

Fuel Choice, Indoor Air Pollution, and Children's Health

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Abstract

Much of the population in developing countries uses firewood for cooking. The resulting indoor air pollution has severe health consequences for children who are close to the fire while their mothers cook. We examine gas stove adoption, firewood consumption, and the effects on children's health in Guatemala. We find that cooking with firewood has significant negative impacts on respiratory health, as well as strong evidence that these impacts have broader health effects. Simulations indicate that policies to accelerate the adoption of LPG may not be as effective at improving health as policies that target cooking habits to directly reduce exposure.

Key words: indoor air pollution, health, children, fuel transition, firewood, Guatemala.

JEL codes: Q53, Q56, D13, I12, O13

1. Introduction

About half of the world population and up to 95% of the population in low income countries still relies on solid fuels, including firewood and other biomass fuels, to meet basic energy needs such as cooking and heating (Smith et al. 2004; Duflo et al. 2008). The overall use of biomass to generate energy is not declining, and is actually increasing among the poorest households (World Health Organization (WHO) 2002a).

The smoke generated by burning biomass contains particulate matter (PM), carbon monoxide, nitrogen dioxide, sulfur oxides, formaldehyde, and carcinogens such as benzopyrene and benzene. The resulting exposures to indoor air pollution (IAP) are orders of magnitude higher than those recommended by international guidelines and higher than outdoor exposures even in highly polluted areas (Smith et al. 2004). For instance, the U.S. Environmental Protection Agency's standards for average daily concentrations of PM₁₀ and PM_{2.5} (particles less than 10 and 2.5 micrometers in diameter) are 150 µg/m³ and 35 µg/m³, respectively, but typical daily concentrations of PM₁₀ in households that use biomass fuels range from 200 to 5,000 µg/m³, with peak concentrations as high as 50,000 µg/m³ in the immediate vicinity of the fire (Ezzati and Kammen 2002), whereas levels of PM_{2.5} have been measured at over 500 µg/m³ (Naeher et al. 2000).

The health consequences of IAP can be severe. Exposure increases the risk of chronic obstructive lung disease in adults and there is growing evidence of links with several other conditions, including tuberculosis, perinatal mortality, low birth weight, asthma, and cataracts. IAP is responsible for approximately two million deaths annually in developing countries and roughly 4% of the burden of disease (in terms of disability

adjusted life years) (WHO 2002b). IAP has particularly harmful effects on women who cook and the young children they care for, who are subject to higher exposures because of longer time periods spent indoors and close proximity to the fire. Children living in homes that burn biomass are two to three times more likely to contract acute respiratory infections (ARI) than those living in households that burn cleaner fuels (Barnes et al. 2005). Exposure to IAP also increases the risk of acute lower respiratory infections (ALRI), a more dangerous form of ARI that is the leading cause of mortality of children up to five years of age in developing countries (WHO 2002a). The World Bank estimates that 60% of premature deaths caused by local air pollution are children younger than five exposed to IAP from cooking fuels (World Bank 1999).

The link between indoor air pollution and ARI is well established. But though adverse, this is a short-term impact. Long-term health consequences of solid fuel cooking are less well understood. One contribution of this paper is to provide some rare summary evidence and magnitude benchmarks for broader, long-term health effects that persist beyond ARI episodes.

The severity of IAP health effects can be mitigated by targeting the source of emissions (mix of fuels and energy technology), modifying household behavior (avoiding exposure by children or changing the cooking location), or altering the living environment (ventilation and permeability of building materials). The energy ladder model of fuel use suggests that as income increases households will switch from traditional, dirtier fuels such as biomass to modern, cleaner fuels such as gas (LPG) and electricity (WHO 2002b; Barnes et al. 2005). However, households commonly use combinations of fuels, such as firewood and LPG for cooking and kerosene or electricity

for lighting. Hence, despite higher prices per unit of usable energy due to inefficient heat generation, the use of biomass can remain high well into the advanced stages of the energy transition.

