How Much do Alternative Cookstoves Reduce Biomass Fuel Use? Evidence from North India

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Abstract

Despite widespread global efforts to promote clean cookstoves to achieve improvements in air and forest quality, and to reduce global climate change, surprisingly little is known about the degree to which these actually reduce biomass fuel consumption in real-world settings. Using data from in-house weighing of fuel conducted in rural India, we examine the impact of cleaner cookstoves – most of which are LPG stoves – on three key outcomes related to solid fuel use. Our results suggest that using a clean cookstove is associated with daily reductions of about 4.5 kg of biomass fuel, 160 fewer minutes cooking on traditional stoves, and 105 fewer minutes collecting biomass fuels. These findings of substantial savings are robust to the use of estimators with varying levels of control for selection, and to alternative data obtained from household self-reports. Our results support the idea that efforts to promote clean stoves among poor rural households can reduce solid fuel use and cooking time, and that rebound effects towards greater amounts of cooking on multiple stoves are not sufficient to eliminate these gains. We also find, however, that households who have greater wealth, fewer members, are in less marginalized groups, and practice other health-averting behaviors, are more likely to use these cleaner stoves, which suggests that socio-economic status plays an important role in determining who benefits from such technologies. Future efforts to capture social benefits must therefore consider how to promote the use of alternative technologies by poor households, given that these households are least likely to own clean stoves.

Keywords: Improved cookstoves; Heckman selection; solid fuel use; India

1. Introduction

Nearly 40% of the world's population relies on solid biomass fuel for cooking purposes (Bonjour and Adair-Rohani, 2013) while in India as much as 70% of the population cooks with biomass fuels (Government of India, 2011). Traditional cooking with solids fuels and inefficient stoves contributes to numerous health problems (Adrianzen, 2013), releases climate-warming greenhouse gases and black carbon emissions (Bond, 2004; Ramanathan and Carmichael, 2008), and exacerbates local air quality and other environmental problems. In particular, unsustainable harvesting of fuelwood for cooking can lead to local forest degradation and accelerate deforestation, especially in densely-populated areas (Geist and Lambin, 2002; Ghilardi et al., 2009; Heltberg, 2004).

Cleaner and more efficient cookstoves have the potential to address these negative impacts of traditional cooking if they allow more efficient combustion of biomass fuel or use cleaner-burning fuel, such as liquefied petroleum gas (LPG).[1] Yet surprisingly little is known, and empirical evidence is mixed, about whether such improved technologies actually deliver their purported benefits, in health, time savings, and air quality and forest stock under real-world conditions (Jeuland et al., 2015; Sambandam, 2015). Low rates of adoption and use of improved stoves, as well as stove and fuel stacking, imply that adopting a new stove may not reduce overall consumption of biomass fuel or alleviate the adverse effects of traditional cooking as much as would be suggested by simple engineering estimates using relative stove efficiencies.

[1] We use the terms "cleaner or improved cookstoves" to describe any stoves that are theoretically more efficient than a traditional stove. "Non-traditional/alternative stoves" describe anything that is not a traditional stove (but may not necessarily be clean). Finally, the term "clean cookstove" is reserved for a stove that is sufficiently efficient to provide health benefits, according to current literature (Grieshop et al., 2011; Sambandam et al., 2014).

This paper contributes to a relatively sparse literature that examines how the use of non-traditional stoves is linked to lower reliance on traditional stoves and biomass fuels. Our analysis uses data from rural households in two states of northern India: Uttar Pradesh (UP) and Uttarakhand (UK), and mainly considers the effects of LPG use, since 94% of non-traditional stove owners in our sample have gas stoves. We hypothesize that using such improved stoves is negatively associated with each of three key outcomes – 1) daily consumption of biomass fuel, 2) cooking time on traditional stoves, and 3) time spent collecting biomass fuels – and quantify the extent of these reductions. Because households that choose to purchase and use an alternative cookstove may be systematically different from those that do not in ways that also affect these outcomes (Pattanayak, 2009), our preferred estimates of the impacts of clean stoves are derived from a Heckman two-step estimator that aims to correct for differential selection into improved stove ownership. We compare the results obtained from this Heckman model with those obtained using propensity score matching (PSM), which also aims to adjust for selection, and simple Ordinary Least Squares (OLS) estimation, which does not, and discuss differences across these specifications.

Also unique for this literature, we assess the sensitivity of our results to measurement error by relying on data collected using different methods. Our preferred outcome variables are based on measures derived using objective measurements (24-hour fuel weighing) or corresponding to shorter recall periods (reporting for the past 24 hours, rather than "average" use). On the one hand, self-reported measures are subject to recall error and respondents' lack of understanding of questions (Blum and Feachem, 1983), while recall periods even as short as a week can challenge respondent memory (Byass and Hanlon, 1994; Feikin et al., 2010; Zafar et al., 2010). On the other, more frequent and intrusive measures may be more subject to

Hawthorne or survey effects, if these serve as a reminder to engage in behavior change or lead to temporary changes in behavior that are perceived as socially desirable (Levitt and List, 2011; Zwane et al., 2011). In this case, we obtain similar results using both survey and weighed measures of fuel consumption, suggesting that Hawthorne effects are not likely to bias our results.

Our preferred (Heckman) models indicate that that using non-traditional stoves lowers biomass fuel use (by 4.5 kg/day), and time spent (a) cooking on traditional stoves (by about 160 minutes/day) and (b) collecting biomass fuels (by 105 minutes/day). The data also provide clear evidence of stove stacking. Our results therefore support the idea that greater use of non-traditional stoves among rural households, and LPG stoves in particular, could lead to significant reductions in solid fuel use and time spent cooking on traditional stoves, even in places where access to clean fuels is somewhat limited. And though our study was not designed to measure general improvements to air quality and the environment, back-of-the-envelope calculations using an existing model of costs and benefits (Jeuland and Pattanayak, 2012) suggests that such gains would be worth at least $1.8/household-month (or $1.0/hh-month if fuel harvesting is fully sustainable). These benefits well exceed current subsidies on LPG in India, and the calculations support the argument that "making clean [LPG] available" may be more effective than "making available [stoves] clean" in achieving environmental and health improvements (Smith and Sagar, 2014).

2. Background and literature

The main alternatives to traditional cooking methods are a) improved efficiency biomass stoves or b) stoves that rely on modern fuels or alternative energy sources (e.g. LPG, electric, or solar). In India, there have been longstanding efforts to promote improved biomass stoves. In particular, the government-sponsored National Program on Improved Chulhas (NPIC) ran from 1985-2002 and worked to distribute approximately 35 million improved biomass stoves (Kishore & Ramana, 2002). Unfortunately, many of the NPIC-sponsored stoves proved inefficient and prone to disuse or breakage (Grieshop et al., 2011; Venkataraman et al., 2010; Kishore & Ramana, 2002). This led to a re-launch in 2009 of the Indian National Biomass Cookstove Initiative (NBCI), a program that aims for adoption of high-efficiency (comparable to LPG) biomass stoves by 160 million Indian households (Venkataraman et al., 2010).

Meanwhile, most Indian households that use alternative fuels for cooking rely on LPG, which is clean burning and emits fewer harmful emissions of particulate matter and black carbon, a short-term forcer of climate change (Grieshop et al., 2011; Smith and Sagar, 2014; Smith et al., 2000). The Indian government has regulated the LPG price since 2004; the direct, flat rate subsidy on purchases was Rs. 22.6 per 14.2 kg cylinder in 2014-15 (IISD, 2014). In addition to this, an indirect benefit that varies with the global price of LPG is passed on to customers in the form of under-recoveries by government-owned Oil Marketing Companies (PPAC, 2015) – this amount was 180 Rs. in June 2015. To purchase LPG cylinders at this subsidized rate, households must obtain an officially registered LPG connection by completing an onerous application process with one of the public sector gas providers (IISD, 2014). There is therefore a significant urban-rural disparity in the distribution of these registered connections, and most LPG users live in urban areas (Government of India, 2011).[2] In addition, the LPG subsidies are expensive, and the Government has imposed a cap of 12 cylinders per household per year since April 2014 to stem their public financing burden (IISD, 2014). Given the

[2] The 2011 Census of India reported that 28% of households use LPG for cooking, but only 11% of rural households use LPG, as compared to 65% of urban households.

disparities in LPG connections, the subsidy has been critiqued on the grounds that it primarily benefits wealthy urban households (Lahoti et al., 2012)

The logic behind these programs to promote the adoption of alternative stoves rests on the idea that these technologies reduce the health and environmental burden of inefficient traditional stoves, but empirical evidence on their impact is varied and contradictory. In what follows, and in this paper, we focus primarily on savings of biomass fuel. Adrianzen (2013) used observational data to argue that improved biomass stoves are associated with lower biomass fuel use, while Nepal et al. (2010) found that improved biomass stove ownership was not correlated with (or in some cases was even related to increased) firewood consumption. Meanwhile, Hanna et al. (2012) used experimental data to show that improved biomass stoves had no effect on biomass fuel consumption in Orissa, in contrast to Bensch and Peters (2013; 2015), who found significantly lower firewood consumption among owners of higher efficiency biomass stoves than among non-owners in Senegal.

On the surface, these mixed findings may seem puzzling. Yet adoption of non-traditional cooking technologies is not simply constrained by barriers such as their high price, limited availability, and lack of awareness of the harms of traditional cookstoves, but also relates to preferences for traditional ones (Jeuland et al., 2015). Different cookstoves or fuels may be better suited to specific cooking tasks, such that these technologies are imperfect substitutes (Edwards and Langpap, 2005; Masera et al., 2000). In particular, households often appear to prefer the taste of certain foods when these are cooked on biomass stoves (Alem et al., 2013; Heltberg, 2005; Ruiz-Mercado et al., 2013; Smith et al., 2011). Traditional technologies may also be more dependable: for example, Malla et al (2011) found that in Sudan, households that acquired gas stoves remained heavily reliant on highly polluting stoves, which provided insurance against

LPG fuel supply interruptions. Finally, households may increase fuel-intensive cooking when they acquire more efficient stoves, due to an income effect (Chaudhuri and Pfaff, 2003). All of these factors may lead to households maintaining the use of "dirty" fuels and stoves even after adopting cleaner technologies, rather than simply moving up the "energy ladder" (Heltberg, 2004; Masera et al., 2000; Nansaior et al., 2011; Ruiz-Mercado et al., 2011).[3]

While the energy transition from dirty to clean fuels is relatively well-documented (Heltberg, 2004, 2005; Masera and Navia, 1997; Masera et al., 2000; Nansaior et al., 2011; Smith and Sagar, 2014), evidence on the impacts of use of alternative fuels such as LPG on biomass fuel consumption remains limited. Garland et al. (2014) documented a roughly 30 percent reduction in charcoal use among LPG-adopting households in Benin (although most of these households did not make a complete switch to LPG). These estimates are similar in magnitude to those obtained by Masera et al. (2000), who compared firewood use by households owning LPG stoves and by those with only traditional wood stoves.[4] Nautiyal (2013) found that households using LPG stoves in Uttarakhand, India saved between 260 MJ (high altitude) and 3740 MJ (low altitude) of energy from reduced fuelwood use. Pattanayak et al. (2004) report a 0.75 percentage point lower probability of collecting fuelwood from forests among Indonesian households owning kerosene stoves, but do not estimate changes in the amount of fuel used or time spent collecting it. Finally, several studies from different locations highlight the continued use of biomass-burning stoves alongside technologies that use modern fuels without quantifying the effects of this behavior (Nansaior et al., 2011; Taylor et al., 2011). While these studies offer suggestive evidence that ownership of non-biomass stoves (and LPG stoves in particular) may

[3] In the "energy ladder" conception of this problem, households strive to move up a ladder where biomass fuels occupy the lowest rung, while clean options such as electricity or natural gas, occupy higher rungs. As income and access to technological solutions increase, households are able to climb up the ladder.
[4] Masera et al. (2000) do not find these differences to be statistically significant, however.

reduce solid fuel consumption, none of them consider that selection into ownership of such alternatives may bias estimates of this impact.

