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Cooking Up Change in the Himalayas: Experimental Evidence on Cookstove Promotion

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Abstract

Improved cookstoves can potentially deliver triple wins by improving household health, particularly for women cooks and their children, by preserving local forests and air quality, and by mitigating global climate change impacts. Despite these promises, cleaner cooking technologies have run into major translation challenges, and there is growing pessimism about the potential for their successful diffusion, dissemination and adoption in rural areas. We report on a 3 year study from the central Himalayan region of India that challenges this pessimism. Our study applied mixed methods that combined expert solicitation, focus groups, baseline surveys, and extensive piloting to define an experimental intervention. Household in the intervention arm (762 households selected randomly from a larger sample of 1,051 households) received a package of information, demonstration, financing, and one of three randomized rebate amounts, which were delivered conditional on use of a purchased stove. The control arm (289 households) received nothing. All treatment households were given a choice of two stoves – one electric coil stove, the other a natural draft rocket stove – that were similar in price. Follow-up measurements revealed that this multipronged demand promotion strategy led to 52% of treatment households purchasing an improved cook stoves (ICS) (compared to 0% purchase of these stoves among control households). Furthermore, sales were higher (a) for electric stoves than natural draft stoves, and (b) when higher rebates were offered. We also found that households in the treatment group reduced solid fuel consumption by 1-2 kg/day on average and lowered time spent collecting solid fuel by 10-30 minutes per day. Without including the emissions from electric stoves, the reduction in biomass fuel use translates into emissions savings that are worth $0.34 (with only Kyoto protocol pollutants) and $1.35 (accounting for black carbon, organic carbon, and carbon monoxide emissions) per household per month. Although these findings point to a high latent demand for ICS, this demand is unfortunately not matched by a robust supply chain, as evidenced by the complete lack of adoption of similar technologies in the control group. Nevertheless the study provides several valuable lessons and we conclude with some recommendations related to the challenges of scaling up sustained use of improved energy products in rural settings.

I. INTRODUCTION: WHY ANOTHER STOVE STUDY?

Improved cookstoves (ICS) have the potential to deliver the triple dividends of household health and time savings, local environmental quality improvements, and reduced impacts on

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climate.[2] However, despite clear scientific evidence on the efficacy of these innovations, these technologies have run into major translation challenges that have impeded their widespread diffusion and dissemination. Barriers to adoption revolve around a complex web of issues, of which, we highlight the critical role of household preferences (e.g., for different stove attributes) and the context of local markets and supply chain. The potential interactions of these factors raise real difficulties with external validity, since standard evaluation methods focus on single channels or implementation factors. Thus, there is a growing refrain of calls for applied research to develop a more refined understanding of these challenges.

Evidence from environmental health behavior adoption studies points to a number of preconditions that must be satisfied if people are to invest in and/or use new technologies (e.g., piped water, water filters, private latrines, or insecticide treated bed nets). The main explanations and empirical tests of this behavioral phenomenon center around arguments that potential stove users do not know and/or do not care about benefits, or cannot pay (i.e., unable to finance) or are not willing to pay prevailing prices (i.e. demand is too low) for the technologies. The household production framework provides a useful construct for considering when households will invest in and use improved stoves; that is, only if their perceived gains exceed costly changes (Pattanayak & Pfaff, 2009). This framework also predicts what needs to change (e.g., information), who will likely adopt new technologies (e.g., educated), and what institutions (e.g., NGOs) can facilitate the required changes. These three insights are particularly helpful because of the overall focus on scaling up and on external validity.

Given this framework, our study objectives were to: (1) update and refine common theories of behavior change based on the field realities in the Himalayan region of northern India; (2) derive and test predictions of which types of interventions can increase the adoption and use of ICS, on the basis of reliable methods of data collection and analysis to learn about ICS adoption and impacts.

Our general evaluation plan for evaluating the features of stove interventions drew on a decade long program of research on behavior change interventions in rural India (Pattanayak et al., 2009; Hamoudi et al., 2012; Bhojvaid et al., 2014). Furthermore, the plan drew on cookstove-specific evidence from two systematic analyses. In the first, multivariate regression analysis of global data from stove dissemination by members of the Partnership for Clean Indoor Air suggested that stove sales are influenced by product characteristics (e.g., testing,

[2] Note that we include electric and LPG stoves in our definition of ICS, and do not limit it to biomass burning stoves alone. Some recent high profile editorials in *Science* confirm this emphasis on modern stoves such as gas and electric stoves (Smith, 2014; 2002).

price) and institutional factors (Lewis et al., 2013). A second systematic review of published quantitative studies of stove adoption suggested that education, credit, social status, and the fuel price all influence the demand for ICS (Lewis and Pattanayak, 2012).

II. Significance of Study

At the time of conception of this research study, there had been very few studies of the household demand for ICS (Lewis & Pattanayak, 2012), and those that had been conducted were almost exclusively observational. The past few years however have seen a notable increase in prominent social science research on ICS, using well-established methodologies to measure demand as well as impact evaluation designs (Miller & Mobarak, 2011; Bensch & Peters, 2011; Duflo, Greenstone & Hanna, 2012; Levine et al., 2013). Each of these studies has provided new and valuable insights related to the cookstove adoption problem. Two studies – Bensch & Peters (2011) and Duflo et al. (2012) – use randomized experiments to investigate household use and benefits from use of ICS, in Senegal and Odisha, India, respectively. They obtain very different results; Bensch & Peters report near universal use of the ICS and fuel savings and respiratory health improvements, while Duflo et al. find that very few households persist in using the ICS stoves over the long term, and that their use may even entail negative welfare effects. Mobarak et al. (2012) and Miller & Mobarak (2011) argue on the basis of survey evidence and sales experiments that demand for ICS is very low, particularly among male respondents, while women express greater interest in ICS but do not have the resources needed to purchase them. Levine et al. (2013) finally find that sales offers with reduced free trials and time payments greatly increase adoption, because these reduce the risk of adopting a stove and ease poor households' liquidity constraints.

Even with this additional research impetus on ICS, our study remains one of a small number of rigorous experimental evaluations of ICS adoption in the literature, and this alone makes it significant. The real value of our study however is not in replication; but rather in the fact that ours is the first study to have a design that allows the following: 1) Observation of household choices between two distinct ICS options in an experimental setting; and 2) Testing of the effect of incentivizing use of ICS through rebates, rather than delivery of simple subsidies on purchases.

III. Conceptualizing the Problem

We discuss progress towards achieving the three study objectives (listed above in Section I) in further detail below.

III. 1. Update and refine common theories of behavior change based on the field realities of

northern Indian villages

The preparatory work we conducted prior to launching our intervention experiment in Uttarakhand was centered on this objective. This involved fieldwork that built on our own background research in three areas: 1) systematic analysis of improved cookstove adoption; 2) cross-country analysis of stove sales; and 3) cost-benefit simulations for assessing the net benefits of changes in cooking technologies. In the field, we conducted a series of focus groups in 11 rural communities (near and far from Project Surya, in UP and Uttarakhand, respectively) to better understand knowledge and perceptions of different stoves and fuels, traditional cooking practices, and preferences for improved stove features – work that is summarized in Bhojvaid et al. (2014). Based on the lessons derived from those focus groups, notably regarding the importance of different stove features, we prepared, field-tested, and deployed our baseline survey instruments, and then analyzed baseline preferences for alternative stove technologies prior to designing our experimental intervention (Pattanayak et al., 2012; Jeuland et al., 2015).

