impact global health. In addition, we recommend longer-term monitoring of health benefits, as well as testing a wider range of objective health outcomes. The results from this study suggest that further investment in biogas programs could have broad positive impacts for rural households.

3. Improved cookstove use reduces air pollution and wood consumption in the Himalaya

3.1 Introduction

The use of traditional stoves and fuels has gained attention as a significant risk for the environment and health. Biomass fuels are still the main fuels used for cooking by 40% of the global population and 75% of rural Indi an households (Bonjour et al. 2013; Census of India 2011a). Inefficient combustion of biomass fuels, kerosene, and coal in households releases harmful concentrations of particles and gases, called household air pollution (WHO 2014). Household air pollution is estimated to cause 3.5 to 4 million premature deaths annually, and is the leading cause of death in South Asia according to the Global Burden of Disease comparative risk assessment for 2010 (Gordon et al. 2014; Lim et al. 2012).

Much of this health burden is attributed to particulate matter ($PM_{2.5}$, or particles of aerodynamic diameter less than 2.5 μm) that can travel deep into the lungs and is associated with significant cardiovascular and respiratory risks (Gordon et al. 2014). Therefore, $PM_{2.5}$ exposure measurements are often considered a proxy for exposure to household air pollution (Smith et al. 2014).

In addition to health burdens, using inefficient stoves places time burdens on households to gather and prepare fuels, as well as cook; these are generally borne by women and children (Lewis et al. 2015). Household biomass use also has local and global environmental repercussions: it contributes to deforestation and degradation

(Bailis et al. 2015; Jagger and Shively 2014), and household air pollution emissions, particularly black carbon, exacerbate regional climate change (Ramanathan and Carmichael 2008). This is especially concerning in the Himalayan region, where black carbon is a major contributor (along with CO_2) to glacial melting, especially at high elevations (Xu et al. 2015). Black carbon concentrations are noticeably higher in northern India in December and January, likely due to additional use of stoves for heating (Praveen et al. 2012).

In reaction to these diverse and significant negative impacts, a growing effort has led to the development of many new improved biomass cookstoves (ICS) with advanced combustion efficiency (GACC 2011; The World Bank and ICCI 2013). Other more established clean stove options such as liquid petroleum gas (LPG) remain too expensive for widespread uptake by poor rural households, and often lack a strong sales and maintenance supply chain. Electric stoves are a growing clean alternative as electricity access increases, although electricity price and unreliability are steep barriers to regular use. Therefore, when possible, households often use clean stoves like electric and LPG models for a portion of their cooking and also continue to use traditional stoves – a phenomenon termed stove "stacking" (Masera et al. 2000).

Clean cooking technologies are suggested as a means to reduce energy poverty (Pachauri and Spreng 2011), and global policies are shifting in reflection of the risks from air pollution and the importance of clean energy access. For example, the World

Health Assembly issued a landmark resolution on the health impacts of air pollution (Sixty-Eigth World Health Assembly 2015) and the United Nations has included access to affordable, reliable, sustainable and modern energy for all as a Sustainable Development Goal (United Nations).

Although support for improved cookstove dissemination is growing, previous attempts at empirical measurements of air pollution, fuel use and health impacts suggest a complicated picture. Achieving household adoption and sustained use of improved cookstove remains a major hurdle (Lewis and Pattanayak 2012; Rehfuess et al. 2014), although there are some encouraging cases of improved stove use in East and West Africa (Beltramo et al. 2015; Bensch et al. 2015).

If adoption occurs, achieving air pollution reductions is challenging (Jeuland et al. 2015a; Thomas et al. 2015). Even when stoves achieve low emission levels in laboratory settings, they may not achieve the same results in households (Jetter et al. 2012; Roden et al. 2009), perhaps due to the use of multiple fuels and technologies for cooking and continued use of dirty sources of energy for heating and lighting. These difficulties in emission reduction make it challenging for many households to meet the household air pollution interim target for particulate matter ($PM_{2.5}$) of 35 $\mu g/m^3$ recommended by the WHO to provide substantial health benefits (Bruce et al. 2015; WHO 2014). Although healthy levels of air pollution may not be achieved, there is some evidence of black carbon emission reduction with ICS use (Patange et al. 2015). Some recent studies, including one in our study area, also suggest reductions in fuelwood use with ICS (Brooks et al. 2015).

3.1.1 Previous work to measure stove use

Many studies with improved cookstoves analyze households based on *ownership* of an improved cookstove, rather than actual ICS use (either as a binary outcome or along a continuous spectrum representing proportion of ICS use). Reliance on observational data for stove use can be misleading, given that households with a history of respiratory illness may more likely purchase ICS (Mueller et al. 2011). When hours of stove use are reported, studies rely almost exclusively on self-reported use, which may be a poor proxy for actual hours of use. Another limitation of previous studies on stove use and air pollution levels is that measurements are mainly collected for household air pollution levels, which may also not approximate true personal exposure.

The vast majority of studies on improved cookstoves rely on self-reported estimates of stove use, which are subject to many biases including recall bias and Hawthorne effects. Nevertheless, objective measures of stove use have rarely been leveraged to measure adoption due to the expense and the logistical challenges of large-scale objective measures. When they are employed, most studies with objective stove use monitors (SUMs) test sustained adoption of improved cookstoves in intervention settings (Mukhopadhyay et al. 2012; Pillarisetti et al. 2014). In an ICS intervention study in Rwanda, household self-reported use was biased upwards compared to objective

SUMS measurements over a 5 month period (Thomas et al. 2013). Other work with sensors suggests that ICS use may decrease over time after an intervention, and that intra-household variability of ICS use is high (Pillarisetti et al. 2014).

Perhaps nowhere is additional improved cookstove research needed more than India, where household air pollution takes a particularly high toll. Even after decades of promotion of improved cookstoves in India and other successful energy programs, 700 million people still cook with traditional mud stoves or “chulhas” (Bonjour et al. 2013; Smith and Sagar 2014), and more than one million premature deaths are estimated to occur annually in India from household air pollution generated by solid fuel stoves (Lim et al. 2012). In response, making clean fuels available to Indian households has been suggested (rather than focusing on making available fuels clean) (Smith and Sagar 2014), although very few studies measure air pollution in households that have adopted these clean fuels. We attempt to address this knowledge gap with one of the first studies to consider impacts on pollution from household use of the clean gas and electric stoves recently lauded as the most likely to improve health in India (Smith and Sagar 2014).

In this paper, we describe investigation of factors that are associated with high intensity of ICS use and whether ICS use affects 1) air pollution; 2) amount of fuelwood used and time spent collecting; and 3) self-reported symptoms of respiratory illness and pulse rate. To improve upon these limitations, we move beyond measuring just improved stove ownership, more than only self-reported use, and capturing measurements of air quality beyond just household measurements.

We define ICS to include clean (electric, LPG, biogas) and improved biomass stoves. The research we report here is one of the first efforts to include a holistic picture of all energy use in the household, including cooking, heating and lighting. Many previous studies report clean stove use as a binary outcome (e.g., Guarnieri et al. 2014; Romieu et al. 2009), although the overwhelming evidence indicates that clean fuels are rarely used alone in these settings. Here, we consider clean stove use as 1) a discrete variable for ownership of ICS and 2) intense use of ICS, as well as 3) a continuous variable (the proportion of use that is with clean fuels). In order to form the most accurate picture of stove use possible, we compare self-reported and objective (via temperature sensors) measures of stove use. We also respond to calls for individual (personal) measurement of air pollution (Gordon et al. 2014), and include pollution measurements for each household and primary cook.

To permit comprehensive analysis of the factors associated with stove use, we return to a sample of households in northern India for which we have extensive data on household characteristics. We leverage this existing data and the additional measurements described here in order to analyze a suite of energy use impacts in the broader context of energy access in this region.

3.2 Methods.

First, we describe the study location and sample composition. Second, we summarize the main forms of data collection. Details on the data collection and sample processing for analysis are reported in Appendix B. Finally, we summarize the strategy for analyzing these data.

3.2.1 Study location and sample selection

The study sample was drawn from a group of 943 households previously surveyed several times from 2012-2014 (Brooks et al. 2015; Jeuland et al. 2015b; Pattanayak et al. 2014) in the Nainital district of Uttarakhand, India, in the Himalayan foothills. For cooking fuels, this district has heavy reliance on firewood (58% of rural households report this as their primary fuel), followed by LPG (35%)(Census of India 2011c).

Households for this study were identified using stratified random sampling. Using data from the 2014 survey, we first stratified by intensity of ICS use. Intensity of ICS use is defined as the fraction of hours that improved cookstoves were used for heating or cooking divided by the total hours of heating and cooking in the household (on traditional or improved cookstoves). The proportion of cooking and heating on ICS was used rather than the absolute number of hours of ICS use in order to select households with a range of household air pollution levels. The first stratum only used traditional stoves; the second ranged from 0% to 30% of their total heating and cooking hours on ICS; the third included households between 30 and 60%; and the final stratum contained households using ICS for greater than 60% of all heating and cooking hours. The distribution of households in each strata was 183, 162, 30, and 19, respectively. We aimed to have a final sample of around 200, and therefore anticipating a refusal rate of 10-20% we targeted a sample of around 240 households. Thus, we randomly selected 65 households from the first stratum, 128 households from the second, and included all households from the third and fourth strata (30 and 19 households, respectively)[1].

The sample therefore contains 242 households from 17 villages and a total of 39 hamlets or toks (all but 8 of the hamlets were part of the previous ICS sales program) (Figure 8). This study was conducted from February through April of 2015. Surveys were only conducted in households in which the primary cook was present. Two visits, 24 hours apart, were made to each household that agreed to participate.

The study was approved by the Duke University Institutional Review Board.

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[1] Many of these households (73%) received an offer of purchasing an improved biomass stove (Greenway Smart Stove) and/or an electric stove between September-December 2013 at full price over three installment payments as part of a randomized stove adoption study (Pattanayak et al., 2014). However, when selecting households, only the proportion of improved stove use was used, not the type of stove; therefore, our sample also contains households who use ICS (e.g., LPG stoves) which were not part of this previous program.

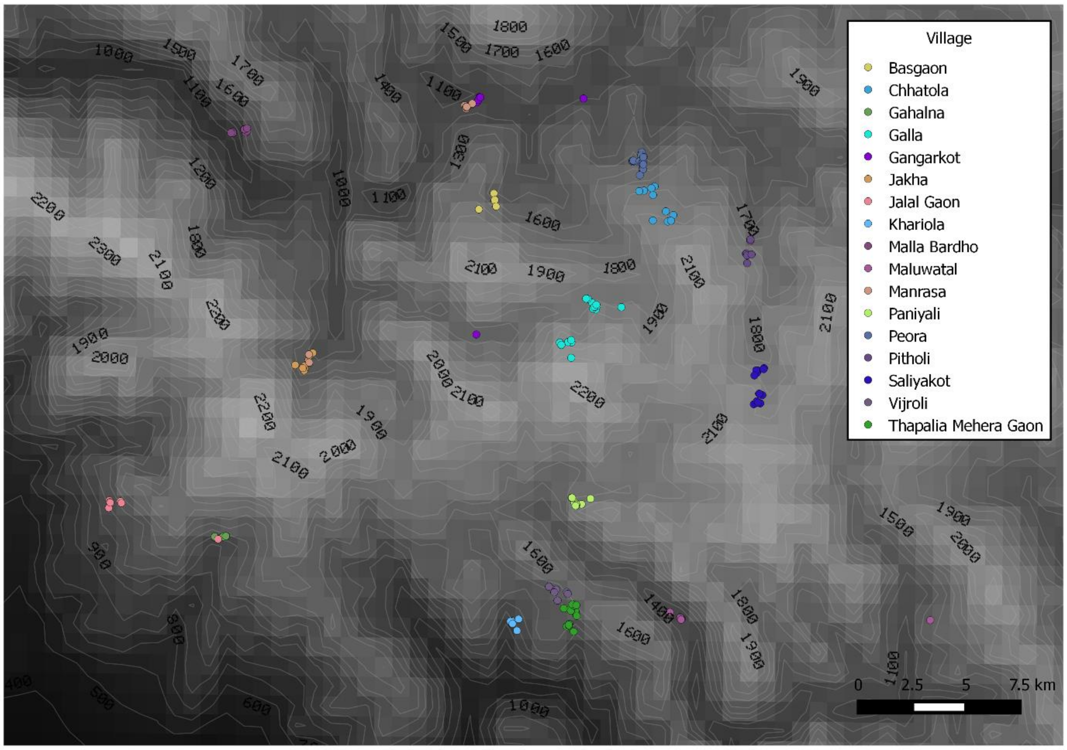

Figure 8. Map of project households in Nanital District, Uttarakhand (elevation shown in meters)

Survey. Household survey questionnaires were designed to collect data on socioeconomic characteristics. Households were asked detailed questions about the stoves they use for cooking (preparing food and tea) and heating (room heating, boiling water for bathing). Stove and heater use was recorded for typical use as well as recent use in the past 24-hour period. Other questions included the quantity of fuel used, stove location, ventilation, the type of food cooked, electricity availability, and time spent gathering or purchasing fuels. A series of questions was asked to assess compliance of primary cooks who wore personal monitors and whether the cook followed a normal cooking and heating routine.

Air pollution measurement. We measured air concentrations of fine particles less than 2.5 μm in diameter ($PM_{2.5}$) using Personal Exposure Monitors (PEMs; BGI Incorporated, Waltham, MA) with 37 mm 2.0 μm pore size Teflon filters (Pall Corporation, Port Washington, NY) filters in three ways. First, in all households, we measured household $PM_{2.5}$ with a sampler suspended for 24 hours. If multiple stoves were used in different rooms, the monitor was hung near the main traditional stove. These samplers were placed within the breathing zone of the cook - 2 meters horizontal distance from the stove, and vertical distance ranging from 0.4 meters (for stoves on the ground) to 1.5 meters (for stoves on a counter or shelf) (Figure 9). The monitors were placed away from walls and windows. Second, in all households, we measured personal exposure using a PEM worn by the primary cook either around the waist or slung across the back and clasped over the chest (Figure 10). Third, we measured outdoor $PM_{2.5}$ in at least one central area in each village.

Figure 9. Household air pollution monitor

Figure 10. Personal air pollution monitor

On the first survey visit, household instruments were placed and households were instructed to follow a normal routine for their day and to ignore the presence of the stove monitors. The cooks were asked to wear the monitor all day other than when bathing or going outside in rain, and to place the monitor next to them while sleeping. After 24 hours (+/- 1 hour), field staff returned to turn off the pumps and collect the monitors.