3. Conceptual framework and econometric strategy

3.1. *Conceptual framework*

To better explore the question of how much biomass fuel households with non-traditional stoves actually save, we draw on a household production framework that links household consumption and production decisions in the domain of fuel use (Chen et al., 2006; Edwards and Langpap, 2005; Heltberg, 2004, 2005; Heltberg et al., 2000; Pattanayak et al., 2004). This framework is useful because it accommodates two important realities of the household cooking problem: first, the fact that many rural households in the developing world do not purchase biomass fuels but rather collect them freely from local forests and commons; and second, the range of potential behavioral adjustments households can make following acquisition of a new stove (Pattanayak and Pfaff, 2009). Households maximize utility generated by consumption of fuel services (cooking and heating), other goods and leisure, subject to the production functions for these, and to the budget constraint. The production function for fuel services depends on the quantity and types of stoves and fuels used, which are themselves determined by availability, preferences, household budget constraints and prices (or shadow prices, for fuels that are collected rather than purchased (Pattanayak et al., 2004)).

The household production model points to a set of economic, demographic, social and preference factors that help to determine stove and fuel choice and consumption. Factors that affect a household's opportunity cost of biomass fuel collection – e.g. income, education, distance to biomass sources of fuel, or terrain and local forest quality variables – determine the relative costs of different fuels (Heltberg et al., 2000; Pattanayak et al., 2004). Income and access to credit directly influence households' ability to finance the purchase of alternative technologies, while perceived relative wealth may be important for those who associate modern stoves and fuels with higher status (Masera et al., 2000). Households with greater education or female heads may be more conscious of the harms of traditional cooking or more aware of the benefits of cleaner stoves or fuels, and therefore more inclined to switch to the latter options (Bhojvaid et al., 2014; Jeuland and Pattanayak, 2012; Pachauri and Rao, 2013). Household demographic factors also affect the demand for fuel. For example, large households have greater cooking needs, but also benefit from economies of scale in cooking. Finally, psycho-social factors play a role in how households weigh the costs and benefits of new technologies. Risk aversion is important given that the benefits of alternative cookstoves are typically uncertain (Jeuland and Pattanayak, 2012). Likewise, to the extent that different households place more or less emphasis on long-term benefits relative to upfront costs of adoption or behavior change, time preferences can influence adoption behavior. The importance of many of these factors in adoption dynamics have been explored in prior empirical literature: Lewis and Pattanayak (2012) provide a systematic review of the evidence and show that improved stove adoption is positively associated with income, education, and access to credit, and negatively related to social marginalization.

3.2. *Econometric specifications*

Besides offering a conceptual framework for thinking about the household cooking problem, the model discussed above provides motivation for carefully considering how selection into clean stove use may influence estimates of the impact of such technologies on outcomes such as fuel consumption. Our main empirical strategy relies on a two stage modeling approach for understanding a) the adoption process; and b) estimating impacts among those adopting clean technologies. Though it does not fully address potential confounding by unobservables, the approach is informed by the household production model and the relatively robust empirical literature on adoption of non-traditional stoves, and allows us to account for many potential biases that could arise due to systematic differences across users and non-users of clean stoves.

Our analyses examine the impact of non-traditional cookstoves on three outcomes: 1) amount of biomass fuel consumed (in kg/day); 2) time spent cooking on traditional stoves (in minutes/day); and 3) time spent collecting biomass fuels (also in minutes/day).[5] We consider these impacts using a Heckman two-step estimator, which aims to correct for the potential bias arising from systematic differences between clean stove users and non-users. To better interpret our findings and assess whether modeling the selection process has an important effect on the impact estimates, we compare the Heckman model results with those obtained using two other approaches. The first is an OLS model with community-level fixed effects that does not control for selection. The second is a PSM estimator that controls for selection on observables by comparing treatment and control households that appear equally likely to adopt a clean stove. We comment on the PSM and OLS results in the paper, and the full results from these alternative approaches are included in the appendix to the paper.

The Heckman estimator employs a two-stage estimation procedure. The first stage describe the process of selection into treatment (in our case use of a clean stove). The second stage regression then yield a treatment estimate that accounts for the correlation between the unobserved factors that affect both the propensity to use such stoves and the outcomes of interest (Heckman, 1976; Heckman, 1979). The model is written as:

[5] The first two outcomes were collected during the 24-hr fuel measurement survey, and the third is from the full baseline survey.

$$S_{ij} = \begin{cases} 1, \ if \ \theta X_{ij} + \mu_{ij} > 0 \\ 0, \ otherwise \end{cases} \quad (1)$$

$$Y_{ij} = \beta_1 S_{ij} + \delta Z_{ij} + \delta \lambda_{ij} + \varepsilon_{ij} \quad (2)$$

In the first stage (equation 1), selection into treatment S_{ij} is a binary indicator for use of a cleaner stove during the monitoring period[6], which is modeled to be a function of a vector of observable characteristics (X_{ij}) for household *i* in community (hamlet) *j*. ε_{ij} is a random error term adjusted for correlation at the hamlet level. The vector X_{ij} includes variables that encompass the range of factors highlighted in the model and empirical literature presented above. In particular, it includes demographic factors (i.e., household size and number of children, age and gender of the household head and respondent, religion and caste); education and knowledge variables (education of the primary cook and head of household, awareness of and belief that clean stoves and fuels can mitigate the negative effects of traditional cooking); c) prices for LPG and firewood; several proxies for income (e.g., number of rooms in the house, perceived relative wealth and logged expenditures); indicators for access to credit and participation in self-help groups; and variables that reflecting risk avoidance and time preferences (e.g., risk/time preference variables and ownership of toilets). We also include an indicator variable for residence in Uttar Pradesh (one of the two states where surveys were conducted). In our case, to maintain consistency and facilitate the comparison of results, the specification of this first stage is identical in the Heckman and PSM models (i.e., X_{ij} contains the same variables).[7]

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[6] Except for the third survey-based outcome, time spent collecting biomass fuel, where the outcome variable is a binary indicator for use of a cleaner stove in the past week that is also derived from the survey.

[7] In the PSM model, we use equation 1 to generate predicted probabilities of clean stove use for each sample household; these probabilities are then employed to pair clean stove-using households with non-user via nearest neighbor matching with replacement (e.g., allowing for re-use of control observations). Outcomes for these matched samples are then compared. Prior to matching, there are large imbalances in observables between users of cleaner stoves and non-users (See Appendix Tables A1A and A1B). PSM is largely successful in eliminating these differences, though normalized differences and t-tests for a few variables (e.g. female-headed households, % households that are able to save, and % below poverty line) remain somewhat large.

In the second stage, each outcome Y_{ij} is modeled as a function of stove use plus a set of independent variables (Z_{ij}) and the inverse Mills ratio (λ_{ij}), which is the ratio of the probability density function from stage 1 normalized by the cumulative distribution function. The inclusion of the inverse Mills ratio in Equation 4 helps to correct for the non-random selection into use of cleaner stoves (Todd, 2008). The vector Z_{ij} again contains all of the variables included in X_{ij}, plus a set of controls that likely influenced cooking practices during the monitoring period, specifically, the number of household members who were cooked for (and the square of this variable), the types of meals and heating that was done (i.e., breakfast, morning tea, lunch, afternoon tea, dinner, and non-food heating), and the average hours of electricity reported by households during the baseline survey (since some households may use electric heaters). Again, to maintain consistency and facilitate the comparison of results across models, the specification of the second stage of the Heckman model is identical to that employed in the OLS model (i.e., Z_{ij} contains the same variables).

4. Data and Analysis

For the majority of our analyses, we utilize data from a 24-hour fuel measurement exercise conducted with 1,234 households in Uttarakhand (UK) (N=460) and Uttar Pradesh (UP) (N=774) in India during the summer of 2012, which comprises a randomly selected sub-sample of a group included in a larger baseline survey (N=2,120) on cooking practices (see below). The fuel measurement survey contains information about household cooking practices, and stove and fuel use during a 24-hour monitoring period. During a first visit, households were asked to bring out more than enough biomass fuel to last them through the next 24 hours, and these quantities were weighed. Enumerators then returned the following day to survey the households and weigh the remaining fuel. The questionnaire included questions on which meals households cooked, the number of household members for whom food was prepared, whether the household cooked the same number of meals as usual, how much time each stove was used for cooking and heating, and which fuels were used during the monitoring period. These other data were self-reported.

The weighed fuel data may be less subject to self-report bias and recall error, while the time spent cooking during the monitoring period was likely easier to remember than the average cooking time recorded in the household survey (see below), because the recall period was limited to a specific and recent 24 hour period. Nonetheless, the 24-hour monitoring is time-consuming and costly to collect (and requires two visits), may not be representative of average use, and may lead to behavior modification (Hawthorne Effects), if clean stove-owning households inferred that they "should" use the LPG stove during the monitoring period because they were being monitored (Levitt and List, 2011).

In addition to the fuel measurement survey, a baseline survey was conducted in a larger sample of households in UP (N=1,057) and UK (N=1,063), from which the households selected for fuel weighing were randomly chosen.[8] The survey data includes information on a wide range of household socioeconomic and demographic characteristics, perceptions about stoves and fuels, typical household cooking practices, stove ownership, amount of fuel used, fuel collection time, and time and risk preferences.[9] The data from the main survey were self-reported and

[8] These sub-samples contain very different numbers of households, because a greater proportion of households were selected for fuel-weighing in UP, owing to budget and logistical constraints in each location.

[9] Time preferences were measured through a series of hypothetical questions that asked respondents to make a choice between receiving 1000 rupees today or receiving a larger amount (1500, 2000, and 2500) in 12 months' time. Respondents who were willing to accept the smallest future payment (1500 rupees) over receiving 1000 rupees today were categorized as most patient. Risk preferences were measured through a series of hypothetical questions that asked respondents to make a choice between receiving 500 rupees with certainty or flipping a coin and receiving a larger amount (1000, 1200, 1250) if the coin lands on heads, and receiving nothing if the coin lands on tails. Respondents who were willing to take the uncertain option with the lowest payoff amount (1000 rupees) were categorized as most risk-taking.

provide the primary source of socio-economic and demographic controls used in the multivariate analyses described above. The data for the time spent collecting traditional fuels (one of our three outcomes of interest) were taken from the household survey, owing to the irregularity of this activity and the fact that households tend to store fuel.[10] They also provide an alternative measure of the stove and fuel use variables that we analyze – by indicating measured behaviors under typical or average conditions rather than in a specific monitoring period; we present the full analyses using these alternative measures in the Appendix.[11]

5. Results

5.1. *Sample description*

Table 1, Panel A presents descriptive statistics for household stove and fuel use, and p-values for differences in means between the two states included in the study (UP and UK). Approximately 13 percent of households used a clean stove during the monitoring period, 94% of which were LPG stoves.[12] Households used approximately 9 kg of biomass fuel per day on average in the 24-hour fuel monitoring period; this includes firewood, crop residues, leaves, twigs, and dung cakes, and is consistent with data from the larger baseline survey. In UK, the average weighed fuel amount was slightly over what was reported in the full household survey, while in UP the amount weighed was slightly below the reported amount (these differences are statistically significant). Households reported spending on average more than 3 hours (199

[10] For this outcome, households were asked how much time households spent collecting or bringing home different types of fuels (firewood, crop residue/twigs, leaves, dung cakes, biomass pellets, kerosene, and LPG) in a typical day/week/month. Households could therefore report these times according to varying frequencies of fuel collection and propensity for stockpiling. The estimates were then converted into hours spent per day for analysis.
[11] For example, households were asked "for a typical day when this [STOVE] is used, how many hours is this stove on / working / used for ONLY cooking or heating water for tea, or other uses?"
[12] The remaining 6% comprised of kerosene stoves, electric stoves, and biogas stoves. Only 4 households reported owning any kind of commercially marketed biomass-burning improved cookstove.

minutes) per day cooking on traditional stoves during the 24-hour monitoring period, similar to the 189 minutes reported in the baseline survey. On average, households spent approximately 130 minutes (2.2 hours) per day collecting biomass fuels (reported in the full household survey), and somewhat more time in UP relative to UK (150 vs. 110 minutes). On average, households owned more than one stove and used more than one kind of fuel during the monitoring period, and spent only 12 minutes per day cooking with cleaner stoves (and less than that in UP). Comparing simple averages across owners of cleaner stoves and other households, we see that weighed biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels – the key outcomes analyzed – are all lower (Figure 1).