What explains this prolonged transition to cleaner fuels? First may be ignorance of the health costs borne directly by family members. Lack of information will play a role if households do not fully understand the link between fuel choices, cooking technology, and health (WHO 2002b). Secondly, the adoption of modern fuels may be hindered by the high startup costs involved in acquiring gas or electric stoves. This problem is exacerbated by restricted access to credit, which is common in developing nations (Edwards and Langpap 2005). Poor households may also be unable to purchase fuel in large enough quantities to benefit from lower per unit prices. Finally, cultural factors and related practical limitations of modern fuels and stoves may render them less attractive; for instance, they may be inadequate for preparing traditional dishes.

A number of policies are commonly suggested to speed up the transition to cleaner fuels, modify the mix of fuels used during the transition, and otherwise lessen the negative health effects of cooking with firewood and other biomass. Cost-related obstacles to increased use of clean fuels may be partially overcome by improving access to credit and subsidizing stoves and fuels (Barnes et al. 2005; Edwards and Langpap 2005). Lack of information and behavioral or cultural factors could be addressed by health education campaigns (Ahmed et al. 2005). Finally, higher permeability of construction materials may reduce exposure to IAP (Dasgupta et al. 2004).

In this paper we use data from a household survey to examine gas stove adoption, firewood consumption, and the resulting effects on the health of children in Guatemala.

We first establish an empirical link between fuel choice, cooking practices, and ARI and then provide strong evidence of broad and chronic impacts through its effect on children's weight-for-age and height-for-age. Although our focus is on the role of fuel choice, we also examine how cooking practices affect health. We investigate the impact of cooking inside, rather than outside the home, the importance of a mother simultaneously cooking and caring for her children, and the role played by the smoke permeability of housing construction materials.

Previous literature has concentrated on the smoke-ARI link. We use our results to assess the effectiveness of a number of potential policy interventions. We find that policies such as information or health-awareness campaigns to dissuade mothers from cooking when children are present and from cooking inside the home are more effective in reducing the short-term frequency of ARI episodes than policies which target the use of wood or the adoption of gas stoves, such as increased access to credit to finance the purchase of a stove or subsidies for a gas stove or for LPG. We also look at broader health consequences of burning firewood. These results suggest that surprisingly large improvements in anthropometric indicators can be brought about by replacing wood with a cleaner fuel.

2. Background

2.1 Literature

There is a large epidemiological literature on the health effects of IAP (for reviews see Smith et al. 2000; Bruce and Perez-Padilla 2000; or Ezzati and Kammen 2002). However, the economics literature in health and development has not devoted much attention to

IAP (see Strauss and Thomas 1998 for a review). Cebu Study Team (1992) estimate diarrhea and respiratory health production functions focusing on identifying individual, household, and community factors that affect these health outcomes. Pitt et al. (2006) examine respiratory health using data from Bangladesh and India, emphasizing the allocation of household responsibilities and the health effects of time spent cooking.

The choice of cooking fuels by households in developing countries and the transition from biomass to cleaner fuels has received more attention in the literature. Amacher et al. (1996) use data from Nepal to estimate household firewood demand and supply functions and examine the use of improved stoves. Heltberg et al. (2000) use data from India to analyze household substitution between forest and non-forest fuels, as well as household response to firewood collection time, common property management institutions, and availability of improved stoves. Pfaff et al. (2004) examine the relationship between income and fuel choice and establish conditions under which a U-shaped relationship between income and IAP may result. Heltberg (2005) uses data from Guatemala to assess the potential of policies that promote inter-fuel substitution. Edwards and Langpap (2005) examine how credit access affects stove ownership and firewood consumption in Guatemala. They find that, although access to credit plays a role in determining wood consumption through its effect on the ability to purchase a gas stove, the impact is small and hence that a stove subsidy would be more effective in reducing wood consumption. None of these papers, however, explores the health consequences of fuel choice. This paper contributes to both strands of the literature by focusing on the household's fuel choice and its effects on children's health.

2.2 Fuel Choice, IAP, and Health in Guatemala

The most commonly used cooking fuels in Guatemala are wood and LPG: 74% of all households use wood, and 45% cook with LPG¹. The use of wood is widespread: practically all households at the bottom of the income distribution use it (99.5% and 98% in the bottom two quintiles), as do most middle-income households (91% and 76% in the third and fourth quintiles) and a third of the wealthier households (34% in the fifth quintile). It is not exclusively a rural phenomenon: although almost all rural households (96%) cook with wood, almost half (46%) of urban households do as well (Heltberg 2005). Most households (55%) combine fuels, using LPG or other clean fuels for quick cooking (such as heating up water) and wood for all other cooking² (Ahmed et al. 2005).