To summarize the results from this preparatory work, the baseline surveys helped to highlight various demographic, socioeconomic, and psycho-social attitudes that are related to clean stove ownership and demand for improved cookstoves, within a sample of 2,120 rural households living in two states in northern India – Uttar Pradesh and Uttarakhand. We found that owners of clean stoves tended to have greater wealth, education, and smaller families compared to non-owners. Data from discrete choice experiments show that households have strong preferences for traditional stoves, but that they are willing to pay (WTP) on average about $10 and $5 for realistic reductions in smoke emissions and fuel needs, respectively (Jeuland et al., 2015). These amounts equal about 10 and 5% of average household monthly expenditure in this low income population, and half to one quarter of the price of less expensive ICS available in India. Finally, we found that preferences for stove attributes are highly varied, and are partly explained by household characteristics (e.g. expenditures, gender of household head, patience and risk preferences).

III.2. Derive and test predictions of which types of interventions can increase the adoption and use of ICS

Taken together, these baseline results suggest that although households exhibit cautious interest in the promise of ICS, there remain significant barriers to achieving their widespread diffusion. They are also consistent with points emphasized in the broader literature on adoption of environmental health improvements (e.g., water treatment, latrines, bednets, vaccines) (Jeuland, Pattanayak & Bluffstone, 2015; Pattanayak & Pfaff, 2009). To us, these results clearly pointed to the importance of a reinvigorated supply chain that (a) would be willing to experiment with product attributes such as price, emissions, and fuel needs, and (b) would appeal to different consumer types and explore the extent to which these could be differentiated by observable characteristics such as education, experience, wealth and location.

On the basis of these findings, we developed a series of pilot intervention experiments, and ultimately, our final intervention design in Uttarakhand (one of the two locations from the baseline survey work), to test a variety of hypotheses related to improved stove adoption. The pilots demonstrated that there are substantial supply-chain barriers confronting these technologies, and achieved highly variable success in selling stoves, ranging from 0% to 60% (Lewis et al., 2015). We also found that households generally preferred electric stoves over improved stoves that burn solid fuel when given a choice between several stove types. Purchasers were more likely to report having viewed informational brochures, or to have attended stove demonstrations, revealing the importance of information provision and marketing. They also reported greater interest in reducing cooking time and the amount of fuel they used (in contrast to the baseline choice experiments which suggested that smoke emissions reductions were perhaps most valuable). Among non-purchasers, cost was cited as the biggest barrier to adoption, and pilots that allowed payment in installments appeared helpful for easing liquidity constraints. Nonetheless, adopting households were more likely to have higher socioeconomic status, access to credit, and reliable electricity. They also spent significantly more time collecting traditional fuels, suggesting that alternative stoves may be seen as a way to reduce fuel consumption. All households that adopted a new stove continued to use it during a two-month monitoring period, but in no households did it fully replace the use of traditional stoves.

Based on the results of the pilots, we judged that liquidity and information provision / stove demonstration were essential to achieving high rates of adoption (and thus not worth manipulating in an experimental context), and therefore opted for an experimental design that included the features summarized in Table 1 below. Randomization of the sales intervention to communities, and of the rebate levels to households, achieved balance on baseline factors related to stove and fuel use and on household and community characteristics related to supply and demand (Table 2), allowing for a clean interpretation of the impacts of the intervention on outcomes.[3]

This design allowed us to rigorously assess 1) whether there were differences in demand for two very different ICS options (electric & biomass-burning); and 2) the extent to which price rebates and experience with ICS would help foster initial adoption. The intervention was targeted to the villages from our baseline surveys in the Uttarakhand region of the Indian Himalayas (Figure 1).

The sampling frame for the study thus consists of 97 geographically distinct communities (or hamlets) located in 38 Gram Panchayats (GPs) in the Bageshwar and Nainital districts of Uttarakhand. Within each of the 38 GPs, we randomly selected households according to the size of the GP. In small GPs, a minimum of 20 surveys were collected; in medium ones 30; and in large ones 40. If a GP was divided by distinct landmarks (e.g., half the village was to the north of the main road, half the village was to the south), the target number of surveys was split equally among these groups. Upon arrival in the village, the population of the GP was divided by the target number of surveys and every n^{th} household (no more than every 8^{th} house) was surveyed until the target number of surveys was reached. This strategy ensured that surveys were collected throughout the entire extent of the GP and created variation in the number of hamlets sampled in each GP. The "official" number of distinct hamlets sampled in this way was 106; some of the smallest of these were later combined with nearby hamlets for the purpose of the stove promotion intervention to yield the final set of 97 hamlets.

Efforts were made to interview each sampled household. If a randomly-selected household was unavailable during the entire day of baseline fieldwork in a particular hamlet, or if it did not have an eligible respondent (i.e., the primary cook and/or head of the household were unavailable) or refused to participate, neighboring houses were randomly selected as replacements.[4] Field supervisors performed household introductions, recorded GPS coordinates and elevation data, and oversaw quality control checks in each village. The final sample at baseline consisted of 1,063 households.

Figure 2 depicts our final study design: from selection of villages and households to surveys at baseline and follow-up, with the design and implementation of the intervention in between, and finally the analysis reported in detail in the next section. This figure also summarizes the village selection process and the randomized assignment of the intervention (described on the previous page). We also report the specific sample sizes at each stage, and note that roughly

[3] For balance across the rebate levels (randomized at the household level), please see supplementary Table A1.
[4] In total, 118 households were replaced in this way. Thirty-three households refused to participate, while an additional 85 could not be interviewed because they were not present during the day of the fieldwork.

6% of households had attrited by the time of the follow-up survey (as summarized in Table 2, attrition was balanced across treatment and control arms), yielding a final follow-up sample of 987 households.

Surveys were repeated at three points in the project cycle: (a) baseline surveys, (b) during intervention, and (c) at follow-up. The quality of the survey depends critically on (i) careful development of survey instruments from focus-groups, contextual knowledge, and pre-tests; (ii) extensive and detailed training of survey enumerators, and quality control during data collection; and (iii) careful community and household sampling. Each of these is described extensively in the baseline report (Pattanayak et al., 2012).

IV. Findings: What does the experimental evidence show?

In this section, we summarize and present the main findings from our study. Specifically, we discuss the following: 1) The significant, but heterogeneous, latent demand for ICS technologies in our sample (and some of the more important drivers of this heterogeneity); 2) the effect of rebate incentives on adoption and use of ICS; and 3) the short-term impacts we observe following adoption of improved stoves.

4.1. Preferences and demand for ICS

The baseline focus groups (Bhojvaid et al., 2014) and household survey data, and the results from the experimental promotion of cookstoves in Uttarakhand **point to high interest and latent demand for improved stoves among survey respondents**. At the same time, as discussed in Jeuland et al. (2015), preferences for ICS are varied and this raises the possibility that the menu of existing technologies (particularly ICS that burn solid fuels) may not be fully compatible with user desires from such technologies.

The **most compelling evidence we can provide for this high demand** comes from the experimental intervention in Uttarakhand. Below, we describe in greater detail the effects of rebates in incentivizing purchase (and use) of the ICS promoted during this experiment. Here, we note that 52% of the households targeted by the sales campaign purchased at least one of the two intervention stoves: 40% of household bought an electric G-coil stove, and 16% bought the Greenway natural draft stove (Table 3). This high rate of ICS adoption led to an increase in ownership of any improved stove to roughly 65% compared to the 30% observed at baseline (Figure 3). At follow-up, most of the households who had purchased these stoves still had them, and most reported using them in the week prior to the survey. Traditional stove ownership did not change much (only a 4% decrease), however, and households continued to use their traditional stoves, though for about 40 minutes fewer per day (Table 3).