Table 1, Panel B presents descriptive statistics for household demographic and socioeconomic characteristics. The sample is predominantly Hindu, with a larger proportion of non-Hindus residing in UP. On average, 26 percent of households are in officially designated scheduled castes or tribes, traditionally disadvantaged populations within India. Households have approximately 5 members, but on average cooked for more than 6 household members during the monitoring period. Eighteen percent of households are headed by women. Both household heads and primary cooks have limited education: In UP, primary cooks have less than three years of education, while in UK they average almost 5 years of education. Households have total expenditures of approximately Rs. 5,800 per month (approximately USD $105), and 67 percent report being below the official poverty line. In the full sample, households average 10 hours of electricity per day; the UK average is 17 hours per day, while in UP households have only three hours of electricity per day. Only 14 percent of households had taken a loan in the past year, saving is possible for only 15 percent and only 13 percent of households participate in self-help groups (SHG).

5.2. *Factors affecting household use of clean stoves*

Results from the first stage regressions for clean stove use, as specified in the Heckman and PSM models, are presented in Table 2 (along with marginal effects); these confirm many of the results highlighted in the extant literature on the determinants of non-traditional stoves. In particular, we find evidence of positive selection into use of these technologies: Proxies for income (relative wealth and number of rooms in the household) and risk avoidance (toilet ownership) have a positive and significant association with stove use in the monitoring period, while household size and socially marginalized status are negatively related to it. In the full sample with self-reported measures of use in the past week, statistical power is greater and the marginal effects appear somewhat greater; older and female head of household, number of children under 5, and years of education are positively related to use, while reported LPG price and lower risk aversion are negatively related to it.[13] The marginal effects of relative wealth, toilet ownership and the price of LPG fuel on the likelihood of reported stove use are particularly large. A one-unit increase in the 6 point relative wealth scale and ownership of a toilet are related to 10 and 23 percentage point increases in the likelihood of using a clean stove, while a 100 Rs. price increase for LPG (or roughly 20% of the average cost of an LPG canister) is related to a 6 percentage point decrease in this probability. Finally, results for the first stage are generally consistent across states, though statistical power is reduced.

5.3. *The effects of clean stove use on the solid fuel and traditional stove outcomes*

[13] Given the importance that risk preferences appear to play, and the fact that our measures of these and of time preferences were rough, we would suggest additional work to better understand and characterize their influence in affecting stove adoption behavior. For example, use of the relatively simple risk lottery design described in Carlsson et al. (2013) would provide greater differentiation in risk aversion measures across respondents, and use of real payments would perhaps better encourage truthful preference revelation (Dohmen et al. 2011; Vieider et al. 2015).

Results for the second stage of the Heckman model are reported in Table 3. Using a cleaner stove is associated with daily reductions of 4.5 kg of biomass fuel, 161 fewer minutes cooking on traditional stoves, and 106 fewer minutes collecting biomass fuels. The coefficient on the inverse Mills ratio (λ) is significant ($p<0.05$) only for the time spent collecting biomass fuels outcome (Table 3). This suggests that the positive selection into using clean stoves (see Table 2) does not substantially bias the other estimates, which is also consistent with the lack of statistically meaningful differences with the PSM and OLS results for the other two outcomes (see discussion further below). On the other hand, the significant Mills ratio in the model for the effects of clean stoves on the time spent collecting biomass fuels suggests that unobserved factors that affect clean stove use as well as this specific outcome may result in bias in that estimate of impact. We consider this issue in more detail further below.

The second stage Heckman results also show that cooking a midday meal is associated with more biomass fuel use and time spent cooking on traditional stoves, which suggests that this meal may be larger than others, and that it is more likely to be prepared on a traditional stove. Preparing dinner is associated with 22 more minutes cooking on traditional stoves, although the estimate is not statistically significant.[14] This could be the result of households re-heating lunch and baking bread for dinner rather than preparing an entirely fresh meal. Relative to households

[14] All relevant variables pertaining to household cooking behavior during the monitoring period have been included in the regression models using this data (such as which meals were cooked, how many people meals were cooked for, and whether household prepared only food with the stove). However, complementary information on the foods cooked with different stove types was collected from the same households in a different survey. Those data reveal that households with LPG stoves still tend to cook almost all types of food on traditional stoves (roti, dal, and vegetables, and boiling water). In particular, 90% of LPG-owning households indicated they commonly used a traditional stove for preparing roti, while only 44% reported commonly using an LPG stove for this task (these totals exceed 100% since some households alternate between stoves for the task). This is consistent with household preferences for cooking traditional breads as reported in other studies (Masera et al., 2000). The only cooking task for which LPG-owning households consistently preferred that stove over a traditional stove, was for preparation of tea, for which 80% of households indicated they commonly used the LPG stove, compared to 52% who use a traditional stove for the task. LPG-owning households reported a slight preferences for preparing rice on an LPG stove, with 69% indicating they use the LPG stove and 65% reporting use of a traditional stove.

that also prepared animal fodder or used stoves for heating purposes, preparing only food during the monitoring period is associated with significantly lower biomass fuel consumption and cooking time with traditional stoves; these other uses for traditional stoves and biomass fuels may persist even when households switch to cleaner stoves for all of their cooking purposes.

5.4. *Robustness of results across states, measures, and models*

We begin our tests of robustness by comparing the measures of impacts across modeling strategies. Results from the PSM and OLS models are mostly consistent with the Heckman estimates (as shown in Tables A2 and A3 in the appendix). With PSM, we find that use of cleaner stoves leads to significant reductions in all three outcomes – 3.0 kg lower consumption of biomass fuel, 93 fewer minutes cooking on traditional stoves, and 41 minutes fewer collecting biomass fuels per day. The OLS estimates are similar – indicating reductions of 2.7-3.9 kg/day, 93-109 fewer minutes spent cooking on traditional stoves, and 36-38 fewer minutes collecting fuels, where the ranges correspond to models that do and do not include hamlet fixed effects. The only estimates that are significantly different across model types are those for biomass fuel collection time, which is also the one for which the inverse Mills ratio is significant, as described above. Though the 95 percent confidence intervals for the coefficient estimates from all models are overlapping, the Heckman estimate is significantly larger than the other two.

In order to better interpret this difference, we first compare the sign and significance of the other model covariates, in order to assess the overall stability of the model estimates for this outcome. Comparing the size and significance of coefficients across the second stage Heckman model and the OLS model, we find relatively few differences. Notable exceptions relate to the effect of UP when fixed effects are included (this likely indicates that supply and demand drivers vary greatly across hamlets), as well as the effect of the reported price of LPG with and without fixed effects (again perhaps indicating different supply conditions for fuels). These differences also lead us to more thoroughly investigate the differences across the states (Table A4). Splitting the sample into UK and UP subsamples, we observe that several notable differences emerge in the second stage for the time spent collecting biomass fuels. In UK and UP, there is inconsistency in the sign and significance of the effects of a number of variables. We find that the effect of clean stoves (the primary variable of interest) on fuel collection time savings in the full sample is driven by the results in UP, which is also where the inverse Mills ratio is significant. The much larger effect of clean stoves on biomass fuel collection time in UP is also observed in the OLS and PSM state-specific analyses (Table A5 and A6). Meanwhile, in the second stage of the Heckman model for UP, we find that households with more educated and male household heads spend more time collecting fuel (these variables are not significant in the full sample). Electricity access is not significantly related to biomass fuel collection time in UP (unlike its positive relationship with collection time in UK and in the full sample). Thus, it appears that there are important differences in the dynamics underlying biomass fuel collection in UP and UK, which is perhaps not surprising given the very different availability of fuels (both biomass and LPG) in these two regions.

Finally, we observe that the estimates of the effects of cleaner stoves on biomass fuel consumption and cooking time with traditional stoves are not sensitive to the use of self-reported measures (Tables A7-A9). These estimates are somewhat attenuated relative to the more objective data obtained from the 24-hour monitoring period, perhaps due to measurement error.

We therefore find no evidence that the measures of key outcome variables are systematically biased by Hawthorne effects or other self-reporting errors.[15]

6. Discussion and conclusion

Many of the purported environmental and livelihoods benefits of non-traditional cookstoves stem from the assumption that these reduce fuel consumption and harmful air pollution emissions. Yet empirical evidence of the impact of such technologies remains surprisingly limited and inconclusive, and is primarily focused on improved biomass stoves. At first glance, it might appear obvious that the use of stoves that burn alternative fuels, such as LPG, would clearly result in large savings of biomass fuel, and that applied field research to understand these savings would perhaps be of limited interest. Yet, this would ignore the reality that many households using such alternative fuels appear to value specific features of traditional stoves or are cash and/or supply constrained, and therefore typically engage in stove-stacking to manage their cooking needs. In this context, there is a real need for applied research to quantify the impacts of these alternative technologies, and to understand the net savings (in black carbon emissions, pressure on local forest stocks, and reduced health damages) that they may provide.

To fill this gap, we evaluated the effect of use of non-traditional stoves (predominantly LPG) on three key outcomes related to use of traditional stoves and fuels – the amount of biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels – by households living in rural communities in Uttar Pradesh and Uttarakhand, India. Our preferred estimates of the effects on these outcomes rely on a two-stage approach that

[15] Both the PSM and Heckman models were also estimated using only households with LPG stoves (which constitute 94% of the clean stove owners). Restricting the models to LPG owners only did not substantively change the magnitude of the results and none of the estimates are statistically distinguishable across models.

first draws on theory and prior empirical evidence to analyze the selection by households into use of cleaner stoves, and then accounts for the correlation in remaining unobservables that drive both that selection process and the outcomes of interest. Besides addressing some of the potential biases that may arise from ignoring selection when estimating treatment effects, this approach also contributes valuable empirical evidence related to the drivers of adoption of cleaner cooking technologies.

We analyzed data on fuel consumption measured during a 24 hour fuel-weighing exercise conducted with 1,234 households, and recorded the time these households spent cooking during the same period. We then considered whether these results were robust to analysis of self-reported "average" outcomes obtained from a larger dataset that included the same households as well as 886 others that did not participate in the fuel measurement survey. This larger sample provides a test for whether our results are robust to the method of data collection and potential threats from recall, measurement error, or bias due to changes in behavior as a result of monitoring (Hawthorne effects).

In using cross-sectional and observational data, we cannot fully eliminate threats arising from confounding by unobservable factors or potential endogeneity. Even so, we found consistent reductions in biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels due to clean stove use in this sample, across methods and measurement types. Our preferred estimates of the effects of use of non-traditional stoves are that they reduce biomass fuel use by 4.5 kg per day (50 percent), cooking on traditional stoves by about 160 minutes (80 percent), and biomass fuel collection time by 105 minutes (80 percent). With the exception of the biomass fuel collection time savings, these estimates are robust across self-reported or objective measures of outcomes, and are somewhat stronger in Uttar Pradesh than in Uttarakhand, where both biomass fuel and LPG are more readily accessible. For biomass fuel collection time, we only observe significant savings in UP, and find that ignoring selection leads to substantially lower estimates of the impacts of cleaner stove use. The latter result may indicate that the combination of relatively limited fuel supplies and lower adoption of cleaner fuels (low supply and demand) can lead to more strongly biased measures of impacts, due to stronger selection on unobservables.