The use of firewood remains prevalent despite the general availability and comparable unit cost (adjusted for efficiency in energy generation) of LPG, a cleaner, faster, and arguably more convenient fuel³. This may to a large extent reflect the high startup costs of LPG: our estimates indicate that the average price for a stove was 775 Quetzales (about US\$ 100) in the year 2000, which represents 46% of monthly household expenditures for households in the lowest quintile of the income distribution, 29% for households in the second quintile, and 20% for the third quintile. Hence, purchasing a stove from current income may not be possible for a majority of households. At the same time, a significant number of households in Guatemala face credit restrictions (36% of households in the 2000 National Living Conditions Survey sample), particularly in the

¹ Only 5.4% of households use kerosene, and the use of electricity is limited to the very top of the income distribution (2.5% of households).

² However, 42% of households in rural areas use firewood exclusively.

³ Heltberg (2005) estimates that 75%-81% of the population has access to LPG.

rural sector (44%), which means that financing the acquisition of a stove may not be an option for many households either.

Fuel consumption patterns may also be affected by other household characteristics, including cultural factors that can determine cooking habits, the number, age, employment, and education level of household members, and the geographic or urban/rural location of the family. For instance, wood-baked tortillas, a staple of the indigenous Guatemalan diet, are said to taste differently when prepared with LPG. Additionally, older households may be more traditional, and thus less likely to adopt more “modern” cooking technologies.

The use of wood as a cooking fuel may have a significant negative impact on household health. ARI was the main cause of morbidity and mortality in Guatemala between 1997 and 2000, causing two to three times as many deaths as acute diarrhea, the second main cause of mortality. Furthermore, during this period the number of morbidity cases caused by ARI increased by an average of 31% per year. ALRI, in the form of pneumonia, was the main cause of infant mortality, accounting for 36% of all registered deaths in 2000 (Ahmed et al 2005).

3. Model and Estimation

In this section we present a simple household model of firewood consumption and children’s health production⁴. The household derives utility from consumption of a market good, x , a household good such as food, z , produced using energy inputs, and the health of the household’s n children, $\mathbf{h} = (h_1, \dots, h_n)$:

$$U = u(x, z, \mathbf{h}; \mathbf{c}) \tag{1}$$

⁴ Given our empirical focus on children’s health, for simplicity we abstract from adult health production.

where c is a vector of household characteristics that are not modeled explicitly but can affect the household's choices. The household good is produced using firewood, w , and a combination of an alternative modern form of energy such as LPG, e , and a stove, s :

$$z = f(w) + g(e, s) \quad (2)$$

where $s \in \{0,1\}$ indicates whether the household owns a stove ($s = 1$) or not ($s = 0$).

Health is a function of the amount of firewood used and household characteristics related to cooking habits or the living environment, l , such as the location of cooking or whether mothers cook with their children nearby:

$$h_i = h_i(w; l_i) \quad i = 1, \dots, n. \quad (3)$$

The household's budget constraint is determined by income, y , and the prices of the market good, p_x , firewood, p_w , LPG, p_e , and a stove, \hat{p}_s :

$$p_x x + p_w w + p_e e + \hat{p}_s s \leq y \quad (4)$$

where \hat{p}_s reflects the cost of the stove on a per-period basis, including the interest payment when a household has access to credit and can borrow at the commercial rate or the opportunity cost when it does not have access to credit and has to borrow against its own future income at a private interest rate (Edwards and Langpap 2005).

The household chooses the amount of the market good, firewood, modern energy, and whether to purchase a stove to maximize utility (1) subject to the production functions (2) and (3), and the budget constraint (4). From the corresponding first order conditions it is possible to derive demand functions for wood and a stove as well as the corresponding health production functions.