Exposure to air pollution (in $\mu g\ PM_{2.5}/m^3$) was calculated by taking the difference between pre- and post-exposure filter weights (the weight of accumulated particles) divided by the volume of air sampled for household and personal samplers with a correction for field blanks; values were log-transformed to improve data normality (additional details on the collection and calculation of $PM_{2.5}$ exposure in Appendix B).

In some cases, as detailed in the results section, the pumps were found operating at a low flow rate when the team returned for sample pick up. The units used in this study did not provide information on the time the pump shut off, and therefore we were unable to determine how long the pumps were running if they were not running when the field team returned. In order to create a conservative estimate of household air pollution concentration, we calculated the average 24 hour $PM_{2.5}$ concentration by averaging the collected $PM_{2.5}$ over 24 hours for these samples, even though the pumps ran for less than this time.

Fuel consumption. During a first visit, households were asked to provide fuel in excess of the anticipated requirement for the next 24 hours, which was weighed. Enumerators returned a day later and weighed the remaining fuel. The fuel consumed (kilograms) over the 24-hour monitoring period was calculated by subtracting the fuel remaining from the initial fuel weight. All solid fuels were weighed including wood, twigs, dung cakes and crop residue. If households reported burning more than the allocated fuel during the return visit (20% of households), they were asked to estimate how much excess was burned (e.g., an additional one half the original amount).

Health. The household survey included questions assessing respiratory health problems experienced by the cook over the past 24 hours. Non-invasive finger pulse oximeters (Santa Medical 110, Tustin, CA) were used to measure pulse rate of the primary cook in each household.

Stove Use. Stove use is defined as the entire time the stove was used for any purpose, including cooking, making tea, boiling water, preparing animal fodder or space heating. We use this broad definition to capture all stove activity, and thus closely relate to the outcomes of interest (air pollution, fuel use and health)[2].

We use two main definitions of stove use over the 24-hour study period: 1) self-reported stove use from the household survey; 2) objective stove use measured with stove usage monitors (SUMs). SUMs are temperature data loggers (ThermoChron® iButtons) that were programmed to take a temperature measurement every minute. SUMS were placed on every stove and heater that households reported using regularly in a pouch made from electrical tape that was taped (LPG, electric stoves) or nailed (mud, brick stoves) to the stove near the heating area but far enough away to avoid exposure to flames or liquids that boiled over (Figure 11). Households were asked to ignore SUMS and proceed with normal heating and cooking.

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[2] We anticipate that the stove measurements reported here may be better approximations of regular stove use than those reported in post-intervention stove use assessment programs (e.g., Pillarisetti et al. 2014) for two reasons: first, the vast majority of households within our study do not have stoves that were involved in an intervention but rather purchased their stoves independently; second, stove use and air pollution measurements took place more than a year after households were offered the opportunity to purchase ICS, therefore any Hawthorne effects in households that purchased ICS may be reduced.

Figure 11. Stove Use Monitor (SUM) nailed to mud stove

A program developed by the Berkeley Air Monitoring Group (SUMs iButton) was first used to calculate use during the monitoring period using an algorithm within the program ("Slope with Slopeout"). This algorithm is designed to register cooking time when the temperature is increasing or stable. It calculates cooking events that begin when the slope of the temperature plot goes above 0.1, and the cooking event ends when slope hits -0.05. Next, each SUMs record was manually reviewed, and each minute of stove use or non-use that the SUM program had coded incorrectly was counted; adjustments to the total cooking time were made accordingly. For example, horizontal lines without any change in temperature over long periods were not considered cooking and were subtracted from the total cooking time. Similarly, gradual increases in stove temperature that matched ambient temperature were not considered cooking and were recoded (see Appendix B for additional details). The adjusted time measured with SUMs was used in the statistical analyses.

3.2.2 Statistical Analysis

First, we compare stove use recorded via the objective measurements (SUMS) and self-reported estimates. Next, we evaluate differences between the subset of households which have usable SUMs data and the entire sample.

We then examine the impacts of stove use. We compare the average of our outcomes of interest (air pollution, fuel consumption, time spent gathering wood, and health) between two sets of groups: 1) ICS users and households that only use traditional stoves; and 2) high intensity ICS users (50% or more total stove use on ICS) and those with low or no improved stove use. We use the metrics of any ICS use to facilitate comparison of our outcomes with most other research studies that use a similar measure. Analyses with the second metric, high intensity ICS use or primary use of clean energy, will suggest whether greater use of ICS has larger magnitude impacts (it is also the indicator approved to assess clean energy access in the sustainable development goals (Dora 2015)).

These comparisons are done using both techniques for assessing stove use: self-reported from household questionnaires and objectively measured via SUMs.

We estimate the following regression of each outcome (Y) on the proportion of time ICS were used, while controlling for covariates such as years of primary cook education, monthly household expenditure, household size, use of electricity for lighting, and outdoor PM pollution:

$$Y = \beta_0 + \beta_1 hh\, covar. + \varepsilon$$

We use OLS and logit regressions with robust standard errors clustered at the hamlet level for all models and hamlet fixed effects.

All statistical analyses were performed in Stata 13 (Stata Corporation, College Station, TX, USA).

3.3 Results

First, we describe the makeup of our final sample by summarizing household characteristics and ICS use. Next, we present associations between high intensity ICS use and (1) household air pollution, (2) personal air pollution, (3) firewood consumption, (4) time spent gathering and preparing fuel, and (5) health.

3.3.1 Cohort Characteristics

Although 242 households were selected as described above, 34 declined to participate in the survey: 65% of the refusals (20 households) simply refused to participate in the study at all; 1 cook was unwilling to wear the sampler; 2 households had the head of household or primary cook out of the village for an extended period; 8 households had no eligible person present during two visits to the household). Therefore the final sample includes 208 households.

Households had 5.5 members and 0.5 children under five on average (Table 9). Education was slightly higher for the head of the household (6.2 years) compared to the primary cook (5 years) on average. All households in this sample were Hindu. Houses contained an average of four rooms, and toilets were the main bathroom facility for all households. This region has high electricity access: all households had some electricity over the preceding 24 hours, and reported receiving 22 hours per day on average, although it was variable particularly in rainy weather. Awareness of stoves that produce less smoke than traditional stoves was high in this sample (74%), as well as the fraction of households that believe improved cookstoves and clean fuels have positive impacts on reducing health or environmental problems. This may be related to the fact that many of the households were part of the previous stove sales program that included messaging about ICS benefits. Household cooked 2.6 meals and prepared tea 5.4 times per day on average.

The vast majority of sample households (93%) report that they use a traditional stove for their cooking most days; about half (54%) report using a clean stove for their cooking most days. The stove use observed during the 24-hour monitoring period fits this pattern. Almost all households (94%) reported traditional stove use for cooking or heating during the 24 hour sampling period: 44% used a three stone fire, 41% used an angheti (a permanent mud and brick stove with a chimney), 17% used a sagarh (a portable steel pan with short legs), and 13% used a mud stove.

Over the same period, 53% of households reported ICS use for cooking or heating: 42% used LPG, 9% used an electric G-Coil stove, 2% used a different electric stove that held a vessel, 2 households used a biogas stove, and 1 household used an electric heater. Three households (2%) used an improved biomass stove (Greenway Smart Stove). Interestingly, 49% of households reported having an LPG canister with fuel in house, although not all used it during the monitoring period. Households that had an improved cookstove report an average of 1.5 hours of use per day.

Table 9. Descriptive Statistics

Variable	N	Mean	St. Dev	Min	Max
Concentration of PM in ug/m^3 for PEM in household	203	723.47	757.78	7.37	3426.83
Concentration of PM in ug/m^3 for PEM cook bag	201	458.14	570.06	2.81	3690.13
Amount of firewood used in 24 hrs – weighed	208	9.69	5.72	0.00	42.00
Cook had runny eyes from smoke over past 24 hours	208	65.87%	0.48	0.00	1.00
Cook had cold / cough over past 24 hours	208	21.63%	0.41	0.00	1.00
Hrs person wearing sampler gathered fuels in past 24 hrs	208	0.23	0.80	0.00	5.00
Hrs person wearing sampler prepared fuels at home in past 24 hrs	208	0.12	0.15	0.00	0.67
Fraction of all stove hours on ICS (self-reported)	208	17.76%	0.27	0.00	1.00
Total hrs all ICS used during monitoring period (self-reported)	208	0.8	1.08	0.00	5.00
Total hrs all ICS used during monitoring period (self-reported; subsample matching SUMs data)	145	0.78	1.03	0	4.33
Total hrs all ICS used during monitoring period (SUMs)	145	2.53	3.04	0.00	13.10
Total hrs all stoves used for cooking and heating in monitoring period (self-reported)	208	5.95	2.85	1.50	26.40
Total hrs all stoves used for cooking and heating in monitoring period (self-reported; subsample matching SUMs data)	145	5.73	2.45	1.5	14.5
Total hrs all stoves used for cooking and heating in monitoring period (SUMS)	145	8.21	4.11	0.25	22.10
Trash burned in household	208	23.56%	0.43	0.00	1.00
Kerosene or mustard lamp used for light in past 24 hrs	208	76.92%	0.42	0.00	1.00
Number of people that food was cooked for in past 24 hrs	208	5.35	2.55	1.00	20.00
Number of meals cooked in past 24 hrs	208	2.59	0.55	1.00	4.00
Number teas in past 24 hrs	208	5.36	2.62	0.00	20.00
Hrs of electricity in past 24 hrs	208	21.88	2.73	10.00	24.00
Baseline: Self assessment of relative wealth on 1-6 scale (6=high)	206	2.14	0.90	1.00	5.00
Log of total expenditure (w/imputed values)	207	8.49	0.79	4.61	11.16
Number of rooms in house	207	5	2.24	1.00	24.00
Education: Head of household (yrs)	202	6.24	4.50	0.00	16.00
Education: Primary cook (yrs)	203	5.01	4.32	0.00	16.00
Household size	208	5.49	2.09	1.00	15.00
Number of children 5 and under in household	208	0.5	0.79	0.00	3.00
Household has taken loan in past year	208	23.56%	0.43	0.00	1.00
Head of household is female	207	18.84%	0.39	0.00	1.00
Age of head of household (years)	206	53.58	13.74	26.00	99.00
Household reports price of fuelwood higher than vlg average	208	68.75%	0.46	0.00	1.00
Avg price of LPG in each GP in 1,000 Rs/cylinder	208	0.47	0.05	0.35	0.70
Household aware of stoves that produce less smoke	208	74.04%	0.44	0.00	1.00
Household feels ICS and clean fuels have medium or better impact on any neg effects	208	71.15%	0.45	0.00	1.00
Household selected to receive the ICS sales offer in 2013	208	77.88%	0.42	0.00	1.00
Hours of electricity per day	208	21.875	2.73	10.00	24.00
Household participates in forest management group	208	31.73%	0.47	0.00	1.00

Most stove use was for cooking (4.3 hours on average) compared to heating (1.7 hours on average). The ambient temperature ranged from 12 to 29 degrees Celsius at initial household visits. All but 20% (n=42) of households used a device to heat their house during the monitoring period. For heating, three quarters of the sample used a traditional stove and 18 households used improved cookstoves (LPG, electric coil stoves[3], and improved biomass stoves). A third of households used a stove for heat while they slept.

Only 11% of households in this sample would qualify as having clean energy use according to the Sustainable Development Goal 7 indicator for clean fuels ("percentage of population with primary reliance on clean fuels and technologies at the household level" (Dora 2015)), if primary reliance is defined as at least half of reported cooking and heating on improved cookstoves (LPG, electric, biogas). In the smaller sample for which we have usable SUM data, 19% of the sample has clean energy use.

The practice of using both a traditional and improved cookstove in the same household was quite common: almost half (47%) of households used both a traditional and improved cookstove (only 12 households (6%) exclusively use an improved cookstove).

In addition to stove use for cooking and heating, lighting and trash burning can have important contributions to household air pollution, although they are rarely

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[3] Electric coil stoves were generally used for heat by households without metered electricity connections.

included as covariates in household energy use analyses. Most households (92%) used clean light sources during the monitoring period, mainly electric bulbs (81%) as well as flash lights (52%), solar lanterns (10%) or an emergency rechargeable light. Many households (61%) used dirty light sources, mainly kerosene lamps (34%) or mustard oil lamps (11%). There are additional households that reported having kerosene present in the house (43% of households) – apparently used exclusively for light or starting fires as there were no kerosene stoves or heaters used by these households. "Stacking" (use of clean and traditional technologies) is even more pronounced for lighting in this sample: 75% of households report using both clean and dirty light sources during the monitoring period. Most households (82%) burned incense during the monitoring period. A quarter (24%) of households burned trash (plastic bags, wrappers, and paper) during the monitoring period - 10% in a three stone fire, 2% in an angheti stove, and 3% in a mud stove.

Households generally followed a normal routine on the day of sampling (only 6% had an unusual cooking routine). One household cooked fewer meals than normal, and seven cooked more than usual. Two households were different because at least some members were fasting, and seven households had a guest. Households made tea an average of 5.4 time per day (4.4 made by cook with sampler). Households cooked an average of 2.6 meals per day (2.4 made by cook with sampler). However, the vast majority of households (91%) reported an unusual heating routine due to the unseasonably warm weather during the winter months in which sampling occurred. Therefore, the stove use that we recorded may be less than typically used during these months.

3.3.2 Analysis

Stove use calculation comparison. Objective stove use was measured with SUMs for every stove or heater that each household reported using regularly. However, a large number of SUMs records was excluded (67 omitted because of download errors; 9 missing stove type data; 21 missing another SUM record for that household and therefore proportions of stove use could not be calculated). We obtained complete SUMs data from 145 households, yielding a total of 218 SUMs records. Following the adjustment process described in the methods and Appendix B, adjustments were made to 193 of these files (average adjustment time was a 134 minute reduction).

We compared two measures of stove use: self-reported and objective (via SUMS) (Table 10). We found that for all stove types (other than biogas and sagarh stoves, for which there are very few pairs), the average hours of use calculated with SUMS was significantly greater (paired t-tests) than the average self-reported hours of use. This suggests that self-reported use is underreporting true stove use by large margins. We calculated the rank correlation of these use measures (Kendall's tau) for all stove types and find significant correlation only with LPG stoves (p-value 0.05). None had significant pairwise correlation.