Our findings on demand are not limited to the experimental intervention, however. During preparatory work, focus groups revealed substantial curiosity about ICS among rural households with higher socio-economic status, and also among households with younger respondents and more mobile adult relatives, who had greater knowledge about and access to alternative and modern cooking technologies (Bhojvaid et al. 2014). Other households were less certain, which helped motivate the information and demonstration feature of the intervention.

During the baseline surveys, we found roughly 30% ownership of clean stoves among households in our intervention sample (primarily LPG), yet these were nearly always used alongside traditional stoves (Jeuland et al., 2015a). Regression analysis of these survey data revealed that households owning and using LPG stoves and clean fuels: a) had higher socio-economic status (e.g., higher reported relative wealth, general caste status, and higher expenditures); b) were more educated and held stronger beliefs that clean stoves deliver positive effects on health, the local environment, or air quality / climate; c) were more likely to be female-headed households or households with greater numbers of young children; and d) were more likely to be patient (as revealed by time preference games) and risk-averse (as revealed by responses to hypothetical time-money tradeoffs and risk gambles).

Finally, analyzing data from a stated preference survey implemented at baseline, we determined that households on average were willing to pay more for smoke emissions reductions (about $10 for reductions of one third of emissions) from ICS than for decreased fuel consumption (about $5 for a similar decrease) or increased convenience (Jeuland et al. 2014). This average however masks considerable heterogeneity in preferences; the largest group of respondents (nearly half of the sample) placed very little value on any of these three improvements of ICS. Among other respondents, roughly 25% valued both fuel and smoke emissions roughly equally, while the group favoring smoke emissions reductions the most also seemed most inclined to select the traditional stove alternative they already owned (Jeuland, Pattanayak & Tan Soo, 2014).

4.2. The effect of rebate incentives on adoption and use of ICS

A key hypothesis that we aimed to test through our intervention was whether providing rebates (delayed subsidies) to households would incentivize purchase of intervention stoves. The motivation for the inclusion of this rebate in the stove offer was twofold. First, it would function like a normal subsidy in reducing the real price of the offered stoves, and would therefore spur adoption through a price effect. Second, it would encourage learning and experimentation with unknown technologies. Learning would be encouraged because the rebate would only be delivered at the time of the payment of the third and final installment for the stove if the household was found to be using it (based on observations by trained sales personnel).[5] To test this hypothesis, all households in the treatment arm of the experiment were randomized to one of three rebate levels, equal to 25 Rs. (~2% of the stove cost), 200 Rs. (~20% of the stove cost), and 33% of the stove cost (320-460 Rs., depending on the stove type). This randomized rebate was announced to households at the time of the sales offer during the stove demonstration visit.

The adoption of intervention stoves across rebate levels is summarized in Figure 4. We observed a very large effect of increasing rebates on purchase, which also translates into significant effects on use. At the lowest rebate level, which delivered the negligible subsidy amount, about 23% of households in the treatment group purchased one of the two intervention stoves. Purchase rates rose to 53% at the middle rebate level, and reached 72% at the highest rebate level.

Further analyzing the effect of rebates by stove type, we find that only 5% of households in the treatment group owned the Greenway stove at the time of the follow-up survey if offered the low rebate level, compared to 17% who still owned the electric G-coil stove (Table 4; these percentages are obtained by adding the coefficient in column 1 to the coefficient in column 2 multiplied by 25 Rs./100).

Thus, we can conclude that intensive demonstration of stoves and information provision alone might prove insufficient to spur high adoption of the Greenway stove in similar communities. On the other hand, interest in the electric G-coil stove was much higher, such that a much larger percentage of households (roughly 20%) would consider adopting it even without subsidies. Also, every 1 Rs. of additional subsidy has about twice the effect for increasing electric stove adoption relative to the Greenway stove.

Finally, as shown in Table 4, larger rebates also induce greater use of ICS and clean fuels, and decrease the amount of time spent cooking with traditional stoves (though the latter effect is not differentiable from zero, perhaps due to limited statistical power). This effect is obviously related to greater adoption of clean stoves among those receiving larger rebates; the overall

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[5] All households in the treatment group were given the option of paying for the intervention stoves in three installments collected at two week intervals, each of which was equal to a third of the price of the chosen stove plus a small, additional financing charge (60 Rs. for the G-coil stove, and 80 Rs. for the Greenway).

proportion of households using an ICS during the past week as a percentage of those purchasing a new ICS decreases slightly with increasing subsidy amounts.

4.3. Short-term impacts observed following purchase of improved stoves

In this section, we examine a set of important short-term impacts of intervention stove adoption. Specifically, we examine changes in awareness of clean stoves, solid fuel use, and total fuel collection time and expenses.

The main results (and post-intervention means by group) are shown in Table 3. As shown, at follow-up, households in the treatment group are somewhat more aware of clean stoves (by 6%), reduce solid fuel use by about 1 kg (or about 8%), spend less time collecting fuel, and have higher fuel expenses (probably due to the use of electric stoves). Due to high variation in these outcomes across sample households, the reductions in the fuel measures are statistically significant only at the 10% level. As Brooks et al. (2015) show, reductions in fuel use are also observed among households owning LPG stoves at baseline, and these findings are robust to the inclusion of socio-economic and demographic covariates. In addition, households continue to use significant amounts of solid fuels, as shown by the mean for solid fuel use in both groups. This is consistent with a larger literature on fuel stacking (Masera and Navia, 1997; Masera et al., 2000). There are also important time trends in the data that are not shown. In particular, households were using much more (nearly two times) solid fuel at follow-up (during the winter season) than at baseline (late monsoon season).

For each of the above outcomes, we also investigated variation across rebate. We find no differential effect of increasing rebate on awareness of clean stoves, which is consistent with the fact that the same information about clean stoves was delivered to all households in the treatment group, regardless of the rebate level. Similarly, there are no differential effects of the rebate level on solid fuel savings (in amount or collection time).[6] This suggests that increasing rebates have limited effects on greater use of the new stoves overall, once these are purchased, and that even a low-level rebate can induce experimentation.

4.4 Implications for climate-harming emissions

On the basis of the observed reductions in biomass fuel consumption, we can estimate the effects of the intervention on emissions of climate-warming pollutants from biomass burning. [Note: Because we do not know how much additional electricity was consumed by these households, we do not include

[6] The one exception is for weighed biomass use if we control for baseline differences (see difference-in-difference estimates reported in supplementary Table A3).

emissions from electricity use in the calculations that follow. Thus, the calculations do not indicate the net effect on emissions]. Based on the comparison of self-reported biomass fuel consumption at follow-up (Table 3) as well as the difference-in-difference (DiD) estimate that adjusts for baseline differences across groups (Table A2), we assume a reduction ranging between 1 and 2 kg/day, which corresponds to 10-16% of fuel consumption.