The empirical specifications for the wood and stove demand functions are

$$w_j = \alpha_0 + \alpha_1 s_j + \alpha_2 p_j + \alpha_3 c_j + \varepsilon_j \quad (5)$$

$$s_j = \beta_0 + \beta_1 p_{sj} + \beta_2 \mathbf{p}_j + \beta_3 \mathbf{d}_j + \mu_j \quad (6)$$

where $j = 1 \dots J$ indexes households, w_j and s_j are household j 's observed wood use and stove purchase choices, \mathbf{p}_j is a vector of fuel prices, p_{sj} is the price of a stove, \mathbf{c}_j and \mathbf{d}_j are vectors of household characteristics including household consumption, age and ethnicity of the head of household, number of people living in the home, access to credit, and district where the household is located, and ε_j and μ_j are random error terms.

The empirical specification for the health production functions is

$$h_{ij} = \gamma_0 + \gamma_1 w_j + \gamma_2 w_j \mathbf{l}_{ij} + \gamma_3 \mathbf{m}_{ij} + \theta_j + \theta_{ij} + \eta_{ij} \quad (7)$$

where h_{ij} is the health of the i^{th} child in the j^{th} household. The vector \mathbf{l}_{ij} contains variables that enter the model as interaction terms with the wood consumption variable w_j . These include the child's age as well as household characteristics that may directly influence the effect of wood use on health, such as whether the child's mother cooks while she takes care of that child, whether cooking takes place indoors or out, and the permeability of the walls and roof. The vector \mathbf{m}_{ij} contains other child- and household-specific characteristics that may influence health, including the child's gender and ethnicity, his or her mother's age, education, and status as household head, household consumption and size, number of rooms in the house, a variable indicating whether the household is rural, and controls for the district where the household is located. The terms θ_j and θ_{ij} capture unobserved household- and individual-specific health heterogeneity, and η_{ij} is a random error term.

We estimate two specifications of the wood consumption model. The variable w_j is first specified as a dichotomous variable that indicates whether the household uses wood to cook. This specification is estimated using a logit model. In the second specification w_j is a continuous variable that measures the quantity of wood used. Since

this variable is censored at zero, we use a tobit model for estimation. The stove ownership model (6) is estimated using a logit since s_j is a dichotomous variable that indicates whether the household owns a gas stove or not.

Estimation of the health model in (7) requires that we account for unobserved heterogeneity and potential endogeneity of wood consumption. We address unobserved household-level heterogeneity by estimating household random- and fixed-effects models. To account for the remaining unobserved individual health heterogeneity that may be correlated with other determinants of health, we take an instrumental variables approach and rely on predicted values of wood consumption obtained from model (5) to estimate the health production model⁵ (Alderman et al. 2006).

We consider three different health indicators. First, we measure the direct impacts of exposure to IAP. In this case, the health variable h_{ij} is a dichotomous indicator of respiratory infection symptoms for the i^{th} child in household j . Next, we enquire whether exposure to IAP has more wide-ranging health impacts by using more general measures of health. Specifically, the health indicators h_{ij} are continuous variables that measure a child's weight-for-age (WAM) and height-for-age (HAM) (Thomas et al. 1990; Alderman et al. 2006). WAM and HAM measure weight and height as percentages of the median weight and height from a random sample of healthy infants and children. The measures were developed by the U.S. National Center for Health Statistics and are widely used by the WHO, World Bank, and others (see Cogill 2003).

⁵ This approach relies on stove ownership as an instrument for wood use. Ownership of a gas stove is correlated with wood consumption, but has no direct effect on health. To assess the validity of the instrument we examine the corresponding F statistics and the predictive power of regressions of wood use and quantity on the instrument alone. The F statistics for stove ownership in the wood use and wood quantity models are 559.68 and 1,208.36, respectively. The R^2 for an OLS model of wood quantity on stove ownership is 31.6. The R^2 for an OLS model of wood use on stove ownership is 28.6, and a logit model of wood use and stove ownership correctly predicts 86% of observations.