Given that 94 percent of clean-stove owning study households were using LPG stoves, and that only 4 were using higher-efficiency biomass stoves of any kind, we can infer based on these savings that stove-stacking is the norm among households owning the clean stoves in this sample. The implied environmental benefits are nonetheless significant, even if the realization of health benefits may require a more complete switch away from traditional stoves (Smith and Sagar, 2014). For example, using an existing model for the costs and benefits of improved stoves, the lower estimate of reductions estimated in this paper (savings of 2.7 kg/hh-day) would yield public benefits of roughly $1.8/household-month from averted greenhouse gas emissions and avoided deforestation, even after accounting for the emissions from burning LPG (Jeuland and Pattanayak, 2012).[16] If biomass harvesting were fully sustainable, the averted black carbon emissions benefits would still be $1.0/hh-month.

[16] This calculation ignores health benefits given that a 30% switch would likely prove insufficient to deliver notable health improvements. It also assumes a daily savings of 2.7 kg/household-day for a household using a cleaner stove and is meant to be illustrative (For additional details, please refer to the appendix to this article). It uses median parameter values from the model developed in Jeuland & Pattanayak (2012). J & P fully acknowledge that the values of each of the model parameters underlying the calculations vary by setting and context; this provides the central justification for the Monte Carlo simulations of costs and benefits reported in their paper. Using these median values, we first calculate the CO_2-equivalent of the avoided black carbon emissions from the 81 kg/month of fuel savings to be about 63 kg/month, assuming a 25% stove efficiency, 12.1 g emissions/MJ of heat produced by the stove, and a heating value of 16 MJ/kg fuel (e.g., 81*0.016*12.1/0.25). This is reduced to about 50 kg/month once LPG emissions are accounted for. Valued at $20/ton of emissions avoided, the value of this savings is $1.0/hh-month. For the cost of deforestation, we again follow J & P in assuming that the environmental cost of lost woodfuel is $0.01/kg. This translates to $0.80/hh-month of benefits related to avoided environmental costs. Clearly, the value of emissions reductions would vary with cooking behaviors as well as technical stove performance and fuel types,

These substantial social benefits from avoided black carbon emissions and pressure on forests are likely not considered by households considering acquisition and use of alternative stoves. The production of these social benefits by private agents – who only consider private benefits such as reduced expenditure and time spent collecting fuel – will therefore be inefficiently low unless Pigouvian subsidies (on stove use, rather than simple acquisition of stoves that may go unused) are instituted to boost demand. Based on the calculations presented above, policies to expand coverage of LPG in similar rural areas of northern India could achieve environmental benefits worth \$12-22/household-year, against a total subsidy cost of about \$15/household-yr under current policy (200 Rs. or \$3.50/cylinder for an average of 4.3 cylinders/yr at the use rates estimated in this sample). Of course, the net benefits of such an expansion policy would also depend on the additional costs of supply to remote areas and the effect of these costs on LPG prices, issues that are worthy of additional study. Further assessments are also warranted given the current push to reduce fuel subsidies in India owing to the strain these impose on the public budget.

Our work also has important implications for the debate over the importance of more objective measurement methods in cookstove studies. There has been a consistent call for more objective measurements of stove use in recent literature (Grupp et al., 2009; Ruiz-Mercado et al., 2012), even though few studies have tested the degree to which recall and self-reporting biases compromise estimates of use of, and benefits from, non-traditional stoves. An important contribution of this paper was the incorporation of measures of fuel consumption and time spent cooking that would seem less prone to reporting errors. Somewhat surprisingly, we found that estimates of the effects of use of cleaner stoves using alternative measures were generally

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and the other environmental benefits would depend on the nature of the ecosystem services lost due to wood harvesting.

consistent, and therefore no real evidence of Hawthorne effects. And though inclusion of controls for the types of meals prepared, the number of household members cooked for, and the other uses of stoves increased the explanatory power of our models, these did not substantially change our estimates of fuel and time savings.[17] This finding contrasts with results in Simons et al. (2014), who found that respondents report significantly more use of improved stoves than is found with objective measures. The reasons for this difference in misreporting across the two studies are not clear, and require further investigation, but they could be related to whether households perceive it to be socially desirable to report specific behaviors. The accuracy of reporting of cooking behaviors has important implications for quantification of the benefits of non-traditional stoves, and is critical to stove promotion efforts that rely on instruments such as carbon finance.

For policymakers working to promote alternative cookstoves, our results have other important implications. First, we find that wealthier, smaller and more educated households, as well as risk-averse households, are more likely to use clean stoves, and are also more likely to experience fuel savings than households with lower socio-economic status. Once use of clean stoves is considered, however, income variables have little discernible effect on fuel savings. This suggests that in the rural areas considered in this study, even wealthy households maintain use of biomass fuels, rather than simply progressing up an energy ladder. Stove dissemination programs endeavoring to foster a more complete switch away from traditional stoves may need

[17] Collection of such data may however point to strategies that might lead to greater impacts on fuel consumption and time spent cooking, if for example they can be used to identify fuel-intensive cooking periods and then can inform campaigns to change behavior during those times. Further efforts to collect detailed, objective data on stove and fuel use for different cooking activities appears warranted to better understand these complexities and the potential bias that arising from ignoring them.

to focus on both lowering the price of purchase, and seeking to identify new ways to incentivize continued use of clean technologies (or penalize polluting ones).

Secondly, because households appear to prefer different technologies for specific types of cooking activities (as evidenced by the stove stacking behaviors we observe), efforts to increase use of cleaner cooking options will have to address their lack of suitability for cooking particular foods or meals. Neither subsidies nor education campaigns will be sufficient to induce households to use cleaner stoves for all purposes, unless designs are appropriately responsive to user needs, local fuel types and cultural preferences. Conversely, cleaner stoves that better match preferences are more likely to be used and thus will have greater potential to reduce biomass fuel consumption.

Finally, clean cooking technologies that use non-biomass energy sources already exist, and judging by the relatively high adoption rates of LPG in Uttarakhand, rural households appear to value them. The almost single-minded focus on developing new and more efficient biomass stoves in the policy community therefore appears somewhat misplaced. Instead, more attention should be given to development of policies and supply chains that achieve greater dissemination of modern fuels.

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Table 1. Stove, fuel use and household characteristics

	Full Sample			UK			UP			Difference
	N	Mean	SD	N	Mean	SD	N	Mean	SD	p-value
Panel A: Household stove and fuel use										
% Used clean stove during monitoring period	1234	13%	34%	460	30%	46%	774	3%	17%	0.000
Total biomass fuel used during monitoring (kg)	1234	9.0	4.8	460	8.6	5.5	774	9.1	4.3	0.087
Total biomass fuel used - average (kg/day)*	2120	9.3	12.5	1063	6.7	6.3	1057	12.0	16.2	0.000
Cooking time on traditional stoves during monitoring (min/day)	1234	199.8	96.1	460	222.6	127.7	774	186.2	67.3	0.000
Cooking time on traditional stoves - average (min/day)*	2120	191.1	157.4	1063	290.8	141.8	1057	90.9	97.1	0.000
Time spent collecting traditional fuels (min/day)*	2120	130.1	120.0	1063	109.9	98.4	1057	150.3	135.5	0.000
Cooking time on clean stoves during monitoring	2120	7.3	31.9	1063	11.2	37.6	1057	3.4	24.1	0.000
Total # of stoves owned*	2120	1.3	0.5	1063	1.4	0.6	1057	1.1	0.3	0.000
Total # of fuels used during monitoring	2120	1.1	1.0	1063	0.8	1.0	1057	1.4	0.9	0.007
Total # of meals prepared during monitoring period	1234	3.5	1.2	460	4.1	1.4	774	3.2	0.9	0.000
% Cooked the usual # of meals during monitoring	1234	93%	25%	460	85%	36%	774	98%	15%	0.000
Reported market price of firewood (Rs./100kg)*	2120	523.3	462.3	1063	628.6	581.6	1057	417.4	257.6	0.000
Reported market price of LPG (Rs./14.2kg cylinder)*	2120	477.3	75.9	1063	452.3	55.5	1057	502.4	84.8	0.000
% who spend money on firewood*	2120	35%	48%	1063	23%	42%	1057	47%	50%	0.000
Panel B: Household demographic and socioeconomic characteristics										
% Hindu*	2118	93%	26%	1063	100	0%	1055	85%	36%	0.000
% Scheduled Caste or Tribe*	2120	26%	44%	1063	25%	43%	1057	28%	45%	0.207
Household Size*	2120	5.3	2.4	1063	4.8	2.1	1057	5.7	2.7	0.000
# of individuals for whom food was prepared during monitoring	1154	6.3	2.7	426	5.3	2.5	728	6.9	2.6	0.000
% Female headed household*	2095	18%	38%	1054	27%	45%	1041	8%	27%	0.000
Years of education (head of household)*	2082	5.0	4.8	1044	5.8	4.6	1038	4.1	4.9	0.000
Years of education (primary cook)*	2065	3.7	4.5	1031	4.6	4.5	1034	2.8	4.4	0.000
Average monthly expenditures*	2051	5,786	5,108	1062	5,657	4,833	989	5,924	5,385	0.237
Average hours of electricity*	2071	10.0	9.1	1022	17.2	7.1	1049	3.0	4.0	0.000
Number of children under 5*	2120	0.5	0.8	1063	0.5	0.8	1057	0.5	0.8	0.035
% Taken a loan*	2120	14%	35%	1063	15%	35%	1057	13%	33%	0.204
% SHG membership*	2117	13%	33%	1061	15%	36%	1056	11%	31%	0.005

Notes: *data from full household baseline survey. P-values are reported for the difference in means between UP and UK. At the time of the survey in 2012, US$1=Rs.55

Table 2. Probit regression results for factors associated with use of clean stoves (with marginal effects for the overall sample)

VARIABLES	**Full Sample**	**Marginal Effects**	**UK**	**UP**	**Full Sample**	**Marginal Effects**	**UK**	**UP**
	Used cleaner stove: Monitoring period	dy/dx (at means)	Used cleaner stove: Monitoring period	Used cleaner stove: Monitoring period	Used cleaner stove: Past week[1]	dy/dx (at means)	Used cleaner stove: Past week[1]	Used cleaner stove: Past week[1]
Relative wealth	0.3*** (0.1)	0.021***	0.4*** (0.1)	0.4 (0.3)	0.5*** (0.06)	0.095***	0.6*** (0.08)	0.5*** (0.1)
Average monthly expenditures (log)	0.05 (0.1)	0.005	0.1 (0.1)	-0.4 (0.3)	0.10 (0.07)	0.019	0.08 (0.08)	0.2 (0.2)
# of rooms	0.04 (0.03)	0.004*	0.05 (0.04)	-0.1 (0.1)	0.04* (0.02)	0.008**	0.04* (0.02)	0.03 (0.05)
Years of education (head of household)	0.04 (0.02)	0.002*	0.06** (0.03)	0.08 (0.07)	0.05*** (0.01)	0.009***	0.05*** (0.02)	0.05** (0.02)
Age (head of household)	0.003 (0.006)	0.000	0.01 (0.007)	-0.004 (0.02)	0.009*** (0.004)	0.002**	0.01*** (0.004)	-0.003 (0.007)
Scheduled Caste or Tribe	-0.4* (0.2)	-0.026	-0.4 (0.3)	-0.5 (5.8)	-0.3** (0.1)	-0.047*	-0.2* (0.1)	-0.2 (0.3)
Household size	-0.1*** (0.05)	-0.009***	-0.2** (0.06)	-0.09 (0.1)	-0.08*** (0.02)	-0.015***	-0.1*** (0.03)	-0.05 (0.04)
Number of children under 5	0.04 (0.1)	0.004	0.1 (0.1)	-0.3 (0.7)	0.1** (0.06)	0.029***	0.1* (0.08)	0.2 (0.1)
Taken a loan	0.0003 (0.2)	0.002	0.08 (0.3)	-0.3 (4.5)	-0.06 (0.1)	-0.007	-0.1 (0.2)	0.1 (0.3)
SHG membership	0.2 (0.2)	0.015	0.4 (0.3)	-5.4*** (1.6)	0.3** (0.1)	0.049*	0.3** (0.1)	0.08 (0.2)
Female only respondent	0.04 (0.2)	0.006	0.3 (0.2)	-0.3 (0.4)	0.07 (0.1)	0.013	0.1 (0.1)	-0.10 (0.2)
Female headed household	0.3 (0.2)	0.011	0.4 (0.3)	0.9 (1.1)	0.4*** (0.1)	0.072***	0.4** (0.2)	0.6* (0.3)
Years of education (primary cook)	0.03* (0.02)	0.001	0.03 (0.02)	0.01 (0.05)	0.04*** (0.010)	0.008***	0.04*** (0.01)	0.06*** (0.02)
Hindu	-0.2 (0.6)	-0.028		0.2 (1.0)	0.1 (0.3)	0.047		0.2 (0.3)
Reported higher than village average price of firewood	-0.2 (0.1)	-0.013	-0.1 (0.2)	-0.7 (0.4)	0.2* (0.09)	0.03*	0.1 (0.1)	0.3 (0.2)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-0.2 (1.2)	-0.084	-1.7 (1.8)	0.6 (2.5)	-3.3*** (0.7)	-0.593***	-2.9*** (1.0)	-4.1*** (1.2)
UP (=1 if household lives in UP)	-0.8***	-0.055***			0.7***	0.123***		