Next, we calculate the efficiency gain from the "new" mixture of cooking technologies relative to baseline as an increase from 14% to 16.5% (this is the gain that yields a 15% reduction in fuel consumption).[7] We then reduce all emissions in direct proportion to this improvement in "net" efficiency. Finally, using a model of the costs and benefits of improved stoves that accounts for the timing of emissions damages (using the atmospheric lifespan of the pollutants and the social discount rate), we obtain reductions in the time-weighted carbon dioxide equivalent forcing and the value of these reductions as summarized in Table 5 (Jeuland & Tan Soo, 2015). This calculation assumes that 23.7% of biomass harvesting in Uttarakhand is non-renewable, which is the India estimate from a recent global analysis performed by Bailis et al. (2015). It also relies on the median value across 18 runs from 3 integrated assessment models that are used by the US EPA to estimate the social cost of carbon as a function of the discount rate (Inter-Agency Working Group on Social Cost of Carbon, 2015).

In the base case with a social discount rate of 3.5%, the estimated reductions in emissions are 51 g and 203 g CO_2-eq/kg fuel consumed, for the Kyoto Protocol pollutants and for a more comprehensive set of pollutants that includes black carbon, organic carbon, and carbon monoxide. At the fuel consumption levels observed in this study, these reductions translate into avoided damages that are worth $0.34 and $1.4 per household per month, respectively. At a very low discount rate of 1%, these savings rise to $1.6 and $7.1/hh-month, while a higher 6% discount rate translates to much smaller savings of $0.07 and $0.28/hh-month, respectively.

VI. Lessons: Is it possible to increase ICS demand?

Here we reflect not only on the results reported so far, but on all stages of this study – focus group discussions, expert consultations, pilot studies, stove intervention program, data analysis, and conferences and seminars that span half a decade – and on several valuable lessons for the policy community and future ICS dissemination programs. These lessons can be summarized as follows:

- First, households have **different preferences** for stove attributes and different cooking needs. Greater attention must be paid to household needs and cultural practices when developing or disseminating new stove technology. It is extremely unlikely that a one-stove-fits-all approach will be successful and stove programs should be designed to reflect

[7] This calculation assumes that the 11.9 kg of fuel consumed in the control group using traditional stoves that are ~14% efficient represents 1.67 kg of useful biomass. Given that treatment households consumed about 10.1 kg on average, we obtain the new "net" efficiency as 1.67/10.1 = 0.165.

this heterogeneity. Offering multiple stoves allows households to select the model that is most appropriate for their needs, and is a better strategy for increasing adoption of ICS than interventions that only provide one stove type. However, stoves and intervention strategies must be carefully chosen to be mindful of location, fuel availability, and gender roles; one successful intervention technique cannot be replicated everywhere.

- **Second, demonstrations are crucial** for educating households about the benefits of a new cookstove. Stove demonstrations allow households to become familiar with the new technology, observe correct usage, and taste a food or tea cooked on the improved stove. In addition, demonstrations provide a valuable opportunity to inform households of the diverse benefits of improved cookstoves. Household demonstrations were more effective than community demonstrations at encouraging sales; direct engagement with households proved necessary to demonstrate that the benefits of ICS outweigh the costs. A promotional brochure and intensive social marketing by highly trained salespeople from the local culture were other critical components driving stove sales.
- Third, we found a **high latent demand** for ICS. In contrast to a large body of literature that finds very low willingness to pay for environmental health technologies, households in our study purchased stoves at fairly substantial prices. In particular, we found very high demand for **electric stoves**. Nevertheless, liquidity constraints remain a serious barrier to adoption and such barriers could be overcome by offering an installment plan to purchase an ICS. Otherwise, the price represents too large of an upfront cost for many households. We found that **reducing the price of stoves** by offering a rebate (conditional on stove use) led to dramatic increases in stove sales.
- Fourth, **supply chain problems are very real** and add to translation challenges and implementation costs. Unless there is an effective and ready supply chain, stimulating demand on its own will fall short. Even as global knowledge and discourse on ICS increases, stove supply in rural India remains sparse at best. The complete lack of any local supply chain for ICS in our setting caused major delays. We were forced to simultaneously develop a stove supply chain from the ground up. Most importantly, supply chain does not stop with stove transport to remote areas, but requires developing an entire infrastructure for maintenance and service. An effective maintenance program is necessary for ICS dissemination and scale up in the long-term and to deliver the manifold household benefits.
- Lastly, **local institutions** are vital to a successful stove programs. In Uttarakhand, our NGO partner was widely respected in the region, which brought trust and credibility to our ICS

intervention. Additionally, it is crucial for local partners to have the ground game to implement a widespread intervention.

VII. Recommendations for future cookstove programs

Based on the findings and lessons learned from this study, we provide some recommendations for policy-makers and implementers of improved cookstove programs.

- First, given the heterogeneity in user preferences, policies must be implemented that **stimulate research and development of new ICS** technologies that are **responsive to these differential tastes**. Policies should foster competition and diversity in the ICS market rather than being overly prescriptive about which specific technologies to use. Naturally, there is a fine line: Innovation will clearly be impeded by a burdensome and costly regulation process for new ICS, but technologies that do not meet standards required to deliver benefits are obviously problematic.
- Second, the lack of a robust market for ICS or ICS maintenance despite significant latent demand suggests the need for policies that would support **investment in the complementary infrastructure** (roads, electricity, reduced barriers to shipping and trade across boundaries, development of retailer or maintenance networks) needed **for supply-chain development in rural areas**.
- Third, policy-makers and implementing agencies must consider the **complementarities between price subsidies, financing, and information or social marketing** when designing interventions to promote ICS. Given the bewildering array of constraints faced by potential beneficiaries (e.g., low income, competing priorities, liquidity constraints, lack of awareness, present bias, risk aversion), we need multi-faceted interventions that apply a "full court press."
- Fourth, despite increasing efforts to learn about adoption of environmental health technologies such as ICS, relatively little is known about the range and relative importance of demand and supply side constraints in this domain. The policy community should therefore work to continue to **foster knowledge generation about the demand for ICS and the barriers to ICS promotion**, and should also seek **to leverage learning from other environmental health domains** (e.g., water and sanitation, malaria, vaccine-preventable diseases). Such knowledge, and the research that produces it, is a public good that is provided by academics, policy researchers and forward-thinking community development activists.
- Fifth, our research experiments show that demand is highly price elastic, which means that small changes in the price faced by households can have a large effect on the ICS purchasing decision. Accordingly, the policy community should strongly **consider the case**

for subsidies designed to better align private demand with public benefits. Such subsidies can reduce the user price of ICS and/or support of demand stimulation through behavior change approaches such as social marketing. However, there remain very important **unanswered questions** about the role of such subsidies and interventions in achieving **long-term use of ICS**. This **critical gap must be addressed** to comprehensively evaluate different ICS policies.

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Table 1. Features of the experimental stove promotion intervention

Intervention element	**Level of assignment**
1. Stove sales offer, including information-provision & household demonstration of two ICS options (natural draft & electric G-coil)	Treatment communities only
2. Choice of financing over 3 installments	Treatment communities only
3. Three levels of randomized rebates, announced at time of sales (to be delivered at third visit if the household was found to be using the stove)	Randomized at household-level

Note: Households in control communities were not exposed to the sales offer.

Table 2. Households and communities with & without experiment were balanced at baseline (i.e., small normalized differences).