Table 10. Stove Use Comparison

Stove Type	Obs	Average Hrs. Stove Use (SUMS)	Average Hrs. Stove Use (Self Reported subsample)	Paired T-Test p-value	Kendall's Rank Correlation Statistic (tau-a)	Kendall's Rank Correlation p-value
Angheti	59	5.8	4.8	0.02**	-0.00	0.97
LPG	59	4.3	1.5	0.00***	-0.18	0.05*
3 Stone	50	6.2	4.3	0.00***	0.12	0.23
Mud Stove	21	6.6	5.1	0.02**	0.20	0.20
G-Coil	12	4.7	0.6	0.00***	-0.11	0.67
Greenway	5	3.7	0.9	0.08*	-0.10	1.00
Sagarh	4	5.4	3.6	0.56	0.00	1.00
Electric Stove (not G-Coil)	3	5.7	0.9	0.01**	1.00	0.30
Biogas	2	4.8	1.7	0.54	-	

The degree of difference between these two methods was greater for ICS than for traditional stoves. The number of households that use an improved cookstove at all is similar when comparing ICS use verified with SUMs with survey data (p=0.57)(Table 11). However, intense ICS users are twice as common when calculated with SUMs compared to self-reports (p<0.01). SUMs record a significantly higher fraction of improved cookstove use than self-reports (p<0.01). These differences are explored in the discussion.

Table 11. ICS use measured by two stove use calculation methods

Variable	Mean		p-value	N
	Self-Reported	SUMS		
ICS Use (for any cooking or heating)	51.7% (.50)	53.1% (0.50)	0.57	145
Intense ICS Use (>= 50% cooking and heating)	11.0% (0.31)	20.7% (0.41)	0.00***	145
Fraction of all stove hours (heating & cooking) on ICS	17.8% (0.27)	28.3% (0.32)	0.00***	145

We compare the subset of households (n=145) for which we collected usable objective stove use measurements with the entire sample. The households with SUMs data were not significantly different across a variety of household characteristics, with the exception of participation in women's groups (higher in the SUMs subsample) and the price of LPG and fuelwood (lower in the SUMs subsample). For simplicity, in the remainder of the analyses we present self-reported stove use in the manuscript. We also compared objectively measured stove use with self-reported use for the subset of households with SUMs data, and note where these findings diverge from the full sample of self-reported data (presenting additional analyses in Appendix B).

ICS and air pollution. Although personal and household air pollution samples were taken in all 208 study households, 4 household and 7 personal samples were dropped due to lab or field errors[4], leaving a total of 204 and 201 $PM_{2.5}$ concentration measurements, respectively. Twenty-four outdoor $PM_{2.5}$ concentrations were collected from 16 villages and a total of 23 hamlets. In addition, we collected 8 field blanks, although two were eliminated (due to enumerator error in the field), leaving 6 usable field blanks from 6 villages.

When we returned to households to collect the samplers after 24 hours, 30% (n=62) of household samplers and 20% (n=44) of personal samplers were no longer

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[4] One was dropped because the air flow tube was blocked and therefore no PM mass was collected; one was dropped because of impossibly high post-weight value; one was dropped because it had a net negative weight; seven dropped because of errors recording filter numbers (filter numbers had been recorded twice); one dropped because of missing filter pre-weight value.

operating between 80-100% of desired flow (2 liters per minute); 20% household samplers and 12% personal samplers had a zero flow rate at pick up.

In order to help reduce the number of samples that overloaded, we changed the distance of the household sampler to 2 meters (from 1 meter). However, changing the distance of the sampler did not reduce the average rate of household pump failure. The rate of pump failure for household and personal samples is significantly associated with the level of $PM_{2.5}$ measured (in t-tests), suggesting that the pump failure may be due to filter overloading. Interestingly, we find evidence suggesting that pump failure occurred for different reasons for household and personal pumps: personal filters that were in pumps with problems were less heavy than household filters in pumps with problems: the proportion of low weight samples (<1000 μg) in blocked pumps was much lower (12%; n=7) for household samplers than personal samplers (45%; n=18). We hypothesize that the personal system pump failures might often have been due to other problems (filter saturation in rain, pinched cords and inlets blocked by sari fabric), whereas household pump problems were due exclusively to overloaded filters.

At concentrations over 2000 $\mu g/m^3$, the filters are likely to become saturated. We report 21 household and 14 personal samples over this threshold, although all but 3 of the personal samples had flow less than 80% of the target at time of pick up. One personal concentration measurement was an outlier and the filter weight was trimmed at the next highest value.

The primary cook was asked to wear the air pollution sampler, although in 11 households the secondary cook wore the sampler because the primary cook was unable to do so (out of the village, menstruating, or sick). Four of the cooks who wore the sampler were male (only one secondary cook was male), and all other cooks were female. The average age of the cooks for which we have usable personal air pollution data (n=201) was 37 years, although there were 4 cooks younger than 18 (the youngest was 13) and the oldest was 75.

Household air pollution was significantly higher than personal air pollution on average (n=198; $p<0.01$).

We found that improved stove use and high-intensity use were associated with significantly lower levels of household $PM_{2.5}$ (30% reduction for ICS users, p=0.01; 86% reduction for high-intensity ICS users; $p<0.01$) (Table 12). Improved stove users did not have significantly lower levels of average personal $PM_{2.5}$, although high-intensity ICS users did (9% reduction for ICS users, p=0.55; 59% reduction for high-intensity ICS users; $p<0.01$). These analyses were repeated for other formulations of use (Appendix B Table 25 and Table 26). The relationship between the percent of stove improved use and air pollution levels is shown graphically in Figure 12.

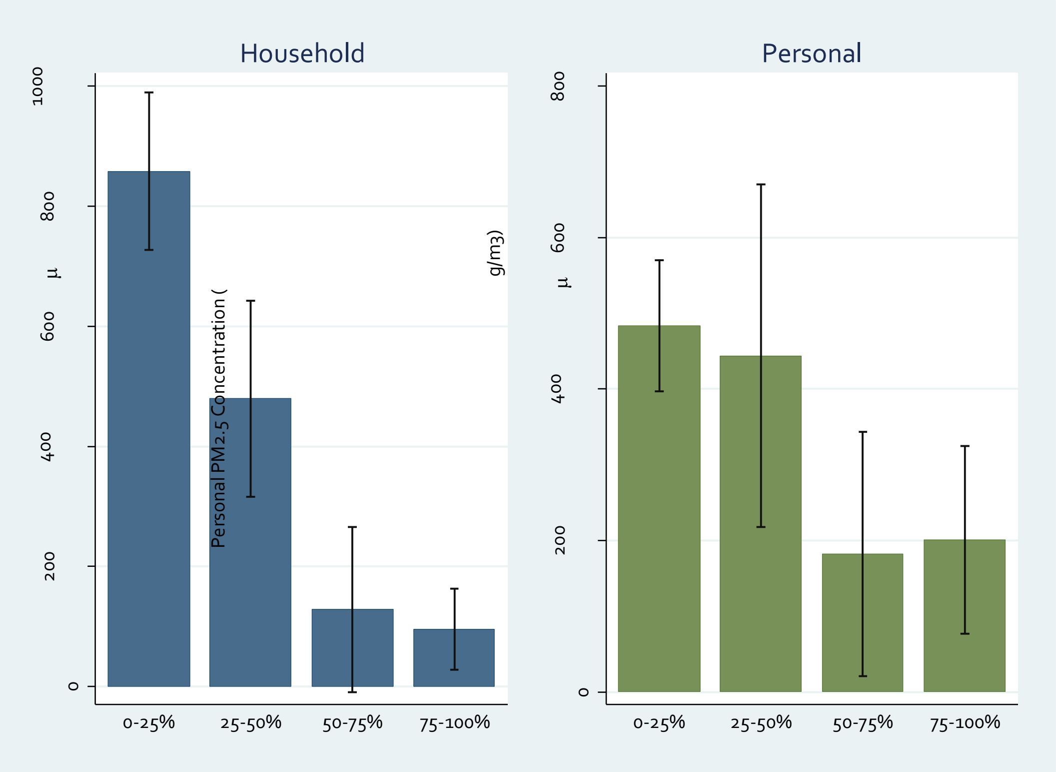

Figure 12. Air pollution over the 24 hour monitoring period, by proportion of hours that households reported use of improved stoves, shown with 95% confidence intervals.

Table 12. Air pollution, fuelwood and health outcomes for (a) full sample, (b) households with no ICS use, (c) households with any ICS use, (d) households with low improved stoves use (less than half of total heating and cooking), and (e) households with high intensity improved stove use (50% or more of total heating and cooking). Stove use data is self-reported. Reported p-values are from two-sided t-tests for differences in means between (b) and (c) or (d) and (e) for continuous variables, and Pearson's chi squared tests for categorical variables (* p<0.01, ** p<0.05, * p<0.1).**

			Any ICS Use					Intensity of ICS Use				
Household Characteristics	(a) Full Sample		(b) No ICS Use (Only Traditional Stoves)		(c) Any ICS Use		p-value	(d) Low ICS Use <50%		(e) High ICS Use (>=50%)		p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs	Mean (s.d.)	Obs	
Household Concentration of PM in ug/m3 [5]	714.4 (756.1)	204	845.8 (791.4)	100	588 (701.4)	104	0.01**	787.5 (767.5)	182	109.1 (139.7)	22	0.00***
Personal Concentration of PM in ug/m3[5]	443.6 (529.8)	201	466.1 (449.9)	98	422.1 (597.3)	103	0.55	475.9 (550)	178	193.5 (208.4)	23	0.01***
Amount of firewood used in 24 hrs - weighed	9.7 (5.7)	208	10.9 (5.6)	101	8.5 (5.6)	107	0***	10.6 (5.4)	184	3.1 (3.6)	24	0.00***
Hrs cook gathered fuels in past 24 hrs	0.2 (0.8)	208	0.4 (1)	101	0.1 (0.58)	107	0.02**	0.3 (0.9)	184	0 (0)	24	0.14
Hrs cook gathered and prepared fuels in past 24 hrs	0.3 (0.8)	208	0.5 (1)	101	0.2 (0.6)	107	0.02**	0.4 (0.9)	184	0 (0.1)	24	0.05*
Pulse rate of cook wearing sampler	78 (10.5)	187	77.7 (10.3)	92	78.2 (10.6)	95	0.73	77.7 (10.3)	167	80.8 (11.4)	20	0.20
Cook had runny eyes from smoke over past 24 hours	66% (0.48)	208	70% (0.46)	101	62% (0.49)	107	0.19	70% (0.46)	184	38% (0.49)	24	0.00***
Cook had cold / cough over past 24 hours	22% (0.41)	208	21% (0.41)	101	22% (0.42)	107	0.77	22% (0.42)	184	17% (0.38)	24	0.53
Cook had sore throat over past 24 hours	22% (0.42)	208	23% (0.42)	101	21% (0.41)	107	0.82	23% (0.42)	184	13% (0.34)	24	0.23
Cook had running/blocked nose/sinusitis over past 24 hours	12% (0.33)	208	14% (0.35)	101	10% (0.31)	107	0.43	13% (0.33)	184	8% (0.28)	24	0.56
Cook had faster than normal breathing over past 24 hours	13% (0.34)	208	12% (0.33)	101	15% (0.36)	107	0.52	13% (0.34)	184	17% (0.38)	24	0.63
Cook had wheezing in chest/nose over past 24 hours	13% (0.34)	208	10% (0.3)	101	16% (0.37)	107	0.2	13% (0.33)	184	17% (0.38)	24	0.57

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[5] Data are lognormally distributed. Means and standard deviations shown here use untransformed data, but t-tests and significance presented use logged data.

To confirm these associations, we use multivariate regressions to model the relationship between air pollution and improved cookstove use (

Table 13). In these analyses, we regress intense use and the proportion of ICS stove use on air pollution measures. We also control for a suite of household characteristics (socio-economic factors, electricity access), stove use behaviors (number of meals, total hours of stove use), pollution determinants (total hours of traditional stove use, use of dirty lighting sources, village-level outdoor air pollution, rain), and a set of dummy variables for sampling problems encountered (pumps outside of range, cooks who were not wearing the samplers at pick up).

Intense ICS use and the fraction of stove use with an improved cookstove (self-reported and from SUMs) are both significantly associated with reduced household air pollution (

Table 13). Although there is also a negative association between these ICS use variables and reduced personal air pollution, it is only significant for a single specification. The total hours of traditional stove use is positively associated with air pollution level, as expected.

Using multivariate regression analysis, fraction of ICS use has a negative and significant association with personal air pollution exposure in only one specification.

Table 13. Ordinary Least Squares regressions for household and personal $PM_{2.5}$ (in natural log μg/m3) with robust standard errors clustered by hamlet and household covariates. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Variables	Household $PM_{2.5}$ ug/m3 (natural log)				Personal $PM_{2.5}$ ug/m3 (natural log)`			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Intense ICS Use (>=50%)	-1.24***	-1.20***			-0.67**	-0.47		
	(0.32)	(0.40)			(0.31)	(0.37)		
% ICS Use			-1.46***	-1.06**			-0.68	-0.39
			(0.33)	(0.45)			(0.45)	(0.54)
Traditional Stove Hours	0.08***	0.07**	0.06**	0.07**	0.07*	0.07*	0.07	0.07*
	(0.03)	(0.03)	(0.02)	(0.03)	(0.04)	(0.04)	(0.04)	(0.04)
Household Controls	YES	YES	YES	YES	YES	YES	YES	YES
Hamlet Fixed Effects	NO	YES	NO	YES	NO	YES	NO	YES
Observations	196	196	196	196	193	193	193	193
R-squared	0.52	0.64	0.50	0.61	0.22	0.45	0.21	0.45

ICS and Firewood. The field team measured firewood before and after the monitoring period. On average, households burned almost 10 kilograms of wood during the 24-hour sampling period. Twenty-two cooks gathered wood during the sampling period, spending an average of 2.2 hours.

Users of ICS (and high-intensity users) burned significantly less firewood (ICS users 22% reduction, $p<0.01$; intense ICS users 71% reduction, $p<0.01$; Table 12, Figure 13). The amount of time that was spent gathering and preparing fuels during the monitoring period was significantly less for ICS households (56% reduction in hours for households with any ICS use, $p=0.02$; 91% reduction for intense ICS users, $p=0.05$).