We start by estimating a household random-effects logit model for ARI with instrumented values for wood consumption. This approach allows for unobserved household-level health heterogeneity, but assumes that the household-specific effects are uncorrelated with the explanatory variables. Incorporating unobserved heterogeneous effects that may be correlated with the explanatory variables requires using a household fixed-effects procedure. This raises two additional issues in our case. First, a fixed-effects procedure differences out all household-level variables along with the household-specific effect, including wood consumption, our focus variable, and the interaction terms with cooking location and permeability. We can only identify the effects of the interaction terms between wood consumption and a child's age and between wood consumption and a variable that indicates whether the mother cooks while she is taking care of a particular child (since these are child-specific variables). Second, we are unable to estimate a fixed-effects (conditional) logit because there are too many households where either all the children or none of the children have had a respiratory infection ($h_{ij} = 1$ or $h_{ij} = 0$ for all i in j). Instead, we estimate a fixed-effects linear probability model⁶.

Estimates of the more general health effects (the anthropometric models) are obtained by regressing (the log of) WAM and HAM on the same set of individual child and household characteristics, including instrumented values for wood consumption. We estimate household random- and fixed-effects specifications.

We estimate two versions of each of these models, using predicted values for both the probability that the household uses wood and the quantity of wood used. We adjust

⁶ A potential problem with this approach is that the predicted probabilities may be negative or larger than one. In our case this is not an issue: practically all predicted probabilities (at least 98.7%) lie in the [0,1] interval.

the asymptotic variance-covariance estimates to allow for the first-stage errors by bootstrapping (Cameron and Trivedi 2005).

4. Data

The data we use to estimate models (5)-(7) come from a household survey, the ENCOVI 2000-*Encuesta Nacional de Condiciones de Vida* (Living Standards Measurement Survey), which gathered information on a wide range of topics, including demographic characteristics, health, education, expenditures, savings, and fuel use. The survey was conducted in Guatemala in the year 2000 by the Guatemalan National Institute for Statistics (INE, *Instituto Nacional de Estadística*) with funding and technical support from the World Bank. This is a stratified, random, national survey with rural and urban strata as well as six ethnic strata⁷. Information is available for a total of 7,276 households, of which we select the 5,816 that have children.

The dependent variables in our empirical models measure a household's wood consumption, stove ownership, children's respiratory health, and weight-for-age and height-for-age (WAM and HAM). Wood consumption is measured first by a dichotomous variable that indicates whether the household used wood in the month preceding the survey, and then as the logarithm of the quantity of wood used by the household in the previous month⁸. Stove ownership is represented by a dummy variable set equal to one if the household owns a gas stove and to zero otherwise. Children's respiratory health is measured by a dummy variable set equal to one if the child

⁷ Documentation on the survey and information about access to the data can be found online at <http://www.worldbank.org/lsmc/country/guat/gt00docs.html>.

⁸ Seasonal variation in wood consumption is not a major concern because in Guatemala's tropical climate temperature variation is mostly due to altitude rather than time of year. Furthermore, 98% of households reported using wood exclusively for cooking, so consumption should be fairly constant throughout the year.

experienced symptoms of a respiratory infection, such as coughing, fever, or trouble breathing, in the month preceding the survey, and to zero otherwise. WAM and HAM are continuous variables that measure a child's weight and height standardized by age.

WAM and HAM were collected for all household members. Since our focus is child health, we confine our attention to the 0 to 15 age range to ensure that observed health outcomes are more likely to be influenced by the home and not a work environment. Information on respiratory infection, however, was gathered only for children 5 years of age and younger. The data in the first subsample for estimation therefore only includes children under the age of 6 with non-missing, correctly coded data. Finally, in order to compare WAM and HAM results to ARI estimates, we also re-estimate the anthropometric indicator models for the younger sub-sample.

The vector of fuel prices includes the natural logarithm of the prices of wood, LPG, electricity, coal, and kerosene. All fuel price variables are unit costs obtained by dividing the reported value of a household's expenditure on a fuel by the quantity of the fuel consumed. For households that do not report expenditures on a fuel we used the average unit cost for the county ("*municipio*") where they reside. The price of a stove is proxied by each household's estimated current market value of their stove. When households did not own a stove, we used the average estimated market value for all households that had acquired a stove during the previous year.