Variable	Mean: Treatment	Mean: Control	Difference: Normalized	Difference: p-value
Household-level				
% households lost to attrition	6.0	6.2	-0.0056	0.91
Stove and fuel variables				
% owning improved stoves	31	29	0.033	0.73
% owning traditional stoves	98	96	0.089	0.25
% use improved stoves	29	28	0.016	0.87
Time spent cooking on traditional stoves (mins/day)	284	305	-0.10	0.13
% use clean fuels	28	27	0.015	0.88
Weighed 24-hour biomass fuel used (kg)	9.5	9.6	-0.020	0.85
Reported daily biomass fuel use (kg)	6.9	6.4	0.046	0.42
Total fuel expenses (Rs./month)	433	408	0.028	0.73
Expenses on clean fuel (Rs./month)	365	345	0.024	0.74
ln[Biomass fuel collection time (min/day)][1]	3.8	3.3	0.11	0.12
Socio-economic and demographic variables				
% below the poverty line	56	60	-0.056	0.40
% accessing loan; past yr	16	12	0.089	0.14
% who say it is possible to save money; past yr	25	25	0.012	0.87
Total expenditures (Rs./month)	5,773	5,537	0.036	0.54
Subjective wealth rating (6 point scale)	2.1	2.1	0.0047	0.95
% scheduled caste/tribe	26	24	0.030	0.82
Household size	4.8	4.9	-0.057	0.49
% female-headed	25	32	-0.11	0.039
Age, household head (yrs)	53	53	0.040	0.42
Education, household head (yrs)	5.9	5.6	0.038	0.45
Education, primary cook (yrs)	4.6	4.6	0.0098	0.87
Electricity supply, hrs per day	17	18	-0.078	0.20
% believe improved stoves/fuels are beneficial	31	27	0.058	0.34
% with at least 1 member with cough/cold; past week	22	20	0.034	0.55
% believe smoke is unsafe	50	47	0.040	0.45
Community-level				
Time to travel to bus stop (minutes)	35	40	-0.11	0.63
Time to travel to doctor (minutes)	9.3	9.2	0.015	0.93
Bank facility in village	32	33	-0.0076	0.97

Notes: P-values are adjusted for clustering at hamlet level. Attrition percentages are based on pre-intervention sample; other balance tests use the final follow-up sample (n=987) that serves as the basis for the analyses shown in Tables 3 and 4. Balance across randomized rebate levels is shown in supplementary Table A1.

[1] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.

Table 3. Summary of stove ownership, use, and fuel-related outcomes.

Adoption / Use outcome	Treatment at follow-up	Control at follow-up	Difference estimate (std. error)		N
Stove ownership and purchase					
Own any improved stove	66%	29%	37%***	(5.9)	987
Own traditional stove	97%	99%	-2.1%*	(1.2)	987
Purchased intervention stove	52%	0%	52%***	(2.9)	987
Own Greenway stove	13%	0%	13%***	(2.1)	987
Own G-coil stove	33%	0%	33%***	(2.6)	987
Stove use					
Used improved stove (prior week)	58%	27%	31%***	(5.6)	987
Used intervention stove (prior week)	29%	0%	29%***	(2.5)	987
Minutes of traditional stove use daily	146	188	-42**	(21)	987
Aware of clean stoves	82%	76%	6.5	(4.3)	987
Fuel use					
Used clean fuel daily	48%	25%	23%***	(5.8)	987
Weighed 24-hour biomass fuel use (kg)	11.6	12.5	-0.89	(0.79)	987
Reported daily biomass fuel use (kg)	11.3	12.6	-1.28*	(0.66)	987
Fuel collection and expenses					
Total fuel expenses (Rs./month)	377	303	73.6	(47.2)	987
Expenses on clean fuels (Rs./month)	302	247	55.4*	(32.3)	987
ln[Biomass fuel collection time (min/day)][1]	3.8	4.2	-0.41*	(0.22)	987

Notes: Column 3 shows the (Treat-Control) differences based on results measured in follow-up surveys conducted in Nov.-Dec 2013. For difference-in-difference estimates that adjust for baseline measures, see supplementary Table A2. *** p <0.01; ** p<0.05; * p<0.1. Standard errors on differences are clustered at the hamlet level.

[1] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.

Table 4. Effect of rebate level on stove adoption, use and fuel-related outcomes

Adoption / Use outcome	TREAT		Rebate (in '000 Rs.)		Constant		N	R^2
Stove ownership and purchase								
Own any improved stove	0.23***	(0.067)	0.071***	(0.016)	0.29***	(0.052)	987	0.13
Own traditional stove	-0.027*	(0.015)	0.003	(0.004)	0.99***	(0.008)	987	0.004
Purchased intervention stove	0.28***	(0.039)	0.079***	(0.014)	0	(0)	987	0.34
Own Greenway stove	0.032	(0.022)	0.051***	(0.011)	0.0074	(0.0051)	987	0.070
Own G-coil stove	0.15***	(0.032)	0.095***	(0.015)	0.0037	(0.0036)	987	0.18
Stove use								
Used improved stove (prior week)	0.21***	(0.063)	0.055***	(0.015)	0.27***	(0.048)	987	0.091
Used intervention stove (prior week)	0.099***	(0.027)	0.10***	(0.013)	0.0037	(0.0037)	987	0.17
Minutes of traditional stove use daily	-37.0*	(22.4)	-0.027	(0.042)	188.3	(18.7)	987	0.017
Aware of clean stoves	0.065	(0.046)	-0.0001	(0.011)	0.76***	(0.037)	987	0.005
Fuel use								
Used clean fuel daily	0.14**	(0.064)	0.049***	(0.015)	0.26***	(0.049)	987	0.055
Weighed 24-hour biomass fuel use (kg)	-0.86	(0.83)	-0.018	(0.17)	12.5***	(0.71)	987	0.005
Reported daily biomass fuel use (kg)	-1.35*	(0.74)	0.036	(0.19)	12.6***	(0.57)	987	0.006
Fuel collection and expenses								
Total fuel expenses (Rs./month)	75.8	(48.2)	-1.13	(11.0)	304***	(37.6)	987	0.008
Expenses on clean fuels (Rs./month)	62.4*	(34.5)	-3.7	(7.9)	247***	(25.2)	987	0.009
ln[Biomass fuel collection time (min/day)][1]	-0.37	(0.24)	-0.017	(0.059)	4.22***	(0.17)	987	0.006

Notes: All estimates are obtained using ordinary least squares (OLS) regression. The coefficient for TREAT corresponds to the effect of treatment status on the outcome as represented by a binary indicator (0 or 1). The coefficient on Rebate shows the effect of a 100 Rupee increase in the rebate on the outcome. For difference-in-difference estimates that adjust for baseline measures, see supplementary Table A3.

*** p <0.01; ** p<0.05; * p<0.1. Standard errors on differences are clustered at the hamlet level.

[1] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.

Table 5. Emissions implications of the reductions in solid consumption

	Baseline global warming potential (GWP)	Post-intervention GWP	Benefit: Base estimate	Benefit: Low estimate	Benefit: High estimate
Basic accounting: CO_2, N_2O and CH_4 only (g CO_2-eq/kg fuel)	341.3	290.1	0.34	0.07	1.6
Full accounting: Also includes BC, OC, and CO (g CO_2-eq/kg fuel)	1350.3	1147.8	1.4	0.28	7.1
Discount rate (%)	3.5	3.5	3.5	6	1
Social cost of carbon (US$/ton CO2-eq)	n.a.	n.a.	18.7	3.4	102.5

Notes: Base estimate uses a cost of carbon and weights the time series of emissions forcing that is consistent with a 3.5% social rate of discount. The low estimate uses a 6% discount rate (and corresponding cost of carbon of $3.4 and therefore has slightly different GWP reductions), and the high estimate uses a 1% (and corresponding cost of carbon of $102.5) discount rate. The cost of carbon is the median of EPA estimates across 3 integrated assessment models that roughly correspond to these three discount rates (Interagency Working Group on Social Cost of Carbon, 2015). For CO2 emissions from biomass, we assume that only 23.7% of harvesting is non-renewable, as estimated for India in Bailis et al. (2015).