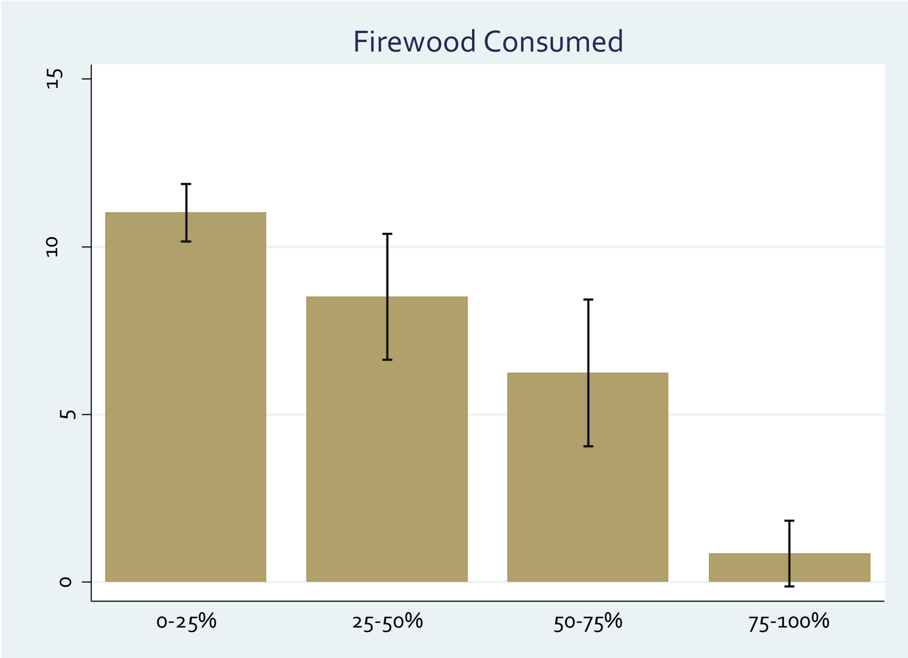

Figure 13. Firewood consumption and air pollution over the 24 hour monitoring period, by proportion of hours that households reported use of improved stoves, shown with 95% confidence intervals.

We confirm these results with regression analysis (Table 14). Intense ICS use and the fraction of time spent cooking with improved cookstoves is associated with a reduction in fuelwood consumption. The total hours traditional stoves were used, household size, less education and involvement in a women's club or self-help group were all associated with increased fuel use. An increase in time spent using improved stoves is also associated with a significant reduction in the time households spend gathering and preparing fuels for all models. Interestingly, hours spent on traditional stoves is negatively associated with hours gathering and preparing wood; perhaps because households this variable is the hours spent during the past 24 hour period on these tasks for the primary cook—therefore, if the cook is gathering wood they are less likely to be using the traditional stove.

Table 14. OLS regressions for firewood consumption and time spent gathering and preparing wood in past 24 hours with robust standard errors clustered by hamlet and household covariates *** p<0.01, ** p<0.05, * p<0.1

	Fuelwood Consumption (kg)				Hours Gathering and Preparing Fuel			
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Intense ICS Use (>=50%)	-3.62**	-2.66			-0.45***	-0.25*		
	(1.34)	(1.61)			(0.13)	(0.13)		
%ICS Use			-5.38***	-4.35			-0.83***	-0.70**
			(1.84)	(2.59)			(0.29)	(0.32)
Traditional Stove Hours	0.73***	0.72**	0.64**	0.63*	-0.02**	-0.01	-0.04**	-0.03
	(0.25)	(0.28)	(0.26)	(0.32)	(0.01)	(0.02)	(0.02)	(0.02)
Household controls	YES	YES	YES	YES	YES	YES	YES	YES
Hamlet fixed effects	NO	YES	NO	YES	NO	YES	NO	YES
Observations	196	196	196	196	196	196	196	196
R-squared	0.39	0.52	0.40	0.52	0.09	0.27	0.11	0.29

ICS and Health. Health parameters were evaluated based on survey and objective measurements. Runny eyes from smoke (over the past 24 hours) was a problem commonly reported by cooks (67% of cooks). Rates of other respiratory symptoms were lower: cold or cough (22%), sore throat (22%), running or blocked nose (12%), faster than normal breathing (13%), or wheezing (13%). For the 187 cooks that we observed, the average pulse rate was 78 beats per minute (Table 12).

The association between intense ICS use and health outcomes is less clear than for air pollution and fuel use. There is no significant difference between pulse rates for high- or low-intensity ICS users on average (Table 12). High-intensity ICS users have significantly fewer reports of runny eyes from smoke ($p<0.01$). No other respiratory symptoms are significantly different on between these groups for either households with any level of ICS use or high-intensity users (this finding is confirmed with regression analysis in Table 15).

Table 15. Regression models for health outcomes.
Pulse rate analyzed with OLS models with robust standard errors (R^2 reported). Self-reported incidence of runny eyes over the past 24 hours was analyzed with logit (pseudo-R^2 reported) and household covariates.

VARIABLES	Pulse				Runny Eyes	
	(1)	(2)	(3)	(4)	(5)	(6)
Intense ICS Use (>=50%)	3.06	0.17			-1.36**	
	(4.23)	(5.07)			(0.54)	
%ICS Use			0.21	-4.43		-0.92
			(5.72)	(6.74)		(0.65)
Traditional Stove Hours	-0.06	-0.46	-0.19	-0.66	0.03	0.05
	(0.25)	(0.35)	(0.29)	(0.41)	(0.06)	(0.06)
Household Controls	YES	YES	YES	YES	YES	YES
Hamlet Fixed Effects	NO	YES	NO	YES	NO	NO
Observations	176	176	176	176	196	196
R-squared	0.08	0.28	0.07	0.29	0.08	0.06

Robustness Checks. To confirm the robustness of these findings, we analyzed the impact of any use of ICS on the outcomes of interest using two additional stove use metrics: objective use with SUMs and the self-reported data from only the subset of households which had valid SUMs data (any ICS use: Table 25; intense ICS use: Table 26). We find very similar results to the previously reported data from the full sample. The only substantial difference was a lack of significant association between households with any ICS use (calculated SUMs and the corresponding subset of self-reported data) and a reduction in household $PM_{2.5}$.

The findings from t-tests that compare the ICS users with nonusers are extremely similar for both data sources (self-reported and objective); this is also true for comparisons between intense users and low intensity users.

3.4 Discussion

We find evidence that increasing time spent cooking with clean stoves (LPG, electric stoves and biogas) is associated with a reduction in household and personal air pollution, fuel use and time burdens. Our sample of 208 households contains many users of clean fuels (53% including efficient biomass stoves; 51% with clean non-biomass stoves).

Responding to calls for verification of stove use, we include both objective and self-reported stove and heater use. On average, households use improved cookstoves for 18% of all stove use based on recall, or 28% as measured with temperature monitors (SUMs).

Our comparison of self-reported and objectively measured stove use revealed that households under-reported the amount of time they used all stoves. This is likely due to the fact that the SUMS measured additional time that the stoves were used before (to build a fire or come to a cooking temperature) and after (as the fire died down or the cooking surface cooled) the cooking period as remembered by the household. Alternatively, these results may simply signal that households underestimate the amount of time they used stoves for cooking and heating. We encountered a number of challenges with our SUMS instruments (as detailed in Appendix B: SUMS) and therefore some of the differences between the stove use measures could be due to measurement error. Not only do SUMS report significantly more time that ICS is used, but they also record a significantly higher fraction of total cooking time that ICS are used. This difference may be due to the particular challenges of using SUMs on ICS, many of which have smaller temperature increases during cooking than traditional stoves, and therefore may have been more subject to false positive recording because it was less obvious when the stove was being used.

These findings are markedly different from another recent comparison of stove use in the literature that finds positive bias in household reporting (Thomas et al., 2013). However, only improved cookstove use was measured, and households in that study likely had a greater tendency to over-report stove use because they had just received a free intervention stove. In contrast, we find negative bias in household reporting for improved and traditional stove.

Household air pollution is substantially higher than personal, and improved stove use is more strongly associated with a reduction in household air pollution levels than personal PM. This is likely because cooks did not spend all 24 hours in front of the stove where the household samplers were located. All outdoor air pollution village averages were lower than almost of all household measurements (80%) and personal air pollution exposure measurements (75%). This fits expectations that cooks move between cooking areas, other parts of the house, and outside areas. This study collects 24-hour measurements; these may not be representative of typical exposure, especially if exposure varies seasonally.

In order to really understand the picture of air pollution in rural households, it is critical to consider all sources of pollution. This study is one of the first to analyze stove use time as a continuous variable that includes time spent cooking and heating. We also consider the impact of lighting, which is often considered an important contributor to household pollution. Even though almost all households (92%) used a clean source of lighting during the past 24 hours, we find very high levels of use of dirty lighting such as mustard oil lamps and kerosene lamps (77% of households). These findings illustrate the importance of asking about the use of multiple stoves, heaters and lights and the amount of time they were used. Other important sources of pollution to include in pollution assessments are trash burning (a quarter of households burned trash in the past 24 hours) and proximity to industrial areas (none in this region). However, use of stoves and heaters was a much more important determinant of air pollution than use of lighting or burning of trash.

Only 9 households (4%) in our sample had 24-hour air pollution levels below the WHO interim guideline level of 35 $\mu g/m^3$; 9 cooks (4%) had exposure below the WHO guideline level. Only a single household had a household and cook PM concentrations below the guideline. In comparison, almost half (46%) of village outdoor measurements were below the WHO guideline. Therefore, although dispersion of pollution outdoors certainly makes the outdoor concentration lower than the 24-hour household or personal levels, over half of village measurements exceed the recommended standard. Given the extremely rural location of this region and the lack of large industrial sources of pollution, it is likely that outdoor pollution is mainly generated by household cooking, heating, lighting and trash burning, as well as burning pine needles to keep flies away from animals or ambient dust from roads. In order to meet $PM_{2.5}$ guidelines outdoors it is likely that pollution from household energy must be reduced. We also note that air pollution estimates presented here are underestimates for the 30% of household and 20% of personal PM measurements that had low or zero flow pumps at sample pick-up (and therefore did not run for a full 24 hours, although we calculated air pollution concentration with a 24 hour sampling period). Therefore, true concentrations may be even higher than reported here.

Although we did not measure exposure to air pollution of everyone in the household, the reduction in household air pollution from ICS use shown here likely has positive impacts on the entire household. However, this benefit may be greatest for the cooks (98% female) who spend the most time near the fire and also preparing and gathering fuel, as well as for infants who they frequently carry.

Use of improved cookstoves is significantly associated with a reduction in fuel use and associated time burdens. Interestingly, the association is only significant with the fraction of time on improved cookstoves according to household recollection (70% less wood used), and not using SUMs (45% less wood used). Many cooks do not gather wood daily, therefore data on wood collection and gathering over the past 24 hours do not provide a complete picture of the time burdens tied to fuel use. Future studies should collect data on time spent gathering fuel over a longer time frame.

Although we found striking results with air pollution and fuel use, we did not find a strong association between respiratory symptoms (other than running eyes due to smoke), pulse rate and stove use. This finding could be due to very high air pollution levels or inadequate health assessments. The cookstove community does not yet have sufficient empirical data to answer the question: “How clean is clean enough?” (Lewis et al. 2015), i.e., how low do air pollution levels need to reach to reduce health impacts? Recent models (Johnson and Chiang 2015) suggest that households need to use traditional stoves less than one hour per week to meet the WHO guidelines. ICS owners and users ‘stack’ fuels and technologies, i.e., they owned multiple stoves and use clean and dirty stoves simultaneously (Masera et al. 2000). Almost half of households (47%) used both clean and traditional stoves; 75% used both clean and dirty lighting technologies. In the 14 households in this study who report using traditional stoves less than one hour per day (including the 12 exclusive ICS users), only three had household air pollution levels below the WHO interim standard.

3.5 Conclusion

In a sample of Indian households in the Himalayas, we find evidence of benefits from use of LPG and electric stoves, two clean cooking technologies receiving powerful praise recently. A metric for ICS use that represents the fraction of all stove use that is on improved stoves was more associated with air pollution reductions than a simpler metric of household who use ICS at all. In our sample, greater intensity of ICS use was associated with significantly reduced household pollution, firewood consumption, and less time spent gathering and preparing fuels (but less clear evidence of statistically significant reductions in personal air pollution and respiratory health symptoms). We caution that stove stacking remained a large problem (89% of ICS users), and household exposure was generally far above the WHO interim standard of 35 $\mu g/m^3$. In order to achieve a greater proportion of use with these clean stoves in this region of rural north India, it is likely that improvements in supply and/or price reductions for LPG and electricity may be necessary.

We provide a rare accounting of total stove use for cooking and heating, and urge future studies to assess the full spectrum of household polluting activities (cooking, heating, lighting, burning trash) and consider ICS use on a spectrum rather than a binary outcome in order to capture an accurate picture of household pollution. Unfortunately, the challenges of measuring personal pollution exposure as well as objective stove may remain major hurdles to widespread use of these measurements in future stove impact studies. We observe that households significantly underreport total use of all stove types, although both self-reported and objective stove use have significant associations with environmental outcomes. Certain stoves appear to have stronger impacts: three stone fires have the greatest association with higher air pollution; biogas and electric are associated with the greatest reduction in air pollution.

This study yields an encouraging picture of the benefits to air quality (and presumably climate), livelihoods and forests from improved cookstove use in the Himalayan region.

Appendix A

PM Measurement

The PEM units were attached with Teflon tubing to pumps (SKC, Eighty Four, PA) running at 2 liters per minute. Sampling flow rates were measured thrice prior to the start of sampling and thrice when the PEM was removed using VWR acrylic flow meter #97004-644 (VWR, Radnor, PA). Flow rate was calculated as the average of the pre-flow and post-flow averages. The volume of air sampled was calculated by multiplying the flow rate by the total pump run time. The weight of accumulated particles was calculated by subtracting the weight of the filter paper before exposure from the weight of the filter paper after sampling, with each measurement done in triplicate on a microbalance that was zeroed between filters. Three samples were not included in the data analysis due to a negative net filter weight; 5 were excluded because the pump was stopped when the sample was collected due to filter loading. The $PM_{2.5}$ concentration was calculated as the weight of accumulated particles divided by the volume of air sampled.