	(0.3)				(0.2)			
Aware of clean stoves	-0.1	-0.010	-0.05	-0.2	-0.2	-0.035	-0.2	-0.3
	(0.3)		(0.3)	(0.9)	(0.2)		(0.2)	(0.3)
Believe clean stoves / fuels have ≥ medium impact on negative effects of traditional stoves	0.4*	0.027	0.08	1.4	0.2	0.034	0.2	0.3
	(0.2)		(0.3)	(1.0)	(0.1)		(0.2)	(0.3)
Toilet	1.0***	0.065***	5.0***	1.5*	1.3***	0.232***	1.1***	1.5***
	(0.2)		(0.9)	(0.8)	(0.2)		(0.3)	(0.2)
Most patient	-0.1	-0.008	-0.1	-0.2	-0.03	-0.003	0.03	-0.3
	(0.2)		(0.2)	(1.0)	(0.1)		(0.1)	(0.3)
Most risk-taking	0.1	0.004	0.1	-0.6	-0.2	-0.036**	-0.2	-0.4
	(0.2)		(0.2)	(0.5)	(0.1)		(0.1)	(0.3)
Constant	-2.4**		-7.6***	0.1	-3.4***		-3.3***	-3.2*
	(1.2)		(1.4)	(3.3)	(0.7)		(0.9)	(1.8)
Observations	991		373	618	1,782		910	872

Notes: *** p<0.01, ** p<0.05, * p<0.1; Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses. This is the first stage of the Heckman model.

[1] Self-reported outcome as reported in the full household survey.

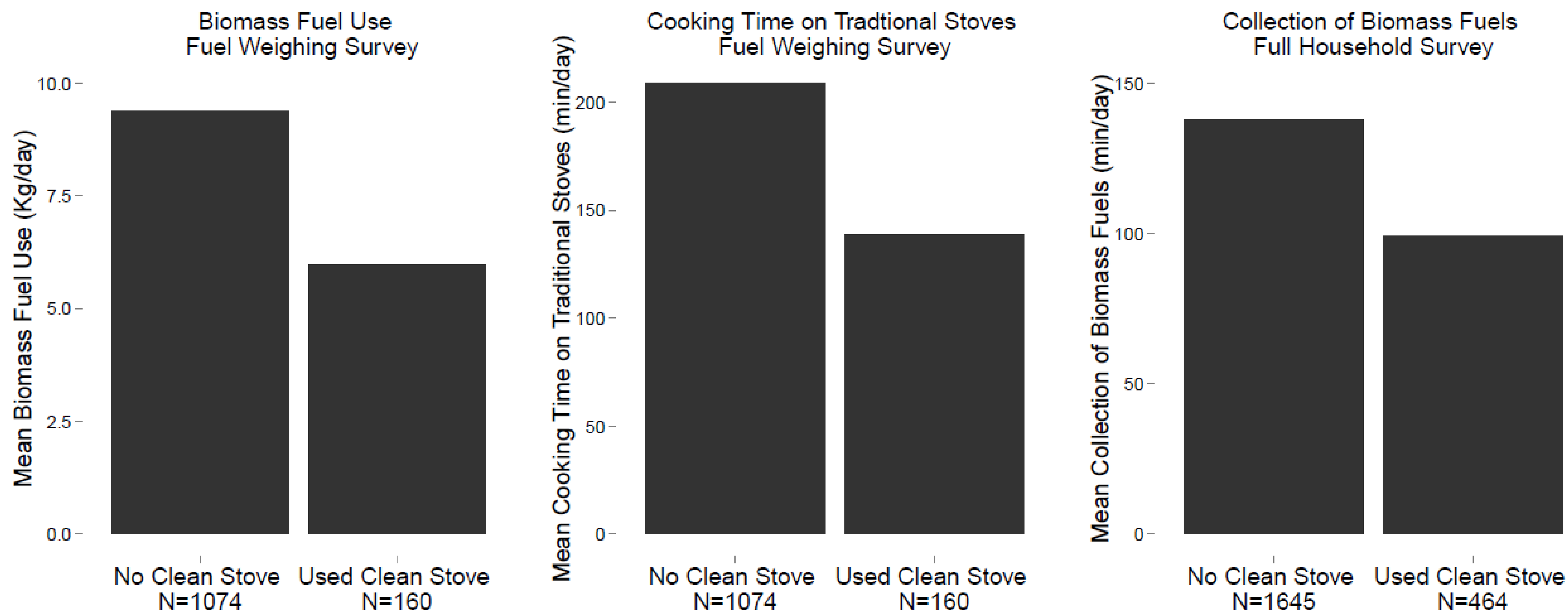
Table 3. Heckman estimator results for the effects of use of clean stoves (second stage)

VARIABLES	(1) Biomass fuel (kg/day)	(2) Cooking time w/ traditional stoves (mins/day)	(3) Time collecting biomass fuels (mins/day)
Used clean stove+	-4.5***	-161***	-106***
	(1.5)	(35)	(30)
Number of household members cooked for	0.5**	10.0***	
	(0.3)	(3.7)	
Number of household members cooked for (squared)	0.005	-0.2	
	(0.02)	(0.2)	
Household size			-1.9
			(3.8)
Household size squared			0.2
			(0.3)
UP (=1 if household lives in UP)	-2.7***	-101***	47***
	(0.9)	(20)	(12)
Female headed household	-0.1	-1.9	-11
	(0.5)	(8.8)	(8.8)
Female respondent only	-0.4	-4.6	-3.0
	(0.3)	(5.7)	(6.3)
Years of education (head of household)	-0.04	-0.3	-0.1
	(0.04)	(0.7)	(0.9)
Years of education (primary cook)	-0.006	-0.1	0.4
	(0.03)	(0.6)	(0.7)
Age of head of household	0.007	0.0001	0.3
	(0.01)	(0.2)	(0.2)
Average monthly expenditures (log)	0.2	-1.3	2.2
	(0.2)	(4.0)	(4.3)
Relative wealth	0.2	1.3	24***
	(0.2)	(3.6)	(5.3)
# of rooms	0.04	0.10	0.2
	(0.09)	(1.6)	(1.5)
Scheduled Caste or Scheduled Tribe	-0.05	10*	8.2
	(0.3)	(5.8)	(6.5)
Hindu	0.3	4.6	-5.7
	(0.5)	(7.5)	(13)
Reported higher than village average price of firewood	0.4	4.5	3.3
	(0.3)	(5.1)	(5.7)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	1.8	68**	60
	(1.8)	(31)	(46)
Number of children under 5	0.2	5.0	-2.3
	(0.2)	(3.1)	(3.7)
Hours of electricity	-0.06*	0.6	1.8***
	(0.03)	(0.6)	(0.5)
Taken a loan	0.04	-1.0	12
	(0.4)	(7.9)	(7.8)
SHG membership	-0.6	12	16*
	(0.4)	(8.4)	(8.7)
Toilet	-0.1	15	5.0
	(0.6)	(12)	(11)
Most patient	0.2	-0.4	-3.9
	(0.4)	(7.6)	(6.3)
Most risk-taking	-0.1	0.1	-4.8
	(0.4)	(8.2)	(6.7)
Aware of clean stoves	0.1	0.7	11
	(0.4)	(7.2)	(10.0)
Believe clean stoves / fuels have ≥ medium impact on negative effects	0.2	-7.4	-22**

	(0.4)	(8.2)	(9.4)
Breakfast (=1 if breakfast was cooked)	-0.05	-5.7	
	(0.6)	(10)	
Morning tea (=1 if morning tea was cooked)	0.2	20***	
	(0.4)	(6.5)	
Lunch (=1 if lunch was cooked)	1.1**	42***	
	(0.4)	(8.4)	
Afternoon tea (=1 if afternoon tea was cooked)	0.3	-29***	
	(0.5)	(7.3)	
Dinner (=1 if dinner was cooked)	1.0	22	
	(0.7)	(14)	
Food only (=1 if only food was prepared)	-1.1*	-31**	
	(0.6)	(13)	
Inverse Mills ratio	0.4	34	43**
	(0.8)	(22)	(17)
Rho	0.1	0.40	0.400
Constant	3.9*	164***	8.3
	(2.3)	(41)	(44)
Observations	991	991	1782

Notes: *** p<0.01, ** p<0.05, * p<0.1; Standard errors, calculated with the jackknife method, in parentheses.
+For outcomes (1) and (2), the independent variable "used clean stove" indicates a household reported using a clean stove during the monitoring period and for outcome (3) indicates a household reported using a clean stove in the past week (from the baseline survey).

Figure 1. Key outcomes for users and non-users of non-traditional stoves



Appendix

Detailed explanation of the calculation of social benefits from clean stove use

Following Jeuland and Pattanayak (2012) – J&P hereafter, we assume that the value of CO_2 emissions savings (Carb) from switching stoves can be calculated using equation A1:

$$\text{Carb} = ccarb \cdot \chi \cdot [\text{Fuel}_0 \cdot (\gamma_0 \cdot \mu_0 / \varepsilon_{f0}) - \text{Fuel}_i \cdot (\gamma_i \cdot \mu_i / \varepsilon_{fi})] / 10^6 , \qquad \text{(A1)}$$

where:

ccarb = social cost of carbon emissions = US$20/ton-$CO_2$ equivalent (CO_2eq);
χ = use of new stove (fraction of cooking) = 0.3;
$Fuel_0$ = amount of solid fuel used prior to adoption of the clean stove (kg/month);
$Fuel_i$ = amount of LPG fuel used in the clean stove (kg/mo) = 4.4 kg/mo;
γ_i = carbon intensity of fuel *i* (g CO_2eq per MJ) = 12.1 (biomass) and 116.5 (LPG);
μ_i = energy conversion factor for fuel *i* (MJ/kg fuel) = 16 (biomass) and 45 (LPG); and
ε_{fi} = Fuel efficiency of stove (MJ useful energy/MJ produced heat) = 0.25 (traditional stove) and 0.55 (LPG stove).

From our empirical analyses, we estimate that $\chi \cdot Fuel_0$= (30 day/mo)$\cdot$(2.7 kg/day) = 81 kg/mo. On the basis of the average fuel savings calculated in the paper (as a % of total fuel consumption), we assume use of the LPG stove to be 30%. All other parameters are set at the levels used for base case estimated in J&P, and we therefore calculate the carbon emissions savings to be worth US$1.0/hh-mo.

For the value of avoided deforestation (*Bio*), we again follow J&P in using equation A2, noting that replacement cost is not a true measure of economic benefits in the absence of policies that ensure replacement of lost forested land:

$$\text{Bio} = \chi \cdot ce \cdot Fuel_0 , \qquad \text{(A2)}$$

where:

ce = Cost of tree replacement = US$0.01/kg wood.