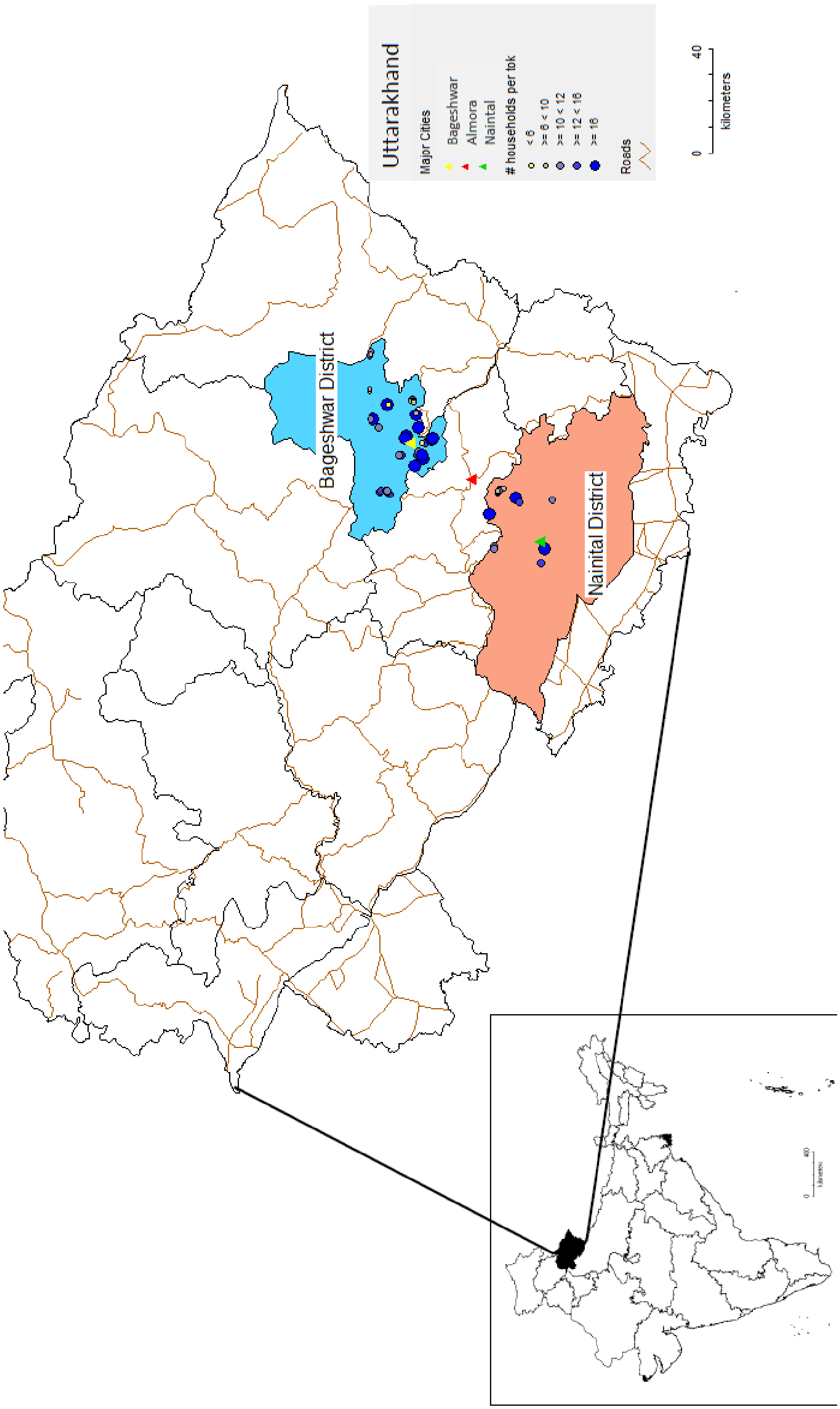

Figure 1. Study area in the Uttarakhand region of the Indian Himalayas

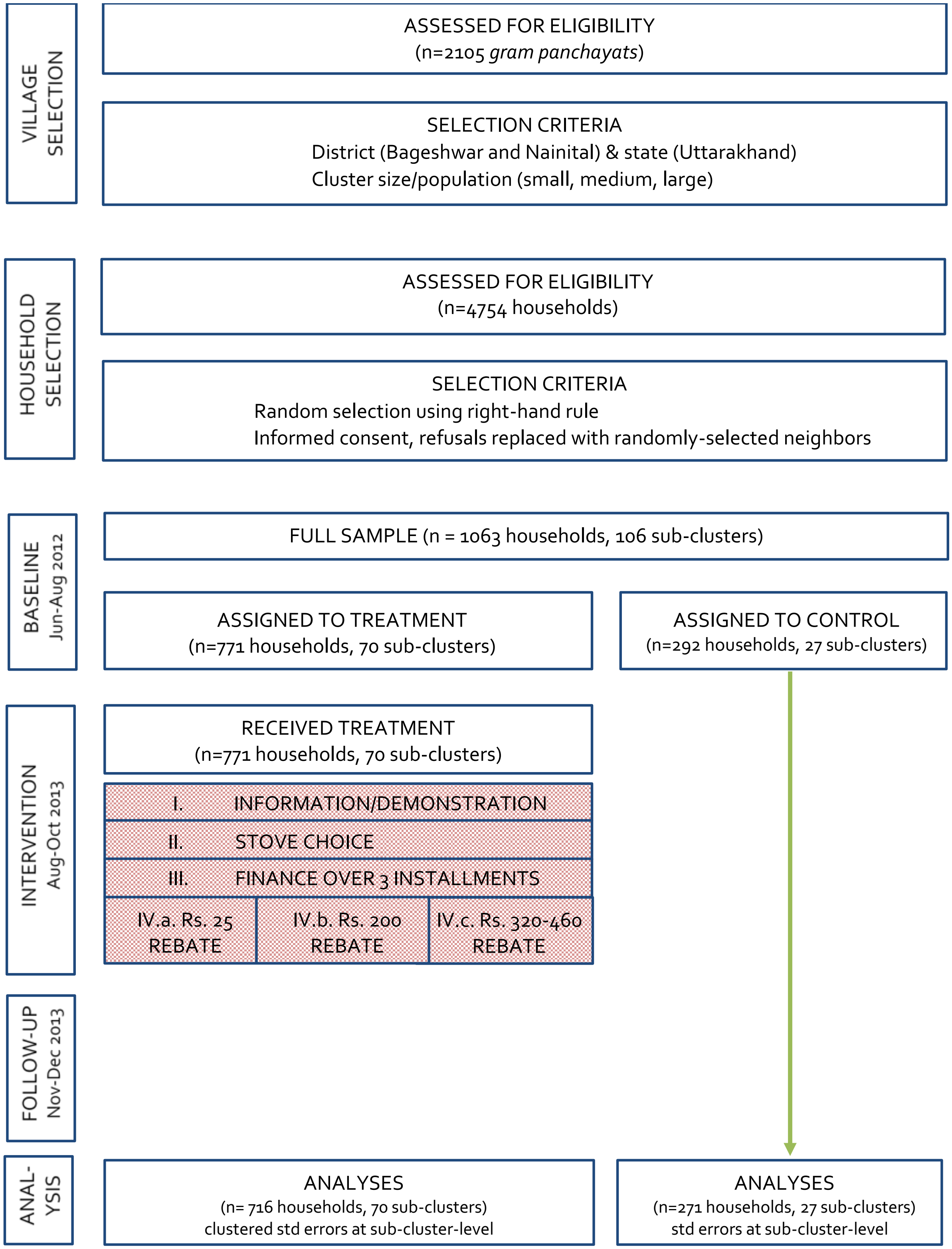

Figure 2. Study design.