In addition, we measured personal $PM_{2.5}$ exposure over approximately 24 hours using the MicroPEM version 3.2 (RTI International, Research Triangle Park, NC) with a 25 mm, 3 µm pore size Teflo filter (Pall Corporation). The MicroPEMs were calibrated before each sample using VWR acrylic flow meter #97004-640. The MicroPEM is a lightweight device that was worn around the neck and clipped to the cook's clothing near the neck. The cook was instructed to wear the device at all times other than sleeping or bathing, at which times it should be placed nearby. Two randomly selected households from the sample in each village were selected for personal exposure monitoring. Two samples were dropped due to missing weight data or faulty calibration.

Finally, outdoor ambient $PM_{2.5}$ exposure was measured over 24 hours at one randomly selected household in each village via a PEM sampler placed on the roof of a house; therefore, nine outdoor samples were collected, ranging from 10 to 170 $\mu g/m^3$. One sample was dropped due to missing weight data.

PAH Measurement

The PAH methods were developed in-house. They are modified (to extract filters instead of sediment) from those used by Clark et al. (2013). Dried air filter samples containing the collected particulates were cut in half and weighed. For PAH extraction, half of each filter sample was placed in a glass centrifuge tube with 1:1 acetone: hexane and spiked with a surrogate standard mix containing 6 deuterated PAHs (D10-2-methylnaphthalene, D10-fluorene, D10-fluoranthene, D12-chrysene, D12-perylene, and D12-indeno[1,2,3-c,d]pyrene) to assess recoveries. Samples were extracted by sonication, and the extract was concentrated to 0.2-0.5 mL using rapid evaporation under N2 (SpeedVac (ThermoSavant, Holbrook, NY, USA). Extracts were cleaned with solid phase extraction using activated silica and eluted with hexane. Purified extracts were concentrated under N2 to approximately 0.5 mL, and spiked with an internal standard mix containing D8-naphthalene, D10-anthracene, D10-pyrene, D12-benz[a]anthracene, and D12-benzo[a]pyrene. Prior to extraction, samples were randomized and split into 15 test batch sets. Each batch set included blanks (n=3), a matrix spike containing 100 µL of a PAH calibration standard (n=6) and extracted alongside samples, and a quality assurance/quality control sample consisting of an autosampler vial containing all surrogates, internal standards, and amount of PAH standard used for the matrix spike.

Samples were analyzed for 35 PAHs by gas chromatograph mass spectrometer (GC/MS; Agilent GC 6890N, MS 5975C mass selective detector. Agilent Newark, DE) in electron ionization mode (GC/EIMS) using select ion monitoring and pulsed splitless injection at 250 °C. Analytes were separated on a DB-5 column (30 m, 0.25 µm film thickness) using a thermal gradient (40 °C for 0.6 min, increase to 280 °C over 14.6 min, hold at 280 °C for 24 min). GC/MS data were quantified using MSD chemstation software, and for each batch, samples were blank-corrected by subtracting the average value of the blanks. Method detection limits (MDLs) were calculated for each PAH (MDL= (3* standard deviation of the analyte in the 3 blanks)/(average sample mass)). PAH samples with values that were <MDL were replaced with MDL/2 for statistical calculations.

Water Soluble Organic Carbon and Nitrogen

The concentration of WSOC and WSON (mass divided by total air sampled) as well as the fraction of total particulate that was WSOC or WSON were analyzed. Prior to sample extraction, 24 mL glass vials were thoroughly rinsed well with tap water, NanoUV water (Barnstead Infinity™ Ultrapure Water System, Thermo Scientific, 17.3 $M\Omega cm^{-1}$) then placed in an acid bath of 5% HCl and rinsed three additional times with NanoUV water. The vials were wrapped in aluminum foil and placed in a muffle furnace (Thermolyne™, Thermo Scientific) overnight to remove any organic matter remaining on the glassware. This protocol was applied to all glassware used during the experiment, while all other materials that came into contact with the filters were washed in a hot soap and water bath, then rinsed with water, then acetone (BDH, ASC Grade). Sub-samples were collected from each Teflon filter using an arch punch (C.S. Osborne & CO.) of 3/8" diameter. Each sub-sample was added to a pre-cleaned 24 mL glass vial and materials were re-cleaned to avoid cross contamination between samples, as described above. After the sample collection, 15 mL of NanoUV water was added to each vial using a volumetric pipette. To ensure the sample was completely embedded in the water, needles (BD PrecisionGlide™) were used to push the filters below the meniscus. The needles were held above the water by placing the end of the needle into a piece of Parafilm, which was wrapped around the neck of the vial. Sub-samples then were subjected to sonication for 30 minutes (Branson 8510 Ultrasonic Cleaner). Teflon filters

(Pall Corporation) were prepared and treated in an identical way as a method blank. Samples were analyzed using a total carbon analyzer (TOC-V_{CHS}, Shimadzu). An ASI-V autosampler was used to inject the samples into the TOC interface. A calibration curve was generated through a series of auto dilutions from a 10ppm stock solution of potassium hydrogen phthalate (KHP, Fisher Scientific) using the TOC Control-V software. NanoUV water samples were run to assess the concentrations of dissolved organics in the water and 5ppm check standards of KHP were run every 10 samples to assess the variability in the TOC measurements. The remaining fractions from the TOC analysis were diluted by adding 8 mL of NanoUV water to the each vial using a volumetric pipette and analyzed using a total nitrogen-measuring unit (TNM, Shimadzu). A calibration curve was generated through a series of auto dilutions from a 20ppm stock solution of glutamic acid. Glutamic acid and EDTA were check standards in this analysis. Check standards were run after every 10 samples. Filter loadings were determined by scaling the surface area of the sub-samples to the total surface area of the samples.

Five samples were unable to be analyzed; 93 filters were analyzed for WSOC and WSON mass. Samples with WSOC or WSON as a fraction of total PM that exceeded 100% were dropped leaving a 68 WSOC and 88 WSON.

Spirometry

The spirometer was calibrated daily using a 3L syringe (MicroLoop Spirometer, CareFusion, San Diego, CA). Spirometry was conducted on participants while sitting and wearing a nose clip, or pinching nose closed if facial jewelry interfered with the clip. Subjects completed at the spirometry test at least three times. Spirometry that met ATS criteria was included in the data analysis. Spirometry was collected from 102 cooks; 70 were dropped because they failed to meet ATS criteria, leaving 32 cooks (26 primary, 6 secondary; all but 1 female). Blood pressure was collected from 113 cooks (95 primary, 18 secondary); self-reported time spent in the hospital due to ARI was collected from each household (n=105) and 114 cooks answered the questions about incidence of cold/cough.

Supplemental Figures and Tables

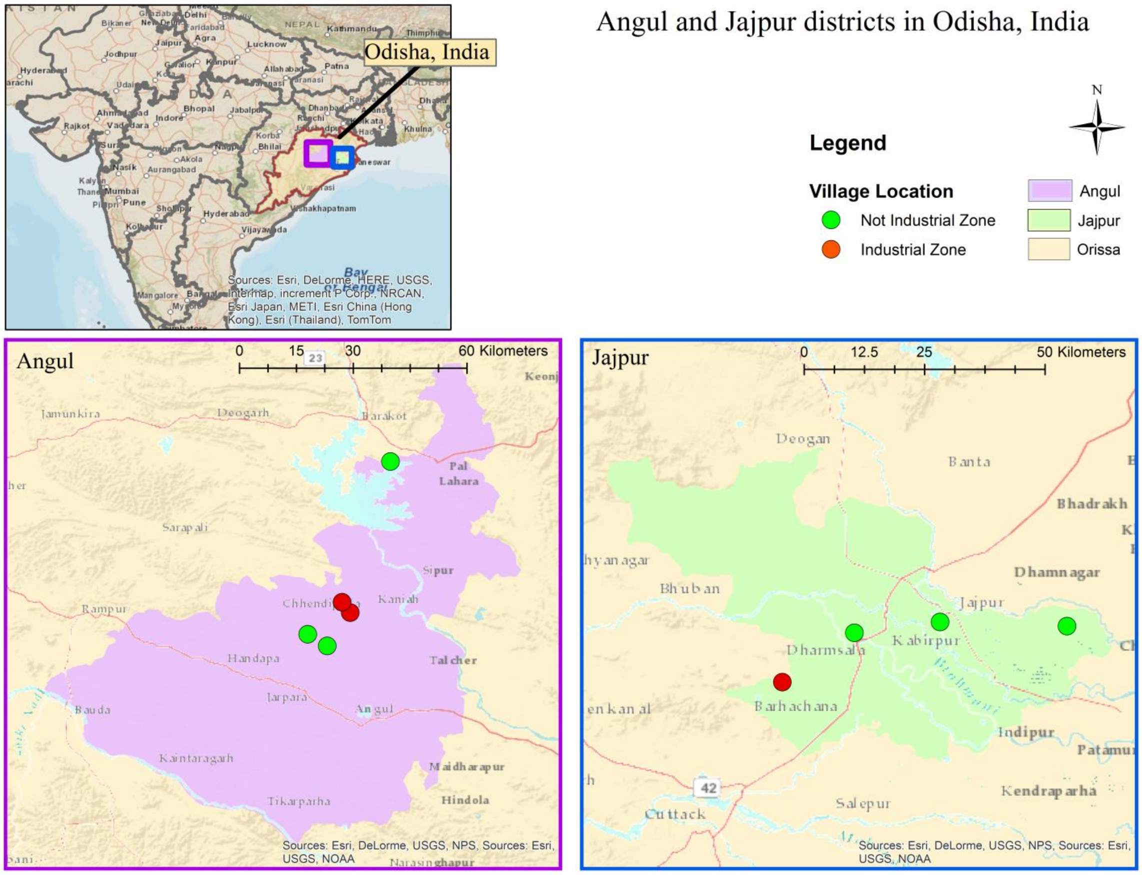

Figure 14. Map of Project Area and villages

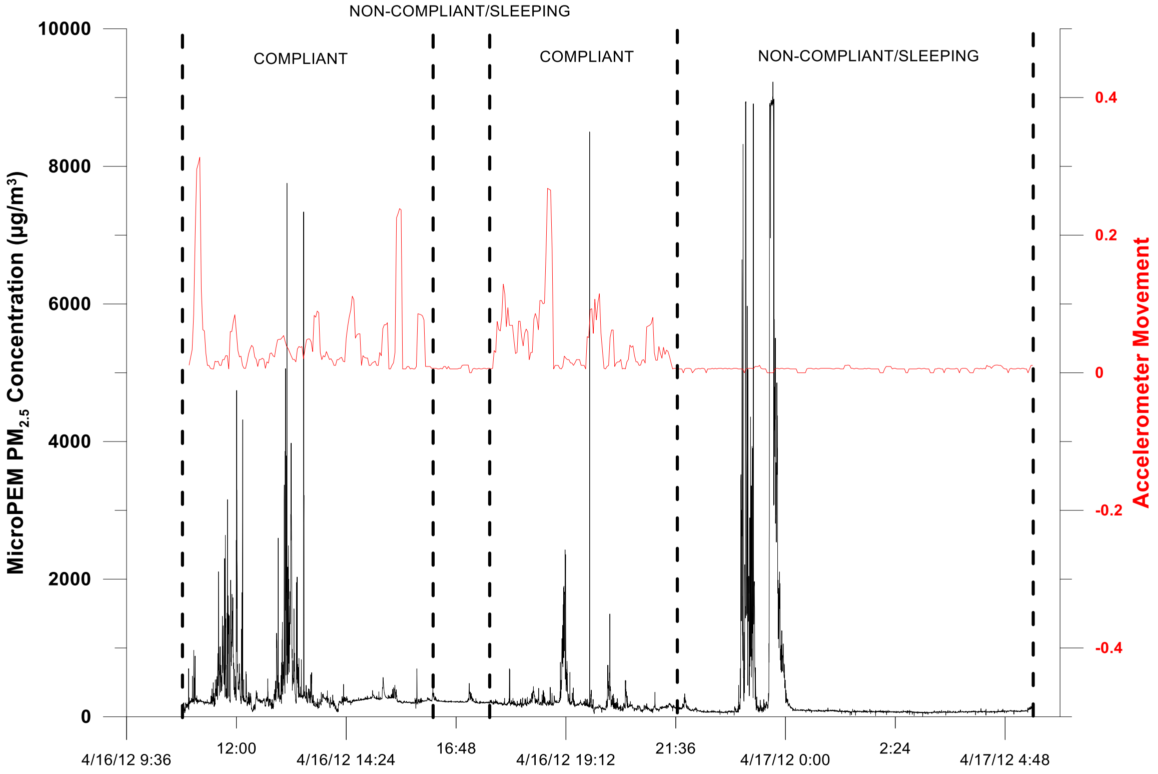

Figure 15. Personal PM2.5 exposure (left axis) from one cook over 24 hour period showing movement of monitor (right axis).

Table 16. Ordinary Least Squares regressions for firewood consumption (in kilograms; Models 1-3), household PM$_{2.5}$ (in log µg/m3; Models 4-6), and total of 345 measured PAHs (in log ng/m3; Models 7-8) with robust standard errors.

VARIABLES	(1) Firewood	(2) Firewood	(3) Firewood	(4) PM$_{2.5}$	(5) PM$_{2.5}$	(6) PM$_{2.5}$	(7) PAH[1]	(8) PAH[1]	(9) PAH[1]	(10) WSON	(11) WSON	(12) WSON
Uses any improved stove [2]	-4.77***	-5.33***	-5.19***	-0.57***	-0.66***	-0.69***	-1.15***	-1.37***	-1.29***	-0.18**	-0.23***	-0.22***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Education of primary cook		-0.02	-0.08		0.00	-0.00		0.03	0.03		-0.00	-0.01
		(0.86)	(0.39)		(0.89)	(0.87)		(0.26)	(0.36)		(0.70)	(0.47)
Outdoor PM value			0.01*			0.00**			0.00			0.00
			(0.06)			(0.04)			(0.68)			(0.59)
Log of total monthly expenditure		0.63	0.45		0.20**	0.18**		0.28	0.14		0.06	0.06
		(0.27)	(0.47)		(0.01)	(0.05)		(0.10)	(0.55)		(0.26)	(0.32)
Household size			-0.02			0.03			0.11*			0.00
			(0.94)			(0.37)			(0.07)			(0.92)
Electricity main source of lighting			-1.76			0.03			0.26			0.13
			(0.39)			(0.86)			(0.52)			(0.17)
Constant	5.22***	0.03	2.57	2.34***	0.67	0.46	4.61***	2.11	2.36	1.23***	0.79*	0.67
	(0.00)	(0.99)	(0.64)	(0.00)	(0.29)	(0.51)	(0.00)	(0.14)	(0.18)	(0.00)	(0.06)	(0.12)
Observations	105	92	82	99	89	80	87	77	71	85	76	69
R-squared	0.28	0.39	0.44	0.26	0.31	0.35	0.25	0.31	0.30	0.08	0.13	0.14

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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[1] Results similarly significant for 7 PAHs considered individually: chrysene, benzo(b)flouranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo[a,h]anthracene, indenopyrene

[2] Results similarly significant for use of biogas stove

Table 17. Ordinary Least Squares regressions for household $PM_{2.5}$ (in log μg/m3; Models 1-2), and total of 345 measured PAHs (in log ng/m3; Models 3-4) with robust standard errors.