To measure access to credit we use a section of the survey that asked households whether they had received or applied for a loan in the preceding year. If the answer was no, the household was asked about the main reason for not applying. We define a household as not having access to credit if the respondent reported not having applied for

a loan because no loans were offered in the community, because he or she did not know how to apply for a loan, did not have enough income or assets to offer as collateral, or reported that loans were “not given to people like them”. We define a household as having access to credit if it had outstanding loans, it had applied for a loan (even if the loan was rejected), or chose not to apply for a loan because of fear of losing the collateral, high interest rate, preference to use its own resources, lack of investment opportunities, or no need to borrow.

In the health production functions, the wood-use dummy or the wood quantity consumption variables are interacted with the child’s age and with four household characteristics: whether the child’s mother cooks while she is looking after children, whether cooking takes place inside or outside, and the permeability of the home’s walls and roof. We rely on the time-allocation section of the survey to create a dummy variable that identifies women who cooked while they were taking care of children, and link mothers to their children through an identification code created as part of the survey. Households were also asked where cooking usually takes place. We use this information to construct a variable that indicates whether cooking takes place inside or outside of the home. Finally, households were asked about the predominant material in the walls and the roof of their home. We use this information to construct indicators for permeability. The walls are considered permeable if they are made of metal sheets, wattle and daub, or cane and sticks. The roof is considered permeable if it is made of metal sheets, shingles, palm leaves, or similar materials.

We control for additional characteristics of a child’s mother by including her age, a dummy variable set equal to one if the mother has no education, and a dummy variable

set equal to one if the mother is the head of the household. We also control for household income by including the logarithm of total reported consumption expenditures in the month preceding the survey. Finally, other control variables are the size of the household, measured by the number of people living in the home, the logarithm of the age of the head of the household (in the wood use models only), the number of rooms in the house, a variable that identifies whether the household is located in a rural or urban area, and dummy variables describing ethnicity and the district where the household is located. Descriptions and summary statistics are provided in Table 1.

5. Results

In this section, we present and discuss the estimation results for our econometric models. We first focus on wood use and stove ownership and then on children's health. In addition to discussing relevant coefficients and their statistical significance, we interpret the marginal effects in context⁹.

5.1 Wood Use and Stove Ownership

The results for the stove ownership and wood use models are presented in Table 2. Heteroskedastic-robust standard errors appear in parentheses below the estimated coefficients.

The first column of Table 2 presents the estimated coefficients for the gas stove ownership model¹⁰. We find that access to credit and the prices of a stove and of LPG have statistically significant effects on the probability of stove ownership; the estimated

⁹ Marginal effects are evaluated at the sample means.

¹⁰ A stove ownership model that included additional household characteristics and ethnicity and district dummies was estimated as well, but these variables are not significant so we opted for the more parsimonious model. The results are the same.

coefficients for these variables are all significant at the 1% confidence level. Marginal effects suggest that, while the effect of access to credit is also economically meaningful, the effects of changes in prices are relatively small. Specifically, whereas providing access to credit would increase the probability of stove ownership by 15%, a 1% decrease in the price of a stove increases the probability of stove ownership by 0.6% and a 1% drop in the price of LPG increases it by 0.2%. We also find that higher wood prices and lower electricity prices increase the probability of stove ownership. Finally, the coefficient for consumption suggests that gas stoves are normal goods.

The second and third columns in Table 2 present the estimated coefficients for the wood use and wood consumption models. The coefficient for stove ownership is negative and statistically significant, suggesting that if households own a gas stove they are less likely to use wood at all, or if they do they use smaller quantities of wood. Specifically, the marginal effects indicate that owning a stove decreases the probability that a household uses wood by 9% or lowers monthly wood consumption by 79%. Other relevant variables have the expected effects: the price of wood has a negative and significant coefficient, as does the level of total household consumption, suggesting that wood is an inferior good. Older households are more likely to use wood, possibly because they are more traditional and hence less willing to transition to LPG, or because the fact that they are older means they will have fewer years to reap the returns from investing in a gas stove. Finally, larger households require more energy and hence use more wood.