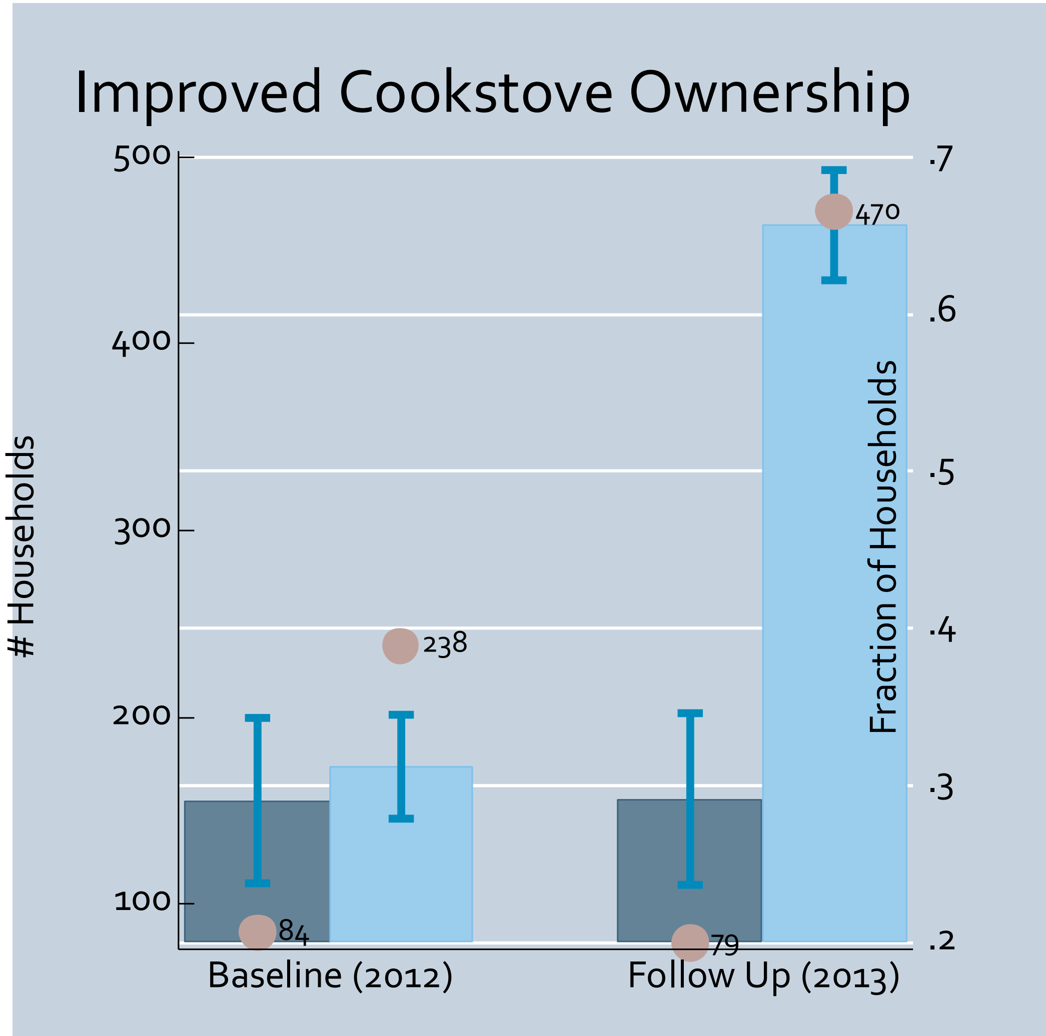

Figure 3. Ownership of improved stoves at baseline and follow-up, for treatment and control households (Notes: Solid bars indicate the fraction of households owning improved stoves, with the standard deviation around that fraction shown by the error bars; dots indicate the number of improved stoves owned by all households)

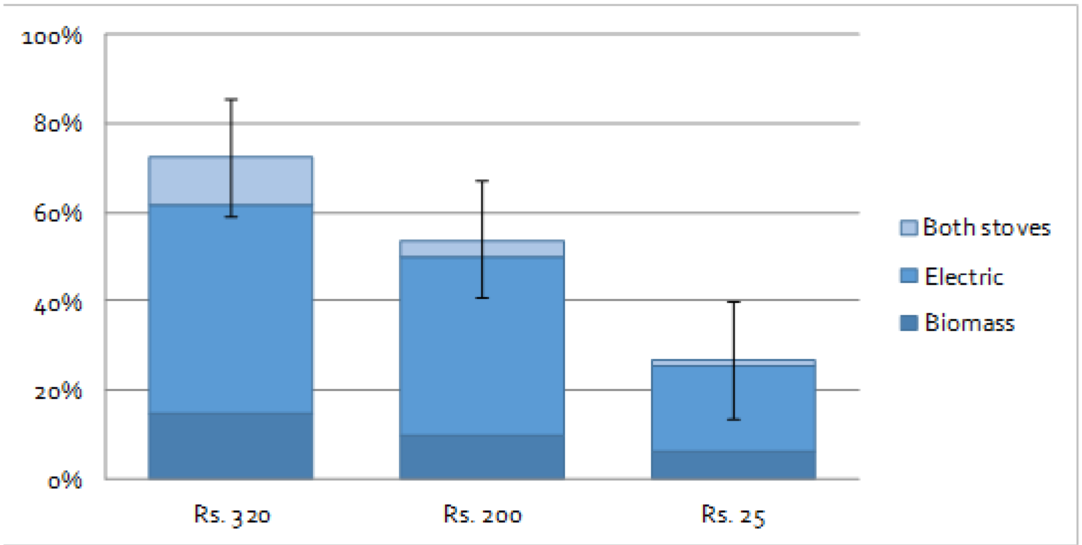

Figure 4. Purchase of intervention stoves, by rebate group

Table A1. Sample balance across rebate levels.