LABELS	(1) $PM_{2.5}$	(2) $PM_{2.5}$	(3) Total PAH	(4) Total PAH
Use of any improved stove	-202.67***	-218.07***	-437.28**	-501.49*
	(0.00)	(0.00)	(0.03)	(0.07)
Location in industrial area	263.05***	285.86***	884.69**	885.44**
	(0.01)	(0.00)	(0.03)	(0.04)
Use of any improved stove in industrial area	-304.94***	-289.31**	-1,030.32**	-970.74**
	(0.00)	(0.01)	(0.02)	(0.04)
Education of primary cook		-0.91		26.25
		(0.90)		(0.36)
Log of total monthly expenditure		40.55		-105.89
		(0.30)		(0.60)
Household size		27.82*		126.82**
		(0.05)		(0.03)
Electricity main source of lighting		162.66*		347.98
		(0.07)		(0.36)
Constant	328.97***	-319.09	700.53***	388.74
	(0.00)	(0.30)	(0.00)	(0.80)
Observations	99	89	87	77
R-squared	0.29	0.36	0.19	0.24

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 18. Regressions for stove use and health, by age of cook: all ages[3]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1	(6) FEV1	(7) FVC	(8) FVC	(9) Cold	(10) Cold	(11) Hospital	(12) Hospital
Use of any improved stove	-3.27	-1.21	-2.86	-3.12	-0.19	-0.15	-0.17	-0.13	0.31	0.77	-1.22**	-1.85*
	(0.34)	(0.79)	(0.15)	(0.18)	(0.12)	(0.34)	(0.19)	(0.39)	(0.48)	(0.18)	(0.03)	(0.08)
Education of primary cook		-0.46		-0.01		-0.02		-0.03		0.08		-0.03
		(0.41)		(0.96)		(0.35)		(0.20)		(0.32)		(0.60)
Log of total monthly expenditure		-1.54		0.80		0.11		0.20		-0.30		1.63*
		(0.67)		(0.67)		(0.51)		(0.25)		(0.56)		(0.09)
Outdoor PM value (µg/m^3)		-0.01		-0.02		-0.00		-0.00		-0.01**		0.01
		(0.76)		(0.42)		(0.18)		(0.26)		(0.03)		(0.28)
Household size		0.34		0.33		0.05		0.04		0.15		0.05
		(0.75)		(0.55)		(0.28)		(0.41)		(0.25)		(0.80)
Electricity main source of lighting		3.79		-0.06		-0.41		-0.31		0.60		0.84
		(0.63)		(0.99)		(0.21)		(0.32)		(0.69)		(0.36)
	80.64***	89.49***	54.20***	49.80***	2.10***	2.04	2.10***	1.01	-3.88***	-4.49	2.22***	-12.86*
Constant	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.17)	(0.00)	(0.51)	(0.01)	(0.19)	(0.00)	(0.08)
Observations	113	89	113	89	32	24	32	24	114	90	105	82
R-squared	0.13	0.13	0.12	0.14	0.37	0.55	0.45	0.63	0.05	0.16	0.03	0.18

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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[3] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).
Results were similar for hypertension (no significant association between use of ICS and hypertension). Regressions were underspecified for normal FEV1.

Table 19. Regressions for stove use and health, by age of cook: <35[4]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1	(6) FEV1	(7) FVC	(8) FVC	(9) Cold	(10) Cold	(11) Hospital	(12) Hospital
Use of any improved stove	-4.49	-3.38	-3.38	-6.78**	0.08	0.47*	0.16	0.68	0.77	1.57	-1.87**	-1.65**
	(0.28)	(0.54)	(0.24)	(0.05)	(0.36)	(0.08)	(0.18)	(0.10)	(0.31)	(0.21)	(0.04)	(0.03)
Education of primary cook		-0.02		0.20		-0.06*		-0.09*		-0.07		-0.05
		(0.97)		(0.57)		(0.09)		(0.10)		(0.51)		(0.68)
Log of total monthly expenditure		-1.26		1.84		0.63		1.00		1.63		1.87*
		(0.80)		(0.53)		(0.11)		(0.13)		(0.15)		(0.05)
Outdoor PM value		0.02		-0.01		-0.00		-0.00		-0.00		-0.00
		(0.73)		(0.74)		(0.23)		(0.35)		(0.97)		(0.63)
Household size		0.39		-0.06		-0.14		-0.22		-0.21		0.02
		(0.79)		(0.94)		(0.15)		(0.18)		(0.45)		(0.93)
Electricity main source of lighting		8.21		4.08		1.15		1.85		-1.45		0.91
		(0.28)		(0.37)		(0.13)		(0.15)		(0.35)		(0.40)
Constant	83.93***	101.28**	34.51**	25.74	4.23***	1.69	4.85***	0.22	-8.59*	-20.49**	2.53***	-13.76**
	(0.00)	(0.02)	(0.02)	(0.30)	(0.00)	(0.11)	(0.00)	(0.76)	(0.06)	(0.04)	(0.01)	(0.04)
Observations	49	37	49	37	14	10	14	10	49	37	42	30
R-squared	0.12	0.21	0.17	0.31	0.71	1.00	0.63	1.00	0.13	0.26	0.04	0.36

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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[4] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).
Results were similar for hypertension (no significant association between use of ICS and hypertension). Regressions were underspecified for normal FEV1

Table 20. Regressions for stove use and health, by age of cook: ≥35[5]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1	(6) FEV1	(7) FVC	(8) FVC	(9) Cold	(10) Cold	(11) Hospital	(12) Hospital
Use of any improved stove	-3.60	-1.44	-2.72	-3.19	-0.29*	0.00	-0.29	-0.09	0.32	2.07*	-0.81	-2.02
	(0.54)	(0.85)	(0.36)	(0.37)	(0.09)	(0.99)	(0.10)	(0.71)	(0.57)	(0.06)	(0.27)	(0.22)
Education of primary cook		-0.72		-0.05		0.00		0.01		0.17		-0.04
		(0.42)		(0.91)		(0.94)		(0.87)		(0.17)		(0.71)
Log of total monthly expenditure		-0.27		1.59		0.11		0.18		-1.59**		1.43
		(0.96)		(0.54)		(0.61)		(0.41)		(0.02)		(0.24)
Outdoor PM value		-0.07		-0.04		-0.00*		-0.00*		-0.02**		0.02
		(0.20)		(0.19)		(0.06)		(0.07)		(0.02)		(0.14)
Household size		0.33		0.57		0.12		0.08		0.21		0.07
		(0.80)		(0.43)		(0.17)		(0.31)		(0.25)		(0.78)
Electricity main source of lighting		4.81		-3.44		-0.69**		-0.65**				
		(0.30)		(0.12)		(0.02)		(0.02)				
Constant	71.50***	67.90	55.09***	51.39**	1.28**	3.74*	1.31**	2.65	-6.93***	-0.46	1.97***	-10.62
	(0.00)	(0.11)	(0.00)	(0.01)	(0.01)	(0.07)	(0.02)	(0.17)	(0.00)	(0.93)	(0.00)	(0.23)
Observations	64	52	64	52	18	14	18	14	64	50	63	52
R-squared	0.12	0.18	0.09	0.14	0.44	0.84	0.57	0.88	0.09	0.35	0.02	0.17

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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[5] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).
Results were similar (not significant) for hypertension and underspecified for normal FEV1.

Table 21. Regressions for household PM$_{2.5}$ and health by age: all ages[6]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1	(6) FEV1	(7) FVC	(8) FVC	(9) Cold	(10) Cold	(11) Hospital	(12) Hospital
Household PM$_{2.5}$ (log μg/m^3)	2.21	1.93	1.84	1.83	0.26	-0.02	0.29	-0.07	-0.12	-0.00	1.29**	1.05*
	(0.40)	(0.53)	(0.24)	(0.25)	(0.13)	(0.94)	(0.12)	(0.77)	(0.75)	(1.00)	(0.03)	(0.08)
Education of primary cook		-0.52		-0.10		-0.04		-0.04		0.07		-0.06
		(0.34)		(0.72)		(0.13)		(0.10)		(0.34)		(0.36)
Log of total monthly expenditure		-1.97		-0.11		0.12		0.22		-0.01		1.17
		(0.58)		(0.95)		(0.49)		(0.25)		(0.98)		(0.15)
Outdoor PM value (μg/m^3)		-0.02		-0.03		-0.00		-0.00		-0.01**		0.01
		(0.54)		(0.20)		(0.12)		(0.25)		(0.02)		(0.44)
Household size		0.20		0.29		0.05		0.05		0.09		0.05
		(0.84)		(0.59)		(0.33)		(0.40)		(0.49)		(0.79)
Electricity main source of lighting		3.94		-0.31		-0.41		-0.31		0.58		0.60
		(0.54)		(0.88)		(0.27)		(0.38)		(0.67)		(0.44)
Constant	75.44***	90.69***	50.35***	54.74***	1.42***	2.27	1.35***	1.23	-4.05**	-6.11*	-0.96	-11.29*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.20)	(0.01)	(0.50)	(0.03)	(0.06)	(0.36)	(0.10)
.												
Observations	107	87	107	87	28	22	28	22	108	88	99	80
R-squared	0.13	0.14	0.12	0.13	0.39	0.57	0.48	0.64	0.05	0.15	0.04	0.14

Robust p values in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

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[6] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).

Results were similar (not significant) for association between household PM2.5 and hypertension; PM2.5 was not significantly associated with normal FEV1 in the regression with the smallest set of controlas, and underspecified when all controls were added.

Table 22. Regressions for household $PM_{2.5}$ and health by age: <35 years [7]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1[8]	(6) FVC[8]	(7) Cold	(8) Cold	(9) Hospital	(10) Hospital
Log $PM_{2.5}$	1.77	0.65	0.07	0.26	-0.09	-0.09	0.24	-0.31	0.97**	0.77*
	(0.47)	(0.81)	(0.97)	(0.90)	(0.52)	(0.68)	(0.66)	(0.57)	(0.02)	(0.09)
Education of primary cook		-0.23		-0.11				-0.03		-0.13
		(0.73)		(0.74)				(0.75)		(0.33)
Log of total monthly expenditure		-2.22		0.51				1.75		1.55
		(0.66)		(0.87)				(0.11)		(0.10)
Outdoor PM value		0.01		-0.02				-0.00		-0.01
		(0.92)		(0.57)				(0.90)		(0.47)
Household size		0.48		0.15				-0.25		0.06
		(0.76)		(0.87)				(0.32)		(0.78)
Electricity main source of lighting		7.23		1.75				-0.65		0.49
		(0.49)		(0.63)				(0.66)		(0.63)
Constant	82.96***	111.15**	36.32**	41.64*	4.66***	5.29***	-8.57**	-20.23**	-0.12	-12.05*
	(0.00)	(0.02)	(0.01)	(0.09)	(0.00)	(0.01)	(0.02)	(0.03)	(0.88)	(0.08)
Observations	47	36	47	36	12	12	47	36	40	29
R-squared	0.13	0.21	0.16	0.22	0.73	0.58	0.10	0.22	0.02	0.33

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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[7] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).

Results for PM2.5 were negatively associated with hypertension in univariate models (controlling for age, BMI, gender); multivariate models underspecified due to limited incidence of hypertension. Normal FEV1 was not modeled because all middle aged cooks have normal FEV1.

[8] Multivariate regressions were underspecified due to limited small sample size

Table 23. Regressions for household PM$_{2.5}$ and health by age: ≥35 years of age[9]

LABELS	(1) Systolic BP	(2) Systolic BP	(3) Diastolic BP	(4) Diastolic BP	(5) FEV1	(6) FEV1	(7) FVC	(8) FVC	(9) Cold	(10) Cold	(11) Hospital	(12) Hospital
Log PM$_{2.5}$	3.99	4.36	4.07	4.41	0.28	-0.34	0.34	-0.16	-0.70	-0.12	1.57	1.32
	(0.43)	(0.47)	(0.17)	(0.17)	(0.28)	(0.67)	(0.19)	(0.85)	(0.23)	(0.88)	(0.17)	(0.31)
Education of primary cook		-0.69		-0.01		-0.02		-0.01		0.14		-0.04
		(0.46)		(0.98)		(0.77)		(0.92)		(0.22)		(0.71)
Log of total monthly expenditure		-0.84		0.29		0.29		0.26		-0.65		0.87
		(0.87)		(0.90)		(0.63)		(0.68)		(0.16)		(0.35)
Outdoor PM value		-0.08		-0.05		-0.00		-0.00		-0.02**		0.01
		(0.18)		(0.14)		(0.33)		(0.33)		(0.02)		(0.18)
Household size		-0.02		0.30		0.18		0.12		0.04		0.06
		(0.99)		(0.70)		(0.45)		(0.61)		(0.80)		(0.80)
Electricity main source of lighting		5.37		-2.42		-0.76		-0.67				0.10
		(0.17)		(0.26)		(0.21)		(0.27)				(0.90)
Constant	59.54**	61.14	43.17***	48.88**	0.75	3.55	0.73	2.83	-6.06**	-5.40	-1.63	-9.64
	(0.02)	(0.11)	(0.01)	(0.01)	(0.38)	(0.14)	(0.39)	(0.22)	(0.04)	(0.26)	(0.43)	(0.28)
Observations	60	51	60	51	16	13	16	13	60	49	59	51
R-squared	0.12	0.19	0.11	0.17	0.38	0.85	0.55	0.88	0.13	0.30	0.06	0.14

Robust p values in parentheses

*** p<0.01, ** p<0.05, * p<0.1

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[9] Columns 1-4 report blood pressure; columns 5-8 observed lung function; columns 9-10 binary incidence of cold/cough; columns 11-12 number of days household members spent in the hospital for the last episode of ARI. All analyses also control for age, BMI and gender except hospital days (because it was measured at the household not individual level). BP, spirometry, and days in hospital were analyzed using OLS models with robust standard errors (R¬2 reported). Incidence of cold/cough was modeled with logit (pseudo-R2 reported).