As discussed in J&P, this calculation (based on replacement cost for tree growth from Hutton et al. 2007) assumes sustainable harvesting of fuel wood. A preferable economic value for the benefit of reduced deforestation would be a measure of the actual value of forest services that are lost due to wood harvesting – e.g., impacting water flow, soil erosion or species habitat, which could theoretically rely on estimates from the forest valuation literature (Ferraro et al. 2012). The difficulty in producing such a calculation for our analysis lies in translating forest values, usually measured in $/hectare for specific ecoregions and climates, into a global measure $/kg of wood, which requires information on variation in yields in different locations, among other challenges. Given that $\chi \cdot Fuel_0$ = 81 kg/mo (as noted above), the value of avoided deforestation is then roughly US$0.81/hh-mo, and the overall social benefits of these fuel reductions come to US$1.8/hh-mo.

References

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Supplementary tables

Table A1A. Balance Tests for Users of Cleaner Stoves vs. Non-User (Fuel Weighing Survey)

	Unmatched				Matched			
	Users	Non-Users	p-value	Normalized Difference	Users	Non-Users	p-value	Normalized Difference
% Hindu	98%	90%	0.2169	0.22	98%	95%	0.6132	0.096
% Scheduled Caste or Scheduled Tribe	13%	29%	0.1144	-0.27	14%	19%	0.6429	-0.105
Household size	4.8	5.5	0.0321	-0.219	4.8	4.9	0.1008	-0.021
Age (head of household)	53.4	49.1	0.0041	0.204	52.9	51.6	0.0108	0.067
Years of education (head of household)	7.1	4.4	0.0325	0.378	7.1	7.4	0.0580	-0.039
% Female headed household	30%	14%	0.2879	0.277	29%	18%	0.6230	0.177
Years of education (primary cook)	6.1	3.2	0.0395	0.405	6	5.8	0.0601	0.028
Hours of electricity	17.5	7.1	0.0179	0.688	17.5	16	0.0314	0.141
% Owns traditional stove	91%	98%	0.1883	-0.205	91%	96%	0.5874	-0.157
Average monthly expenditures	7,455	5,710	0.0000	0.184	7,333	6,933	0.0000	0.04
Relative wealth (Range: 1-6)	2.7	1.9	0.1185	0.532	2.6	2.5	0.2053	0.051
% Below poverty line (BPL)	37%	68%	0.1532	-0.427	38%	51%	0.5104	-0.182
% Saving possible	18%	4%	0.4167	0.309	17%	8%	0.7667	0.187
% Took a loan	12%	13%	0.1731	-0.034	12%	11%	0.6400	0.029
% Access to toilet	94%	30%	0.3750	0.782	94%	93%	0.6158	0.032
# of cellphones	1.8	1.1	0.1347	0.375	1.7	1.6	0.1295	0.104
% Participate in community cleaning	14%	6%	0.3448	0.184	13%	16%	0.6071	-0.062
N	139	939			133	84		

Notes: Six households using cleaner stoves were outside the range of common support, therefore the matched sample was trimmed to include only households that were on support. Matching algorithm used is 1-1 nearest neighbor matching with replacement. Normalized differences are calculated by taking the difference between the two means and dividing by the square root of the sum of the two standard deviations. Imbens (2014) recommends calculating normalized differences when comparing matched samples. Normalized differences greater than 0.20 are considered large differences.

Table A1B. Balance Tests for Users of Cleaner Stoves vs. Non-User (Full Household Survey)

	Unmatched				Matched			
	Owners	Non-Owners	p-value	Normalized Difference	Owners	Non-Owners	p-value	Normalized Difference
% Hindu	97%	92%	0.0008	0.15	97%	98%	0.1777	-0.048
% Scheduled Caste or Scheduled Tribe	14%	29%	0.0000	-0.249	15%	16%	0.6589	-0.024
Household size	5.2	5.3	0.3163	-0.041	5.2	5.1	0.3832	0.026
Age (head of household)	53.6	49.3	0.0000	0.203	53.8	51.9	0.6360	0.088
Years of education (head of household)	7.4	4.3	0.0000	0.419	7.2	6.5	0.9838	0.098
% Female headed household	25%	16%	0.0001	0.152	24%	27%	0.7309	-0.04
Years of education (primary cook)	6.7	3	0.0000	0.495	6.4	5.8	0.8254	0.094
Hours of electricity	16	8.7	0.0000	0.527	16.1	14.6	0.0557	0.133
% Owns traditional stove	88%	100%	0.0000	-0.338	89%	100%	0.0460	-0.328
Average monthly expenditures	7,222	5,426	0.0000	0.225	6,835	6,508	0.8436	0.034
Relative wealth (Range: 1-6)	2.7	1.8	0.0000	0.585	2.6	2.3	0.8021	0.231
% BPL	45%	69%	0.0000	-0.339	45%	58%	0.0020	-0.18
% Saving possible	14%	5%	0.0000	0.214	15%	12%	0.0510	0.046
% Took a loan	12%	15%	0.1331	-0.063	12%	11%	0.7017	0.033
% Access to toilet	87%	38%	0.0000	0.636	86%	78%	0.2416	0.155
# of cellphones	1.9	1	0.0000	0.398	1.9	1.3	0.5490	0.236
% Participate in community cleaning	13%	7%	0.0000	0.155	13%	10%	0.9985	0.071
N	380	1446			361	201		

Notes: 19 clean stove households were outside the range of common support, therefore the matched sample was trimmed to include only households that were on support. Matching algorithm used is 1-1 nearest neighbor matching with replacement. Normalized differences are calculated by taking the difference between the two means and dividing by the square root of the sum of the two standard deviations. Imbens (2014) recommends calculating normalized differences when comparing matched samples. Normalized differences greater than 0.20 are considered large differences.

Table A2. PSM estimates of the effects of use of clean stoves

VARIABLES	(1) Biomass fuel (kg/day)	(2) Cooking time w/ trad. stoves (mins/day)	(3) Time collecting biomass fuels (mins/day)
Used cleaner stove†	-3.0***	-93***	-41***
	(0.8)	(18)	(12)
Observations	217	217	562

Notes: *** p<0.01, ** p<0.05, * p<0.1; Bootstrapped standard errors in parentheses.
†For outcomes (1) and (2), the independent variable "used cleaner stove" indicates that a household reported using a cleaner stove during the monitoring period and for outcome (3) it indicates that a household reported using a cleaner stove in the past week (from the baseline survey). All data for outcome (3) come from the baseline survey, which asked households to specify "typical" fuel collection time.

Table A3. OLS Estimates of the Effect of Use of Cleaner Stoves on Key Outcomes

VARIABLES	(1) Biomass fuel (kg/day)	(2) Biomass fuel (kg/day)	(3) Cooking time w/ trad. stoves (mins/day)	(4) Cooking time w/ trad. stoves (mins/day)	(5) Time collecting biomass fuels (mins/day)	(6) Time collecting biomass fuels (mins/day)
Used clean stove+	-3.9***	-2.7***	-109***	-93***	-36***	-38***
	(0.6)	(0.6)	(12)	(15)	(8.4)	(8.9)
Number of household members cooked for	0.5***	0.5**	11***	11***		
	(0.2)	(0.2)	(3.4)	(3.7)		
Number of household members cooked for (squared)	0.005	0.006	-0.2	-0.2		
	(0.02)	(0.02)	(0.2)	(0.2)		
Household size					-0.5	-5.5
					(3.6)	(3.7)
Household size squared					0.2	0.5*
					(0.2)	(0.3)
UP (=1 if household lives in UP)	-2.7***	-3.1***	-94***	170***	37***	-75***
	(0.8)	(1.1)	(22)	(22)	(13)	(10)
Female headed household	-0.2	0.2	-4.9	-4.5	-17**	-11
	(0.4)	(0.4)	(8.4)	(9.0)	(7.6)	(8.2)
Female respondent only	-0.4	-0.5	-4.3	0.2	-3.2	6.2
	(0.3)	(0.4)	(6.8)	(6.1)	(6.4)	(7.0)
Years of education (head of household)	-0.04	-0.03	-0.4	-0.2	-0.7	0.3
	(0.04)	(0.04)	(0.7)	(0.6)	(0.8)	(0.8)
Years of education (primary cook)	-0.009	-0.03	-0.4	-0.5	-0.5	-1.0
	(0.03)	(0.04)	(0.6)	(0.5)	(0.7)	(0.7)
Age of head of household	0.008	0.002	0.04	0.06	0.2	0.3
	(0.01)	(0.01)	(0.2)	(0.2)	(0.2)	(0.3)
Average monthly expenditures (log)	0.2	0.1	-1.8	-3.1	0.8	-1.6
	(0.2)	(0.2)	(4.3)	(4.0)	(4.8)	(5.2)
Relative wealth	0.2	0.3	-1.1	3.5	16***	9.8**
	(0.2)	(0.3)	(3.7)	(3.3)	(4.2)	(4.5)
# of rooms	0.03	0.06	-0.5	-1.9	-0.8	-0.4
	(0.09)	(0.09)	(1.4)	(1.3)	(1.3)	(1.4)
Scheduled Caste or Scheduled Tribe	-0.02	0.2	13*	4.9	11	3.6
	(0.4)	(0.4)	(6.6)	(5.6)	(7.9)	(9.2)
Hindu	0.3	-0.3	4.1	-13	-6.6	-11
	(0.7)	(0.9)	(9.6)	(11)	(13)	(16)
Reported higher than village average price of firewood	0.4	0.4	4.7	6.9	1.2	7.0
	(0.3)	(0.3)	(6.1)	(6.5)	(6.0)	(6.5)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	1.8	-0.5	66*	16	96*	32
	(2.3)	(2.3)	(35)	(42)	(49)	(56)
Number of children under 5	0.2	0.09	5.5*	0.6	-4.6	-2.9
	(0.2)	(0.2)	(2.8)	(3.0)	(3.7)	(3.9)
Hours of electricity	-0.06*	-0.04	0.6	0.4	1.8***	1.4**
	(0.03)	(0.03)	(0.6)	(0.5)	(0.5)	(0.5)
Taken a loan	0.04	-0.2	-0.5	-6.4	13	5.5
	(0.4)	(0.4)	(7.2)	(7.2)	(7.8)	(8.0)
SHG membership	-0.7	-0.8*	9.8	-3.8	11	8.0
	(0.4)	(0.5)	(9.1)	(11)	(10)	(9.6)
Toilet	-0.2	-0.6	7.2	-8.1	-12	-9.0
	(0.5)	(0.6)	(14)	(9.5)	(9.3)	(9.1)
Most patient	0.2	0.3	1.3	2.1	-2.8	-4.1
	(0.4)	(0.4)	(6.3)	(5.1)	(6.6)	(7.6)
Most risk-taking	-0.1	-0.3	-1.0	1.1	-2.3	-1.4

	(0.3)	(0.4)	(7.5)	(6.6)	(7.4)	(7.9)
Aware of clean stoves	0.1	0.2	1.3	4.1	13	9.4
	(0.4)	(0.4)	(6.7)	(5.9)	(10)	(11)
Believe clean stoves / fuels have ≥ medium impact	0.1	0.4	-9.9	2.2	-25**	-21*
on negative effects of traditional stoves	(0.5)	(0.5)	(7.7)	(7.1)	(10)	(11)
Breakfast (=1 if breakfast was cooked)	-0.05	0.9	-5.8	25		
	(0.6)	(0.8)	(13)	(17)		
Morning tea (=1 if morning tea was cooked)	0.2	0.2	20**	3.5		
	(0.4)	(0.4)	(7.8)	(6.4)		
Lunch (=1 if lunch was cooked)	1.1**	0.4	43***	22*		
	(0.5)	(0.7)	(10)	(12)		
Afternoon tea (=1 if afternoon tea was cooked)	0.3	1.0*	-28***	-5.8		
	(0.5)	(0.5)	(8.3)	(7.7)		
Dinner (=1 if dinner was cooked)	1.0	1.2	21	32**		
	(0.7)	(0.9)	(15)	(15)		
Food only (=1 if only food was prepared)	-1.1**	-0.08	-33***	-2.9		
	(0.5)	(0.5)	(12)	(12)		
Constant	3.9	4.7	164***	18	29	151***
	(2.5)	(3.0)	(46)	(51)	(52)	(58)
Observations	991	991	991	991	1,782	1,782
R-squared	0.236	0.466	0.354	0.624	0.079	0.282
Hamlet FE	NO	YES	NO	YES	NO	YES

Notes: *** p<0.01, ** p<0.05, * p<0.1; Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses. +For outcomes (1) and (2), the independent variable "used clean stove" indicates a household reported using a clean stove during the monitoring period and for outcome (3) indicates a household reported using a clean stove in the past week (from the baseline survey).