Variable	Δ (Low rebate – control)		Δ (Low rebate – control)		Δ (Low rebate – control)	
Household-level						
% households lost to attrition	2.0	(2.3)	0.44	(2.1)	-2.2	(2.0)
Stove and fuel variables						
% owning improved stoves	0.22	(6.4)	2.3	(6.5)	2.7	(6.9)
% owning traditional stoves	2.8	(1.8)	3.2*	(1.7)	2.0	(2.2)
% use improved stoves	-0.69	(6.3)	1.5	(6.4)	2.2	(6.7)
Time spent cooking on traditional stoves (mins/day)	-18.0	(17.2)	-26.6*	(14.9)	-26.3*	(15.5)
% use clean fuels	-1.4	(6.0)	0.85	(6.1)	2.4	(6.6)
Weighed 24-hour biomass fuel used (kg)	-0.75	(0.97)	-0.47	(0.73)	0.78	(0.84)
Reported daily biomass fuel use (kg)	0.69	(0.70)	0.17	(0.57)	0.39	(0.65)
Total fuel expenses (Rs./month)	22.9	(68.0)	36.7	(71.7)	27.0	(62.7)
Expenses on clean fuel (Rs./month)	2.8	(64.7)	30.2	(66.1)	25.2	(58.4)
ln[Biomass fuel collection time (min/day)][1]	0.43	(0.33)	0.52	(0.35)	0.50	(0.34)
Socio-economic and demographic variables						
% below the poverty line	-5.3	(5.2)	-3.4	(5.2)	-4.2	(5.9)
% accessing loan; past yr	-0.64	3.0)	4.2	(3.4)	9.2**	(4.4)
% who say it is possible to save money; past yr	-1.7	(5.3)	3.5	(5.2)	3.0	(5.1)
Total expenditures (Rs./month)	-32.7	(489)	-185	(400)	613	(551)
Subjective wealth rating (6 point scale)	-0.035	(0.092)	-0.038	(0.096)	0.044	(0.099)
% scheduled caste/tribe	0.082	(7.9)	6.5	(8.2)	5.2	(8.2)
Household size	-0.10	(0.28)	-0.37	(0.27)	-0.24	(0.29)
% female-headed	-4.1	(4.2)	-14.4***	(4.2)	-7.1*	(4.1)
Age, household head (yrs)	-0.50	(1.42)	-0.012	(1.34)	1.95	(1.28)
Education, household head (yrs)	0.36	(0.40)	0.63	(0.40)	0.12	(0.43)
Education, primary cook (yrs)	-0.17	(0.43)	0.28	(0.43)	-0.066	(0.43)
Electricity supply, hrs per day	-0.051	(0.82)	-1.35*	(0.74)	-0.83	(0.70)
% believe improved stoves/fuels are beneficial	0.025	(0.045)	0.046	(0.045)	0.062	(0.046)
% with at least 1 member with cough/cold; past week	1.4	(4.1)	3.4	(4.2)	4.4	(3.8)
% believe smoke is unsafe	5.2	(5.1)	2.3	(4.6)	5.2	(5.2)
Community-level						
Time to travel to bus stop (minutes)	-6.4	(12.7)	-6.0	(12.3)	-6.2	(12.3)
Time to travel to doctor (minutes)	0.0003	(1.9)	0.31	(1.93)	0.31	(1.99)
Bank facility in village	0.43	(12.0)	-0.91	(12.0)	-1.4	(11.9)

Notes: The values reported in columns 2-4 are for the difference between the households in the specific rebate group and the control households, as estimated using an OLS regression with an indicator for each rebate group. Attrition percentages are based on pre-intervention sample; other balance tests use the final follow-up sample (n=987) that serves as the basis for the analyses shown in Tables 3 and 4.

*** p <0.01; ** p<0.05; * p<0.1. Standard errors on differences are clustered at the hamlet level.

[1] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.

Table A2. Difference-in difference (DiD) estimates of intervention impacts on stove ownership, use, and fuel-related outcomes.

Adoption / Use outcome	DiD estimate for TREAT*R2	(std. error)	N
Stove ownership and purchase			
Own any improved stove	34%***	(4.9)	2,038
Own traditional stove	-4.3**	(1.9)	2,038
Purchased intervention stove	52%***	(2.9)	2,038
Own Greenway stove	13%***	(2.1)	2,038
Own G-coil stove	33%***	(2.6)	2,038
Stove use			
Used improved stove (prior week)	29%***	(4.6)	2,038
Used intervention stove (prior week)	29%***	(2.5)	2,038
Minutes of traditional stove use daily	-21	(23)	2,038
Aware of clean stoves	4.5%	(6.5)	2,038
Fuel use			
Used clean fuel daily	22%***	(4.2)	2,038
Weighed 24-hour biomass fuel use (kg)[1]	-0.74	(0.82)	1,408
Reported daily biomass fuel use (kg)	-1.7**	(0.67)	2,038
Fuel collection and expenses			
Total fuel expenses (Rs./month)	48.7	(69.5)	2,038
Expenses on clean fuels (Rs./month)	42.7	(62.7)	2,038
ln[Biomass fuel collection time (min/day)][2]	-0.82**	(0.34)	2,038

Notes: Column 3 shows coefficient on an interaction between the treatment group indicator and an indicator for the follow-up period (round 2). The regression controls for baseline differences in the two groups using the binary indicator TREAT as well as the time period. For simple differences, see Table 3. *** p <0.01; ** p<0.05; * p<0.1. Standard errors on differences are clustered at the hamlet level.

[1] Only a subsample of households had fuel weighed over a 24 hour period during the baseline survey.

[2] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.

Table A3. Difference-in difference (DiD) estimates of intervention impacts on stove ownership, use, and fuel-related outcomes, as a function of the rebate level.

Adoption / Use outcome	DiD estimate for TREAT*R2 (std. error)		DiD estimate for TREAT*Rebate*R2 (std. error)		N
Stove ownership and purchase					
Own any improved stove	23%***	(5.3)	0.062***	(0.017)	2,038
Own traditional stove	-5.8***	(2.2)	0.008	(0.006)	2,038
Purchased intervention stove	25%***	(3.9)	0.15***	(0.014)	2,038
Own Greenway stove	3.2%	(2.2)	0.051***	(0.011)	2,038
Own G-coil stove	15%***	(3.2)	0.095***	(0.015)	2,038
Stove use					
Used improved stove (prior week)	21%***	(5.1)	0.045***	(0.016)	2,038
Used intervention stove (prior week)	9.9%***	(2.7)	0.10***	(0.013)	2,038
Minutes of traditional stove use daily	-20.9	(26.2)	-0.007	(5.7)	2,038
Aware of clean stoves	7.7%	(7.0)	-0.017	(0.016)	2,038
Fuel use					
Used clean fuel daily	16%***	(5.0)	0.033**	(0.016)	2,038
Weighed 24-hour biomass fuel use (kg)[1]	0.18	(1.0)	-0.49*	(0.25)	1,408
Reported daily biomass fuel use (kg)	-1.9**	(0.90)	0.14	(0.27)	2,038
Fuel collection and expenses					
Total fuel expenses (Rs./month)	55.9	(76.4)	-3.8	(13.7)	2,038
Expenses on clean fuels (Rs./month)	69.1	(69.0)	-14.1	(11.3)	2,038
ln[Biomass fuel collection time (min/day)][2]	-0.80**	(0.39)	-0.013	(0.090)	2,038

Notes: Column 2 shows coefficient on an interaction between the treatment group indicator and an indicator for the follow-up period (round 2). Column 3 is the coefficient for the three-way interaction of indicators for TREAT and round 2, and the rebate level (in 100 Rs.). The regression controls for baseline differences in the two groups using the binary indicator TREAT as well as the time period. For simple differences, see Table 3. *** p <0.01; ** p<0.05; * p<0.1. Standard errors on differences are clustered at the hamlet level.

[1] Only a subsample of households had fuel weighed over a 24 hour period during the baseline survey.

[2] This variable was log transformed because of the skewness in the distribution of collection times. There is no meaningful difference across groups on the untransformed measure.