Results were similar (not significant) for hypertension and normal FEV1 (in the univariate model (controlling for age, BMI, gender); multivariate model was underspecified).

Appendix B

Air Pollution Measurements

The PEM units were attached with Teflon tubing to pumps (SKC, Eighty Four, PA) running at 2 liters per minute. Sampling flow rates were measured prior to the start and after completion of sampling (TSI 4143 flowmeter, Shoreview, MN). Flow rate was calculated as the average of the pre-flow and post-flow averages. The volume of air sampled was calculated by multiplying the flow rate by the total pump run time. Sampling pumps were powered by four D-cell batteries. Battery voltage was checked prior and following each sampling session to ensure sufficient power for a 24 hour continuous sampling session.

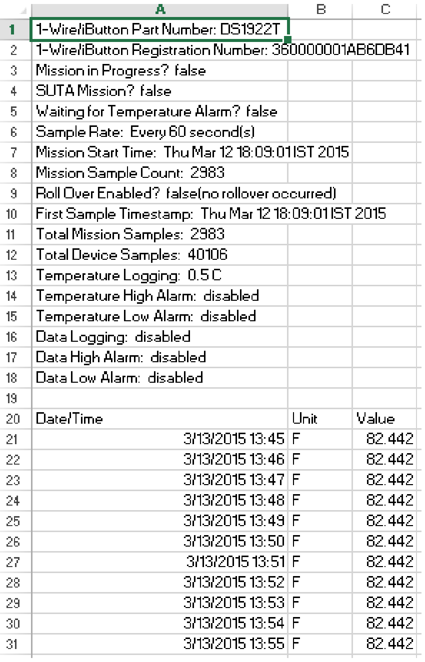
The weight of accumulated particles was calculated by subtracting the weight of the filter paper before exposure from the weight of the filter paper after sampling, with each measurement done in triplicate on a microbalance that was zeroed between filters. The filters were weighed at the Environmental Protection Agency in Research Triangle Park under controlled temperature and humidity (23 degrees C, 35% relative humidity). Filters were left exposed in these conditions for 24 hours before weighing for both pre- and post-measurement weights. After initial weighting, filters were placed in individually labelled cassettes wrapped with Teflon tape. After 24 hour exposure, filters were replaced in cassettes and wrapped with Teflon tape until post-weighing.

For quality control, a filter was placed in PEM monitors that were not attached to pumps and exposed to similar field conditions in each village. Blank correction was performed by subtracting the mean mass of field blanks (13 micrograms).

SUMS

A shortened code was created for each SUM (SUM1 – SUM 30). In the field, each SUM was activated in the field station and was placed in a numbered bag (e.g., SUM1, SUM2, etc.) until it was needed. SUMS were set to record the temperature once per minute. When we arrived at a house, a SUM was removed from the bag and placed on the stove/heater, the abbreviated SUM number was recorded for the appropriate stove type. After 24 hours, the field team removed the SUM from the stove and returned it to the field lab where data was downloaded.

A SUM was placed on every stove that the household reported using for cooking and/or heating. Following this protocol, we generated 290 unique SUMS records from all 208 households (each record contained a temperature measurement every minute for 24 hours). Each SUMS record was saved as a csv file using a program provided when the SUMS were purchased (the 1Wire Program)(Figure 16).



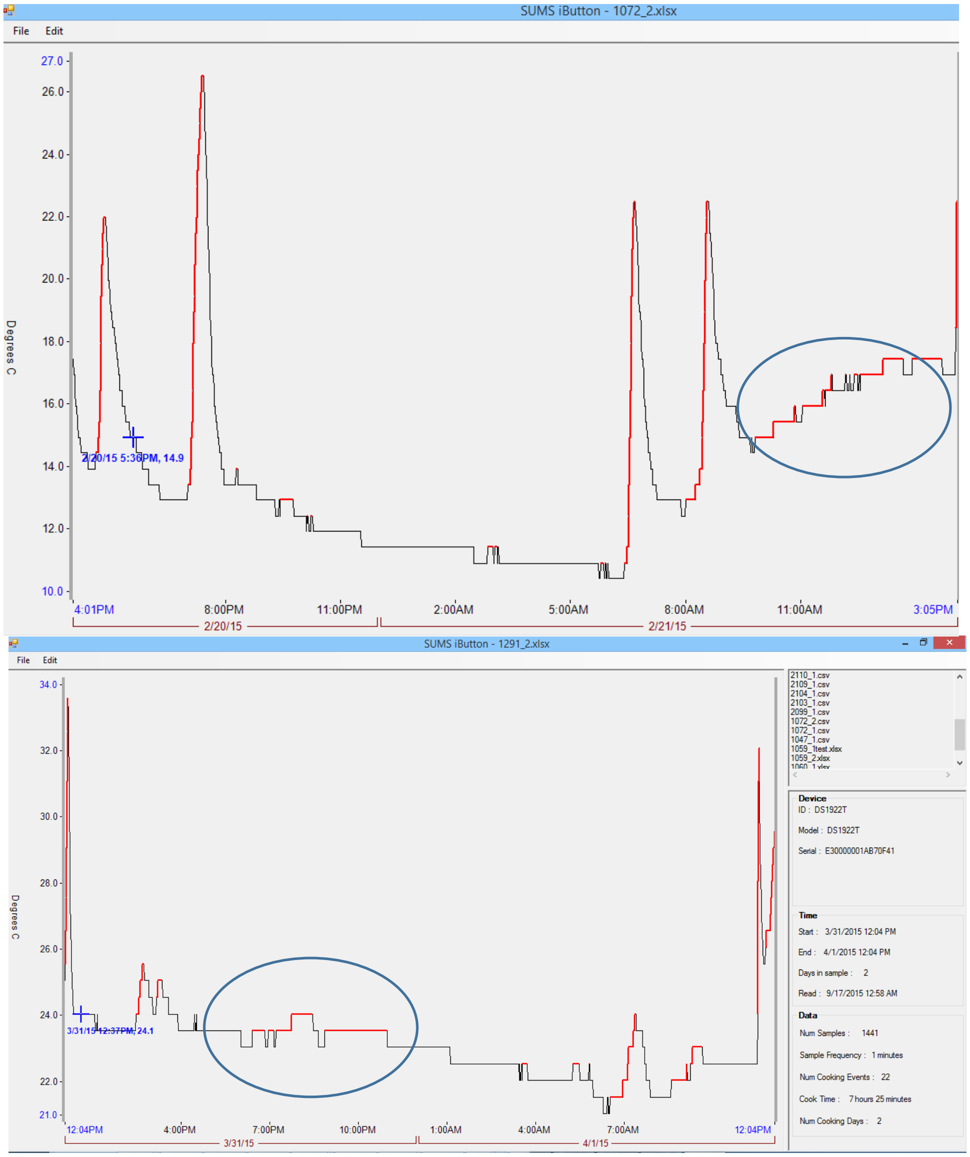
	A	B	C
1	1-Wire/iButton Part Number: DS1922T		
2	1-Wire/iButton Registration Number: 360000001AB6DB41		
3	Mission in Progress? false		
4	SUTA Mission? false		
5	Waiting for Temperature Alarm? false		
6	Sample Rate: Every 60 second(s)		
7	Mission Start Time: Thu Mar 12 18:09:01 IST 2015		
8	Mission Sample Count: 2983		
9	Roll Over Enabled? false(no rollover occurred)		
10	First Sample Timestamp: Thu Mar 12 18:09:01 IST 2015		
11	Total Mission Samples: 2983		
12	Total Device Samples: 40106		
13	Temperature Logging: 0.5 C		
14	Temperature High Alarm: disabled		
15	Temperature Low Alarm: disabled		
16	Data Logging: disabled		
17	Data High Alarm: disabled		
18	Data Low Alarm: disabled		
19			
20	Date/Time	Unit	Value
21	3/13/2015 13:45	F	82.442
22	3/13/2015 13:46	F	82.442
23	3/13/2015 13:47	F	82.442
24	3/13/2015 13:48	F	82.442
25	3/13/2015 13:49	F	82.442
26	3/13/2015 13:50	F	82.442
27	3/13/2015 13:51	F	82.442
28	3/13/2015 13:52	F	82.442
29	3/13/2015 13:53	F	82.442
30	3/13/2015 13:54	F	82.442
31	3/13/2015 13:55	F	82.442

Figure 16. Example of excel output downloaded from Stove Usage Monitor

Due to limitations with data storage that were not uncovered until after the conclusion of the research, the process of downloading data truncated each data file to a maximum of 8212 data rows. Some of the SUMs were activated but waiting to be used in a household for many days. Therefore, we find that about 20% of the SUMS records have partially or entirely incomplete data (the monitoring period occurred either during or after the 8212nd row).

Because the SUMS records often contained multiple days of data (from all days in which the SUM was active), the algorithm was capturing normal diurnal temperature variation and often classified it as cooking. Therefore, we trimmed all SUMs files to contain only the rows that were measured during the actual monitoring period. A spreadsheet with the start and stop time as recorded for the air pollution monitoring equipment in the household was used. All SUM records that fell outside of this time record were dropped.

We next imported each record into the SUMS iButton program provided by Berkeley Air Quality Monitoring Group. This program has four algorithms for identifying how many hours the stove was used for cooking and how many cooking events occurred. After trimming, the Berkeley Air algorithm “Slope with Slopeout” was used to determine stove use. This algorithm calculates that a cooking events begins when the temperature slope goes above 0.1, and the cooking event ends when the slope hits -0.05. Next, each SUMS record was reviewed by counting each minute of stove use or non-use that the SUMS program had coded incorrectly; adjustments to the total cooking time were made accordingly. For example, horizontal lines without any change in temperature over long periods were not considered cooking and were subtracted from the total cooking time (Figure 17). Similarly, gradual increases in stove temperature that matched ambient temperature were not considered cooking and were recoded. The adjusted SUMs time was used in the statistical analyses. Adjustments were made to 193 files. The average adjustment time was -134 minutes. The adjusted SUMs time was used in the statistical analyses.



2110_1.csv
2109_1.csv
2104_1.csv
2103_1.csv
2099_1.csv
1072_2.csv
1072_1.csv
1047_1.csv
1059_1test.xlsx
1059_2.xlsx

Device
ID : DS1922T
Model : DS1922T
Serial : E30000001AB70F41

Time
Start : 3/31/2015 12:04 PM
End : 4/1/2015 12:04 PM
Days in sample : 2
Read : 9/17/2015 12:58 AM

Data
Num Samples : 1441
Sample Frequency : 1 minutes
Num Cooking Events : 22
Cook Time : 7 hours 25 minutes
Num Cooking Days : 2

Figure 17. Examples of Stove Usage Monitor stove use records that needed adjustment

Supplemental Figures and Tables

Table 24. Stove Ownership

Stove Type	**Mean (S.D.)**
Any Traditional Stove	94% (0.23)
Any Improved Stove (incl. improved biomass)	53% (0.5)
Any clean Stoves (no solid fuel or kerosene)	51% (0.5)
Traditional	
Mud Stove	13% (0.34)
Angheti (traditional stove with chimney)	40% (0.49)
3 Stone Fire	44% (0.5)
Kerosene Stove	0% (0)
Sagarh (traditional stove)	17% (0.38)
Improved	
LPG stove	42% (0.5)
Electric stove (other than G-Coil)	2% (0.14)
G-Coil electric stove	9% (0.29)
Electric Heater	0% (0.07)
Biogas	1% (0.1)
Improved biomass stove	2% (0.14)

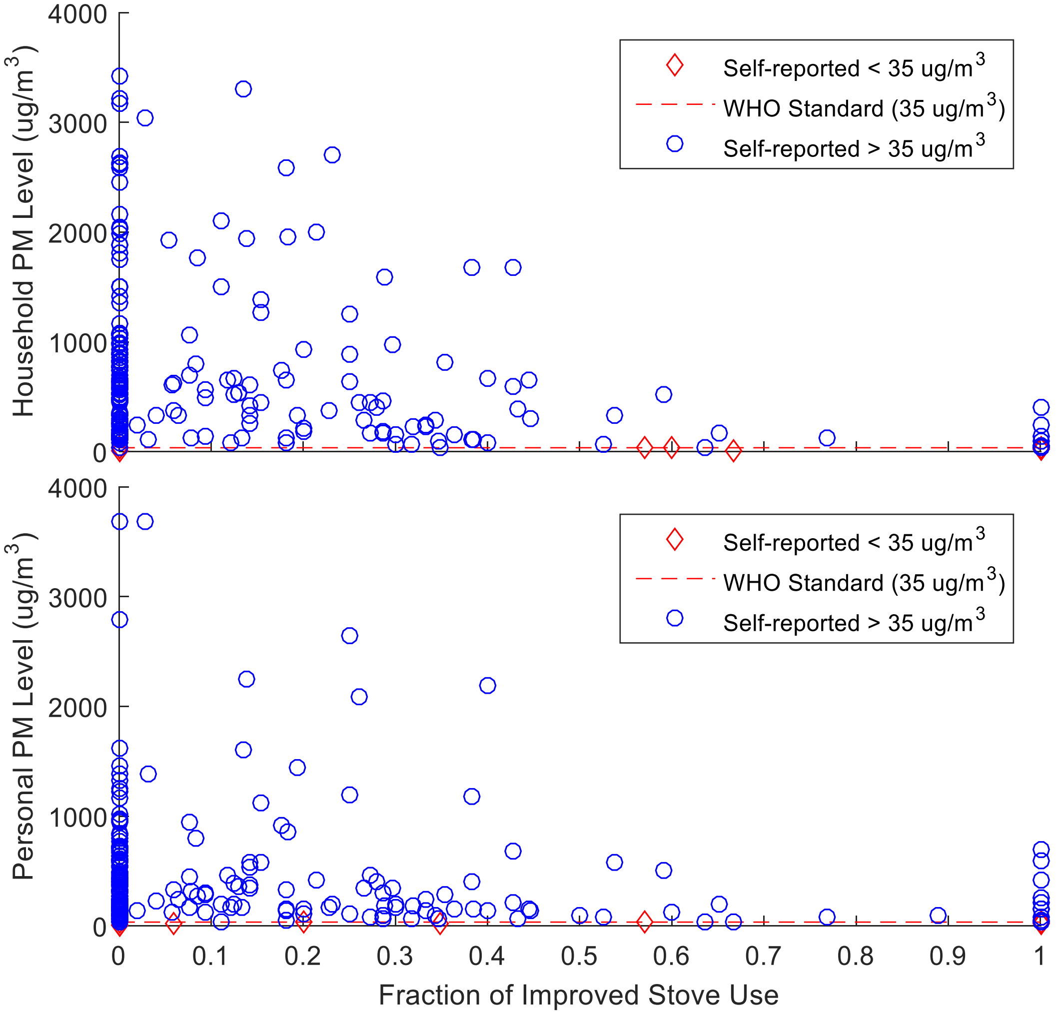


Figure 18. Comparison of fraction of improved stove use and firewood use, household $PM_{2.5}$ and personal $PM_{2.5}$ concentrations