Table A4. Heckman Two-Step Estimator Results for Use of Cleaner Stoves (by state)

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Biomass fuel (kg/day)		Cooking time w/ trad. Stoves (mins/day)		Time collecting biomass fuels (mins/day)	
	UK	UP	UK	UP	UK	UP
Used clean stove+	-4.4	-11***	-103	-192***	42	-228***
	(2.8)	(3.1)	(64)	(60)	(51)	(55)
Number of household members cooked for	0.3	0.5**	13*	3.3		
	(0.6)	(0.2)	(7.2)	(3.4)		
Number of household members cooked for (squared)	0.03	0.002	-0.09	0.04		
	(0.05)	(0.02)	(0.5)	(0.2)		
Household size					10*	-13**
					(6.1)	(6.3)
Household size squared					-0.1	0.8**
					(0.6)	(0.4)
Female headed household	-0.4	0.2	-20	4.8	-13	-35*
	(0.8)	(0.6)	(16)	(9.8)	(10)	(19)
Female respondent only	-0.4	-0.5	-11	-1.8	-13	5.9
	(0.7)	(0.4)	(14)	(5.0)	(8.0)	(9.9)
Years of education (head of household)	-0.08	-0.010	-3.1	0.7	-2.9**	2.4*
	(0.09)	(0.04)	(2.0)	(0.6)	(1.2)	(1.3)
Years of education (primary cook)	-0.08	0.08**	0.09	0.05	0.6	0.3
	(0.06)	(0.04)	(1.4)	(0.6)	(1.0)	(1.3)
Age of head of household	0.002	0.0002	-0.3	-0.07	-0.3	0.6
	(0.02)	(0.01)	(0.5)	(0.2)	(0.3)	(0.4)
Average monthly expenditures (log)	0.07	0.2	-9.5	5.2	4.3	-11
	(0.4)	(0.3)	(6.6)	(4.3)	(5.2)	(8.6)
Relative wealth	0.2	0.5	7.0	-2.1	0.4	29***
	(0.5)	(0.3)	(10)	(3.2)	(9.7)	(7.3)
# of rooms	0.2*	-0.3**	1.4	-3.3**	-2.3	0.3
	(0.1)	(0.1)	(2.4)	(1.4)	(1.7)	(3.3)
Scheduled Caste or Scheduled Tribe	0.2	-0.4	25*	0.4	20**	-2.3
	(0.7)	(0.4)	(13)	(5.1)	(8.5)	(11)
Hindu		0.2		-1.1		-8.6
		(0.5)		(7.1)		(14)
Reported higher than village average price of firewood	-0.05	0.6*	12	-5.2	-1.5	3.9
	(0.5)	(0.4)	(11)	(4.8)	(6.6)	(9.7)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	1.8	2.6	113	82***	331***	-73
	(5.2)	(2.1)	(105)	(29)	(77)	(62)
Number of children under 5	0.3	0.2	5.7	2.3	-8.2	-2.1
	(0.3)	(0.2)	(6.5)	(2.9)	(5.1)	(6.2)
Hours of electricity	-0.07*	-0.07	0.5	-0.07	2.1***	0.3
	(0.04)	(0.04)	(0.8)	(0.6)	(0.5)	(1.3)
Taken a loan	0.03	-0.3	-0.7	-1.6	29***	2.5
	(0.7)	(0.5)	(14)	(7.1)	(9.0)	(14)
SHG membership	-1.3	-0.5	21	-8.7	2.0	23*
	(0.8)	(0.5)	(17)	(7.9)	(11)	(14)
Toilet	0.4	-0.009	7.7	8.7	-7.1	43

	(0.9)	(0.8)	(20)	(12)	(12)	(29)
Most patient	0.7	-0.07	-1.3	-2.2	3.5	-14
	(0.7)	(0.5)	(16)	(6.7)	(8.1)	(11)
Most risk-taking	-0.4	0.4	0.7	-0.7	0.7	-3.9
	(0.7)	(0.4)	(17)	(7.9)	(8.5)	(12)
Aware of clean stoves	1.1	-0.3	4.8	-3.3	19	11
	(1.1)	(0.4)	(22)	(6.1)	(13)	(13)
Believe clean stoves / fuels have ≥ medium	0.2	0.3	-31	6.5	-19	-33**
impact on negative effects of traditional stoves	(1.0)	(0.5)	(21)	(8.0)	(12)	(13)
Breakfast (=1 if breakfast was cooked)	1.5	-1.5**	50**	-51***		
	(1.0)	(0.8)	(22)	(9.3)		
Morning tea (=1 if morning tea was cooked)	1.8	-0.1	43	6.2		
	(1.5)	(0.5)	(29)	(5.8)		
Lunch (=1 if lunch was cooked)	1.5***	-0.7	57***	-5.5		
	(0.5)	(1.1)	(11)	(14)		
Afternoon tea (=1 if afternoon tea was cooked)	-0.8	1.1*	-55	-14**		
	(1.5)	(0.6)	(34)	(6.6)		
Dinner (=1 if dinner was cooked)	1.7	0.7	26	33***		
	(1.3)	(0.8)	(43)	(12)		
Food only (=1 if only food was prepared)	-1.0	1.2	-22*	12		
	(0.6)	(7.2)	(12)	(55)		
Inverse Mills ratio	1.1	1.6	6.1	20	-34	87***
	(1.7)	(2.0)	(39)	(44)	(30)	(28)
Rho	0.3	0.4	0.07	0.4	-0.4	0.7
Constant	2.3	1.7	140	66	-116**	263***
	(3.7)	(7.7)	(87)	(69)	(52)	(79)
Observations	373	618	373	618	910	872

Notes: *** p<0.01, ** p<0.05, * p<0.1; Standard errors, calculated with the jackknife method, in parentheses.
+For outcomes (1) and (2), the independent variable "used clean stove" indicates a household reported using a clean stove during the monitoring period and for outcome (3) indicates a household reported using a clean stove in the past week (from the baseline survey).

Table A5. PSM Estimates of the Effects of Use of Cleaner Stoves (by state)

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Biomass fuel (kg/day)		Cooking time w/ trad. stoves (mins/day)		Time collecting biomass fuels (mins/day)	
	UK	UP	UK	UP	UK	UP
Used cleaner stove†	-2.2**	-9.0***	-87***	-139***	-28**	-62**
	(0.9)	(2.7)	(22)	(46)	(14)	(25)
Observations	186	31	186	31	432	130

Notes: *** p<0.01, ** p<0.05, * p<0.1; Bootstrapped standard errors in parentheses.

†For outcomes (1) and (2), the independent variable "used cleaner stove" indicates that a household reported using a cleaner stove during the monitoring period and for outcome (3) it indicates that a household reported using a cleaner stove in the past week (from the baseline survey). All data for outcome (3) come from the baseline survey, which asked households to specify “typical” fuel collection time.

Table A6. OLS Estimates of the Effects of Use of Cleaner Stoves (by state)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Biomass fuel (kg/day)				Cooking time w/ trad. Stoves (mins/day)				Time collecting biomass fuels (mins/day)			
VARIABLES	UK	UP	UK	UP	UK	UP	UK	UP	UK	UP	UK	UP
Used clean stove+	-2.6***	-8.4***	-1.8***	-6.0***	-93***	-159***	-76***	-151***	-15*	-79***	-17**	-78***
	(0.5)	(1.2)	(0.6)	(1.5)	(13)	(29)	(17)	(34)	(8.2)	(17)	(7.3)	(21)
Number of household members cooked for	0.3	0.5**	0.5	0.4*	14**	3.3	19***	2.1				
	(0.4)	(0.2)	(0.5)	(0.3)	(5.8)	(3.3)	(6.2)	(3.9)				
Number of household members cooked for (squared)	0.03	0.002	0.010	0.009	-0.09	0.04	-0.4	0.2				
	(0.03)	(0.01)	(0.03)	(0.01)	(0.4)	(0.2)	(0.4)	(0.2)				
Household size									8.5*	-12**	7.4*	-18***
									(4.9)	(5.7)	(4.2)	(6.5)
Household size squared									-0.1	0.8**	-0.3	1.2***
									(0.4)	(0.4)	(0.4)	(0.4)
Female headed household	-0.6	0.09	0.4	-0.4	-21	3.9	-15	7.0	-7.2	-40**	2.4	-38**
	(0.6)	(0.6)	(0.6)	(0.6)	(13)	(8.7)	(16)	(7.7)	(7.7)	(17)	(7.6)	(18)
Female respondent only	-0.6	-0.4	-0.6	-0.6	-12	-1.2	-1.2	-0.7	-11	8.4	-3.8	20*
	(0.5)	(0.4)	(0.6)	(0.5)	(16)	(5.4)	(14)	(5.2)	(7.2)	(9.6)	(8.5)	(10.0)
Years of education (head of household)	-0.1*	-0.01	-0.10	-0.01	-3.3**	0.6	-1.8	-0.007	-2.0**	1.5	-0.2	1.3
	(0.06)	(0.04)	(0.08)	(0.05)	(1.4)	(0.6)	(1.3)	(0.7)	(0.9)	(1.2)	(0.9)	(1.3)
Years of education (primary cook)	-0.10*	0.08*	-0.09	0.05	-0.01	0.04	-0.1	-0.2	1.2*	-1.3	0.3	-1.8
	(0.05)	(0.04)	(0.06)	(0.04)	(1.2)	(0.5)	(1.3)	(0.5)	(0.7)	(1.2)	(0.7)	(1.2)
Age of head of household	-0.002	0.002	-0.007	-0.004	-0.3	-0.05	-0.1	0.003	-0.1	0.6	-0.01	0.7
	(0.02)	(0.01)	(0.02)	(0.01)	(0.4)	(0.2)	(0.5)	(0.2)	(0.2)	(0.4)	(0.2)	(0.5)
Average monthly expenditures (log)	0.04	0.2	-0.02	0.2	-9.6	5.2	-13*	5.0	5.4	-15	2.7	-11
	(0.4)	(0.3)	(0.5)	(0.2)	(7.5)	(3.9)	(7.3)	(3.9)	(5.5)	(9.3)	(5.1)	(11)
Relative wealth	-0.06	0.5	0.02	0.6	5.7	-2.5	-1.2	3.4	10.0**	21***	6.6	13*
	(0.2)	(0.3)	(0.3)	(0.5)	(7.4)	(3.5)	(7.0)	(3.4)	(4.6)	(6.6)	(4.1)	(8.0)
# of rooms	0.2*	-0.3**	0.1	-0.1	1.2	-3.3**	-1.6	-1.7	-1.4	-1.8	-1.4	0.1
	(0.1)	(0.1)	(0.1)	(0.1)	(1.9)	(1.5)	(1.8)	(1.5)	(1.5)	(2.6)	(1.6)	(3.1)
Scheduled Caste or Scheduled Tribe	0.3	-0.3	0.6	0.02	26**	0.8	5.7	6.5	17	-0.9	-7.7	10
	(0.6)	(0.4)	(0.8)	(0.4)	(13)	(5.5)	(18)	(5.2)	(11)	(12)	(10)	(14)

Hindu		0.2		-0.2		-1.2		-12		-11		-15
		(0.6)		(0.8)		(8.7)		(11)		(13)		(16)
Reported higher than village average price of firewood	-0.02	0.7*	-0.05	0.6	13	-4.9	12	0.9	-0.1	-0.1	8.6	5.1
	(0.5)	(0.4)	(0.5)	(0.4)	(11)	(5.4)	(13)	(5.4)	(6.5)	(11)	(6.3)	(12)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	2.6	2.3	4.7	-2.1	118	78**	217**	-12	286***	-13	73	-26
	(4.8)	(2.3)	(5.9)	(2.3)	(89)	(35)	(93)	(41)	(73)	(62)	(75)	(79)
Number of children under 5	0.3	0.2	-0.005	0.1	5.8	2.6	-0.8	-1.0	-6.3	-5.3	-4.7	-4.1
	(0.3)	(0.2)	(0.3)	(0.2)	(6.0)	(2.8)	(7.8)	(2.6)	(4.5)	(5.9)	(4.3)	(6.4)
Hours of electricity	-0.07	-0.07	-0.07	-0.02	0.5	-0.08	0.9	0.3	2.1***	0.4	1.3**	0.5
	(0.04)	(0.04)	(0.05)	(0.04)	(0.7)	(0.6)	(0.7)	(0.7)	(0.5)	(1.3)	(0.5)	(1.5)
Taken a loan	0.05	-0.3	-0.9	-0.04	-0.6	-1.6	-6.0	-3.2	27***	0.3	17*	-4.0
	(0.8)	(0.4)	(0.9)	(0.5)	(13)	(7.2)	(15)	(7.2)	(8.0)	(13)	(9.1)	(14)
SHG membership	-1.5**	-0.4	-1.1	-0.3	20	-7.5	7.5	-14	7.8	19	0.8	11
	(0.6)	(0.6)	(0.8)	(0.6)	(18)	(8.2)	(22)	(9.5)	(14)	(14)	(9.3)	(19)
Toilet	0.1	-0.3	0.08	-1.1*	6.0	4.8	-16	-4.7	1.7	-20	1.8	-13
	(0.9)	(0.6)	(1.0)	(0.6)	(26)	(8.0)	(17)	(7.4)	(10)	(18)	(9.5)	(18)
Most patient	0.9	-0.04	1.0	0.1	-0.7	-1.8	-2.7	3.9	3.1	-9.5	2.2	-7.6
	(0.6)	(0.5)	(0.7)	(0.5)	(12)	(6.1)	(11)	(6.2)	(7.7)	(12)	(7.7)	(15)
Most risk-taking	-0.5	0.4	-0.6	0.006	0.2	-0.8	6.8	-0.8	-1.8	1.0	-4.3	-0.2
	(0.6)	(0.4)	(0.8)	(0.4)	(16)	(6.4)	(14)	(6.5)	(9.9)	(11)	(9.8)	(13)
Aware of clean stoves	1.1	-0.3	1.3	-0.1	5.0	-2.9	9.1	1.9	17	14	-1.2	17
	(1.0)	(0.4)	(1.1)	(0.4)	(18)	(5.9)	(19)	(5.0)	(15)	(14)	(14)	(15)
Believe clean stoves / fuels have ≥ medium impact on negative effects of traditional stoves	0.1	0.2	0.5	0.2	-31*	4.9	-8.3	5.5	-15	-37**	0.8	-37**
	(1.0)	(0.5)	(1.2)	(0.6)	(16)	(6.6)	(19)	(6.2)	(13)	(15)	(12)	(16)
Breakfast (=1 if breakfast was cooked)	1.5*	-1.5**	1.9*	-0.7	50**	-51***	40*	-32*				
	(0.8)	(0.7)	(1.0)	(1.1)	(22)	(9.8)	(24)	(17)				
Morning tea (=1 if morning tea was cooked)	1.8	-0.1	1.7	0.02	42	6.1	41	3.1				
	(1.2)	(0.4)	(1.7)	(0.4)	(25)	(6.9)	(27)	(5.5)				
Lunch (=1 if lunch was cooked)	1.6***	-0.8	0.9	-1.3	57***	-6.0	30*	-4.2				
	(0.6)	(1.3)	(0.7)	(1.4)	(12)	(13)	(16)	(17)				
Afternoon tea (=1 if afternoon tea was cooked)	-0.9	1.1*	-0.8	1.6***	-56**	-14*	-56**	12				
	(1.3)	(0.6)	(2.0)	(0.6)	(26)	(7.2)	(23)	(7.2)				
Dinner (=1 if dinner was cooked)	1.8	0.7	1.7	1.2	26	34**	34	40**				

	(1.3)	(0.7)	(1.6)	(1.0)	(36)	(14)	(35)	(16)				
Food only (=1 if only food was prepared)	-1.0*	1.2	-0.08	-0.2	-22*	12	-3.1	13				
	(0.5)	(3.2)	(0.5)	(1.4)	(12)	(26)	(12)	(15)				
Constant	2.9	1.9	1.8	5.1	143**	67	143*	88**	-133**	284***	0.01	271**
	(3.8)	(4.4)	(4.7)	(3.2)	(71)	(52)	(85)	(43)	(61)	(90)	(66)	(111)
Observations	373	618	373	618	373	618	373	618	910	872	910	872
R-squared	0.366	0.225	0.557	0.445	0.422	0.312	0.638	0.600	0.124	0.082	0.430	0.213
Hamlet FE	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES

Notes: *** p<0.01, ** p<0.05, * p<0.1; Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses. +For outcomes (1) and (2), the independent variable "used clean stove" indicates a household reported using a clean stove during the monitoring period and for outcome (3) indicates a household reported using a clean stove in the past week (from the baseline survey).

Table A7. Heckman Two-Step Estimator Results for Use of Cleaner Stoves (Self-Reported Data)

VARIABLES	(1) Biomass fuel (kg/day)	(2) Cooking time w/ trad. stoves (mins/day)
Used clean stove	-5.5**	-93***
	(2.8)	(31)
Household size	-0.3	16***
	(0.8)	(3.8)
Household size squared	0.07	-0.7**
	(0.07)	(0.3)
UP (=1 if household lives in UP)	3.4***	-214***
	(1.3)	(13)
Female headed household	-1.8**	23**
	(0.8)	(9.7)
Female respondent only	1.1*	-4.6
	(0.6)	(5.9)
Years of education (head of household)	-0.06	-1.4*
	(0.07)	(0.7)
Years of education (primary cook)	0.2*	-0.7
	(0.1)	(0.8)
Age of head of household	0.01	-0.3
	(0.02)	(0.2)
Average monthly expenditures (log)	-0.9*	14**
	(0.5)	(5.7)
Relative wealth	0.2	4.0
	(0.5)	(5.1)
# of rooms	-0.04	1.6
	(0.1)	(1.7)
Scheduled Caste or Scheduled Tribe	-0.7	7.7
	(0.6)	(6.6)
Hindu	-4.4**	2.5
	(2.2)	(11)
Reported higher than village average price of firewood	1.2**	8.3
	(0.6)	(5.6)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-5.5	29
	(5.1)	(43)
Number of children under 5	-0.3	8.2**
	(0.4)	(4.0)
Hours of electricity	-0.004	0.7
	(0.04)	(0.6)
Taken a loan	1.7*	0.3
	(0.9)	(8.7)
SHG membership	-0.3	28***
	(0.7)	(8.6)
Toilet	0.4	-6.3
	(1.1)	(13)
Most patient	0.6	30***
	(0.7)	(7.5)
Most risk-taking	1.6**	-5.7
	(0.8)	(7.9)
Aware of clean stoves	3.6***	13
	(1.1)	(8.5)
Believe clean stoves / fuels have ≥ medium impact on negative effects of traditional stoves	-0.4	25***
	(1.1)	(8.6)
Inverse Mills ratio	2.0	-0.8
	(1.8)	(18)
Rho	0.2	-0.007

Constant	18***	91*
	(4.8)	(51)
Observations	1,782	1,782

Notes: *** p<0.01, ** p<0.05, * p<0.1; Standard errors, calculated with the jackknife method, in parentheses. The independent variable "used clean stove" indicates a household reported using a clean stove in the past week (from the baseline survey).

Table A8. PSM Estimates of the Effects of Use of Cleaner Stoves (Self-Reported Data)

VARIABLES	(1) Biomass fuel (kg/day)	(2) Cooking time w/ trad. stoves (mins/day)
Used clean stove in past week	-2.2*	-107***
	(1.0)	(16)
Observations	562	562

Notes: *** p<0.01, ** p<0.05, * p<0.1; Bootstrapped standard errors in parentheses. The independent variable "used clean stove" indicates a household reported using a clean stove in the past week (from the baseline survey).

Table A9. OLS Estimates of the Effect of Use of Cleaner Stoves on Key Outcomes (Self-Reported Data)

	(1)	(2)	(3)	(4)
VARIABLES	Biomass fuel (kg/day)		Cooking time w/ trad. stoves (mins/day)	
Used clean stove	-2.3***	-2.0**	-94***	-75***
	(0.7)	(1.0)	(10.0)	(10)
Household size	-0.2	-0.5	16***	14***
	(0.7)	(0.8)	(4.1)	(4.1)
Household size squared	0.07	0.09	-0.7**	-0.6**
	(0.06)	(0.07)	(0.3)	(0.3)
UP (=1 if household lives in UP)	2.9**		-213***	
	(1.1)		(13)	
Female headed household	-2.0**	-1.9**	23**	26**
	(0.9)	(1.0)	(9.7)	(10)
Female respondent only	1.0	1.5**	-4.6	-1.3
	(0.6)	(0.7)	(5.7)	(6.0)
Years of education (head of household)	-0.09	-0.04	-1.4*	-0.7
	(0.08)	(0.09)	(0.7)	(0.8)
Years of education (primary cook)	0.1	0.1	-0.7	-0.7
	(0.1)	(0.1)	(0.6)	(0.7)
Age of head of household	0.006	0.01	-0.3	-0.2
	(0.02)	(0.02)	(0.2)	(0.2)
Average monthly expenditures (log)	-1.0*	-0.7	14**	6.7
	(0.5)	(0.4)	(5.5)	(6.2)
Relative wealth	-0.2	-0.4	4.1	7.2
	(0.4)	(0.4)	(4.8)	(5.3)
# of rooms	-0.09	-0.03	1.6	0.7
	(0.1)	(0.2)	(1.6)	(1.9)
Scheduled Caste or Scheduled Tribe	-0.5	0.2	7.6	4.7
	(0.5)	(0.8)	(7.7)	(9.9)
Hindu	-4.5*	-2.5	2.5	8.9
	(2.3)	(2.7)	(12)	(11)
Reported higher than village average price of firewood	1.1*	1.1*	8.3	5.8
	(0.6)	(0.6)	(6.7)	(7.3)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-3.9	-0.06	28	-16
	(4.3)	(6.3)	(50)	(59)
Number of children under 5	-0.4	-0.4	8.2**	5.2
	(0.4)	(0.4)	(4.0)	(4.2)
Hours of electricity	-0.004	0.02	0.7	-0.2
	(0.04)	(0.04)	(0.6)	(0.7)
Taken a loan	1.7**	1.7*	0.3	-1.8
	(0.8)	(1.0)	(8.7)	(9.8)
SHG membership	-0.5	-0.06	28***	35***
	(0.7)	(0.7)	(8.4)	(10)
Toilet	-0.4	-0.6	-6.0	-6.8
	(0.9)	(1.1)	(9.7)	(11)
Most patient	0.7	0.7	30***	29***
	(0.7)	(0.9)	(8.0)	(8.4)
Most risk-taking	1.7**	1.6**	-5.7	-11
	(0.7)	(0.7)	(9.7)	(11)
Aware of clean stoves	3.6***	3.3***	13	11
	(1.1)	(1.2)	(10)	(10)
Believe clean stoves / fuels have ≥ medium impact on negative effects of traditional stoves	-0.5	-0.3	25**	23**
	(1.0)	(1.1)	(9.8)	(10)
Constant	19***	14***	91*	71
	(5.2)	(5.4)	(54)	(62)
Observations	1,782	1,782	1,782	1,782
R-squared	0.120	0.224	0.489	0.583

Hamlet FE	NO	YES	NO	YES

Notes: *** p<0.01, ** p<0.05, * p<0.1; Robust standard errors in parentheses. The independent variable "used clean stove" indicates a household reported using a clean stove in the past week (from the baseline survey).