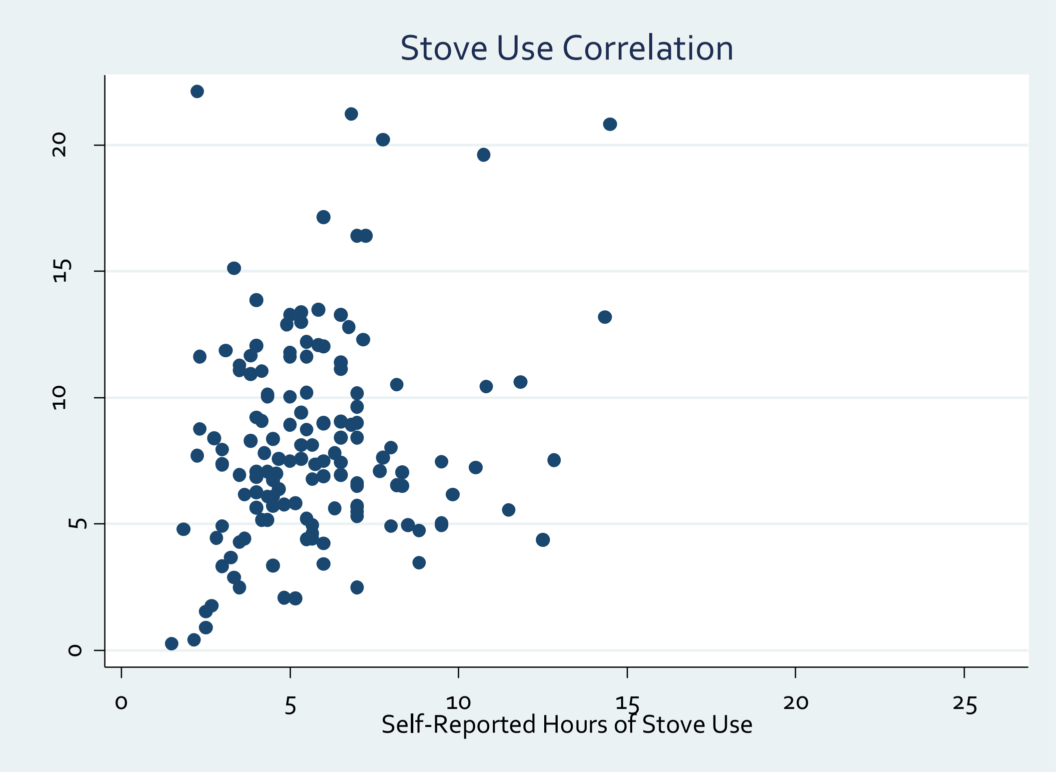


Figure 19. Correlation between self reported and objective measures of stove use.

Table 25. Descriptive statistics of outcomes different metrics of any ICS use. Reported p-values are from two-sided t-tests for differences in means for continuous variables and Pearson's chi squared tests for categorical variables (* p<0.01, ** p<0.05, * p<0.1).**

Household Characteristics	Full Sample		Self-Reported					Self-Reported (subset which also has SUMs data)					SUMS (Adjusted)				
			Only Traditional Stove Use		Any ICS Use		p-value	Only Traditional Stove Use		Any ICS Use		p-value	Only Traditional Stove Use		Any ICS Use		p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs	Mean (s.d.)	Obs	
Concentration of PM in ug/m3 for PEM in household	714.4 (756.1)	204	845.8 (791.4)	100	588 (701.4)	104	0.01**	749.8 (671.9)	69	615 (669.5)	73	0.18	760.3 (681.1)	67	609.1 (659.5)	75	0.18
Concentration of PM in ug/m3 for PEM cook bag	443.6 (529.8)	201	466.1 (449.9)	98	422.1 (597.3)	103	0.55	398.7 (363)	69	481.4 (672.6)	73	0.84	431.8 (397.1)	67	449.6 (650.9)	75	0.84
Household PEM: Log (ln) ug/m3 PM over 24 hrs	6 (1.3)	203	6.3 (1.1)	100	5.7 (1.4)	103	0***	6.2 (1)	69	5.8 (1.3)	72	0.03**	6.2 (1.01)	67	5.8 (1.3)	74	0.03 **
Cook PEM: Log (ln) ug/m3 PM over 24 hrs	5.5 (1.3)	200	5.7 (1.4)	97	5.4 (1.2)	103	0.13	5.5 (1.5)	68	5.5 (1.2)	73	0.79	5.5 (1.6)	67	5.5 (1.15)	74	0.79
Amount of firewod used in 24 hrs - weighed	9.7 (5.7)	208	10.9 (5.6)	101	8.5 (5.6)	107	0***	10.9 (6)	70	8.5 (5.6)	75	0.06*	10.6 (4.6)	68	8.8 (6.7)	77	0.06 *
Pulse rate (measured with oximeter) of cook wearing sampler	78 (10.5)	187	77.7 (10.3)	92	78.2 (10.6)	95	0.73	76.7 (9.8)	64	79.5 (10.5)	68	0.15	76.8 (9.6)	64	79.4 (10.7)	68	0.15
Blood oxygen level (measured with oximeter) of cook wearing	96.4 (3.96)	187	96.6 (4.1)	92	96.3 (3.9)	95	0.61	96.8 (2.6)	64	96.4 (4.2)	68	0.69	96.4 (4.1)	64	96.7 (2.9)	68	0.69
Cook had runny eyes from smoke over past 24 hours	66% (0.48)	208	70% (0.46)	101	62% (0.49)	107	0.19	70% (0.46)	70	60% (0.49)	75	0.21	72% (0.45)	68	58% (0.5)	77	0.09 *
Cook had cold / cough over past 24 hours	22% (0.41)	208	21% (0.41)	101	22% (0.42)	107	0.77	24% (0.43)	70	24% (0.43)	75	0.97	26% (0.44)	68	22% (0.42)	77	0.54
Cook had sore throat over past 24 hours	22% (0.42)	208	23% (0.42)	101	21% (0.41)	107	0.82	26% (0.44)	70	23% (0.42)	75	0.67	26% (0.44)	68	22% (0.42)	77	0.54
Cook had running/blocked nose/sinusitis over past 24 hours	12% (0.33)	208	14% (0.35)	101	10% (0.31)	107	0.43	17% (0.38)	70	13% (0.34)	75	0.52	19% (0.4)	68	12% (0.32)	77	0.21
Cook had faster than normal breathing over past 24 hours	13% (0.34)	208	12% (0.33)	101	15% (0.36)	107	0.52	13% (0.34)	70	16% (0.37)	75	0.59	18% (0.38)	68	12% (0.32)	77	0.31
Cook had wheeing in chest/nose over past 24 hours	13% (0.34)	208	10% (0.3)	101	16% (0.37)	107	0.2	9% (0.28)	70	17% (0.38)	75	0.12	10% (0.31)	68	16% (0.37)	77	0.35
Hrs cook gathered fuels in past 24 hrs	0.2 (0.8)	208	0.4 (1)	101	0.1 (0.58)	107	0.02**	0.5 (1.1)	70	0.1 (0.6)	75	0.01**	0.5 (1.16)	68	0.1 (0.5)	77	0.01 **
Hrs cook gathered and prepared fuels in past 24 hrs	0.3 (0.8)	208	0.5 (1)	101	0.2 (0.6)	107	0.02**	0.6 (1.1)	70	0.2 (0.6)	75	0.01**	0.6 (1.17)	68	0.2 (0.6)	77	0.01 **

Table 26. Descriptive statistics of outcomes different metrics of intense ICS use. Reported p-values are from two-sided t-tests for differences in means for continuous variables and Pearson's chi squared tests for categorical variables (* p<0.01, ** p<0.05, * p<0.1).**

Household Characteristics	Self-Reported							Self-Reported (subset which also has SUMs data)					SUMS (Adjusted)				
	Full Sample		Low ICS Use <=50%		High ICS Use (>=50%)		p-value	Low ICS Use <=50%		High ICS Use (>=50%)		p-value	Low ICS Use <=50%		High ICS Use (>=50%)		p-value
	Mean (s.d.)	Obs	Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs	Mean (s.d.)	Obs		Mean (s.d.)	Obs	Mean (s.d.)	Obs	
Concentration of PM in ug/m3 for PEM in household	714.4 (756.1)	204	787.5 (767.5)	182	109.1 (139.7)	22	0***	742.3 (678.4)	128	115.8 (127.2)	14	0***	745.1 (686.9)	112	439.4 (558.1)	30	0.02**
Concentration of PM in ug/m3 for PEM cook bag	443.6 (529.8)	201	475.9 (550)	178	193.5 (208.4)	23	0.01**	469.2 (564.2)	127	204.1 (226.1)	15	0.07*	489.3 (586)	112	261.4 (289.4)	30	0.04**
Household PEM: Log (ln) ug/m3 PM over 24 hrs	6 (1.3)	203	6.2 (1.1)	182	4.1 (1.3)	21	0***	6.2 (1)	128	4.1 (1.4)	13	0***	6.2 (0.99)	111	5.2 (1.6)	30	0***
Cook PEM: Log (ln) ug/m3 PM over 24 hrs	5.5 (1.3)	200	5.6 (1.3)	177	4.7 (1.1)	23	0***	5.6 (1.4)	126	4.8 (1.1)	15	0.02**	5.6 (1.4)	111	5.1 (1.01)	30	0.08*
Amount of firewod used in 24 hrs - weighed	9.7 (5.7)	208	10.6 (5.4)	184	3.1 (3.6)	24	0***	10.6 (5.6)	129	2.5 (2.6)	16	0***	10.7 (5.7)	115	5.9 (5.2)	30	0***
Pulse rate (measured with oximeter) of cook wearing sampler	78 (10.5)	187	77.7 (10.3)	167	80.8 (11.4)	20	0.2	77.4 (9.9)	118	84.6 (11)	14	0.01**	78.2 (10)	105	77.8 (11.5)	27	0.85
Blood oxygen level (measured with oximeter) of cook wearing	96.4 (3.96)	187	96.4 (4.1)	167	96.9 (3)	20	0.59	96.6 (3.5)	118	96.4 (3.4)	14	0.88	96.5 (3.7)	105	96.7 (2.6)	27	0.86
Cook had runny eyes from smoke over past 24 hours	66% (0.48)	208	70% (0.46)	184	38% (0.49)	24	0.00***	68% (0.47)	129	38% (0.5)	16	0.02**	68% (0.47)	115	53% (0.51)	30	0.14
Cook had cold / cough over past 24 hours	22% (0.41)	208	22% (0.42)	184	17% (0.38)	24	0.53	25% (0.43)	129	19% (0.4)	16	0.59	23% (0.43)	115	27% (0.45)	30	0.72
Cook had sore throat over past 24 hours	22% (0.42)	208	23% (0.42)	184	13% (0.34)	24	0.23	26% (0.44)	129	13% (0.34)	16	0.25	25% (0.44)	115	20% (0.41)	30	0.55
Cook had running/blocked nose/sinusitis over past 24 hours	12% (0.33)	208	13% (0.33)	184	8% (0.28)	24	0.56	16% (0.37)	129	6% (0.25)	16	0.29	16% (0.36)	115	13% (0.35)	30	0.75
Cook had faster than normal breathing over past 24 hours	13% (0.34)	208	13% (0.34)	184	17% (0.38)	24	0.63	14% (0.35)	129	19% (0.4)	16	0.61	15% (0.36)	115	13% (0.35)	30	0.84
Cook had wheeing in chest/nose over past 24 hours	13% (0.34)	208	13% (0.33)	184	17% (0.38)	24	0.57	12% (0.33)	129	19% (0.4)	16	0.48	13% (0.34)	115	13% (0.35)	30	0.97
Hrs cook gathered fuels in past 24 hrs	0.2 (0.8)	208	0.3 (0.9)	184	0 (0)	24	0.14	0.3 (0.9)	129	0 (0)	16	0.18	0.3 (0.99)	115	0 (0.2)	30	0.09*
Hrs cook gathered and prepared fuels in past 24 hrs	0.3 (0.8)	208	0.4 (0.9)	184	0 (0.1)	24	0.05*	0.4 (1)	129	0 (0.1)	16	0.09*	0.5 (1.02)	115	0.1 (0.2)	30	0.06*

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Biography

Birth Place and Date: Cincinnati, Ohio, USA; January 8, 1984

Education:

University of North Carolina Gillings School of Global Public Health, Chapel Hill, NC, MASTER OF SCIENCE IN PUBLIC HEALTH, Environmental Science and Engineering, 2009

Emory University, Atlanta, GA, BACHELOR OF SCIENCE, Environmental Studies, *summa cum laude*, 2006

Publications:

Bhojvaid, V., Jeuland, M., Kar, A., Lewis, J. J., Pattanayak, S. K., Ramanathan, N., … Rehman, I. H. 2014. How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. *International Journal of Environmental Research and Public Health*, 1341–1358. doi:10.3390/ijerph110201341

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Lewis, J.J., and S.K. Pattanayak. 2012. Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives,* 120(5), 637-45.

Fellowships and Awards:

- EPA Science to Achieve Results (STAR) Doctoral Fellowship Grant, *US EPA,* 2012- 2015
- Fellow in *National Network for Environmental Management Studies* (NNEMS), US EPA, 2008 & 2009
- Senior Fellow in *Weiss Urban Livability Program,* UNC Chapel Hill, 2008-2009
- Graduate Fellow in *Weiss Urban Livability Program,* UNC Chapel Hill, 2007-2008
- Master's Merit Assistantship, *Environmental Science and Engineering Dept.,* UNC Chapel Hill, 2007-2008

Membership in Professional Societies:

International Society of Environmental Epidemiology

Delta Omega (Honorary Society in Public Health)