5.2 Respiratory Health

Table 3 shows the estimated coefficients and standard errors for the respiratory health production functions. We estimate two versions of the model, one for a wood use

indicator and another that employs the continuous measure of wood consumption. For each of these we estimate two alternative specifications: a random-effects (RE) logit and a fixed-effects (FE) linear probability model¹¹. All models use instrumented (IV) values for wood use or wood consumption obtained from the models discussed in the previous section. All standard errors are obtained by bootstrapping to account for the use of predicted values in estimation.

A likelihood ratio test rejects the hypotheses that the wood use or the wood consumption variables are jointly insignificant in the RE models¹². The estimated coefficients for wood use and wood consumption in the RE models are not statistically significant on their own, but the coefficients of the interactions with the mother cooking and caring for children and cooking inside the home dummies are positive and significant. This suggests that it is not so much the use of wood in a household *per se* that affects children's respiratory health, but rather its use in conditions that intensify exposure. The marginal effects support this interpretation: conditional on a household using wood (or on the mean quantity of wood consumption), if cooking takes place within the house young children in the household are 9% to 12% more likely to have an upper respiratory infection within the last week. If a mother cooks while she is caring for her children, then those children are an additional 12% - 14% more likely to report symptoms of respiratory infection. The estimates of the relevant coefficient in the FE linear probability models are consistent with these results, but they are only significant in the model with the wood-use dummy variable.

¹¹ We also estimated logit models without random or fixed effects, and the results are consistent with those presented in Table 3.

¹² $\chi^2(6) = 23.7$ and $\chi^2(6) = 16.3$, respectively.

The coefficient of the interaction term with age is not significant, suggesting that the respiratory health effects of IAP exposure do not significantly change with age for children 0-5 years old. The coefficients of the interaction terms with the roof and wall permeability indicators have the expected negative sign, but they are not statistically significant. This suggests that, after controlling for other relevant exposure factors, permeability of construction materials does not play an important role in children's respiratory health. One possible explanation for this result, suggested by the summary statistics in Table 1, is that there may not be enough variation in permeability in our sample (most homes have permeable roofs and non-permeable walls) for it to be a relevant factor.

5.3 Anthropometric Health Measures

Tables 4-7 show parameter estimates and standard errors for models based on anthropometric measures of children's health. We report results for all children ages 0 to 15 years of age. We also separately report results for the 0 to 5 age subsample, in order to facilitate comparison with the ARI estimation results. Tables 4 and 5 show estimation results for weight-for-age, while tables 6 and 7 show results for height-for-age. As we did for respiratory health, we estimate random- and fixed-effects specifications for models with instrumented wood use and wood consumption¹³.

We find significant evidence that the use of wood has wide-ranging negative effects on children's health that extend beyond specific symptoms of respiratory problems to more general measures of health and which, furthermore, reach beyond the early childhood years. The coefficients for the wood use/consumption and age interaction

¹³ OLS versions of each model were estimated as well. The results are consistent with those presented in Tables 4-7.

terms are negative and significant in all but three of the models. Additionally, the coefficients of the interactions with indicators for cooking inside the home and cooking and caring for children are negative and significant in the RE models. This suggests that the use of wood, or larger quantities of wood, has a negative effect on children's WAM and HAM measures, and that this effect worsens as children grow.

Other estimated coefficients that are consistently significant across most of the RE models have the expected effects. Children from households with higher consumption and homes with more rooms, both variables that are positively correlated with household income, have higher WAM and HAM. Children from larger, rural households where the mother has no education have lower WAM and HAM.

5.4 Robustness

We check the robustness of our results by estimating alternative specifications of our models. First, the results discussed above for wood use (or consumption) and stove ownership are based on estimating the two models separately. However, it is possible that stove ownership is endogenous in the wood use and consumption models. Hence, we consider two additional specifications. In the first one, models (5) and (6) are estimated together using full-information maximum likelihood. In the second one, we use access to credit as an instrument for stove ownership¹⁴, obtain predicted probabilities for stove ownership from model (6), and use them to estimate model (5). The results are consistent with those discussed above.

¹⁴ Access to credit is an adequate instrument since it is correlated with stove ownership but not directly with wood use. The F statistics for access to credit in the stove ownership model is 182.65. The R^2 for an OLS model of stove ownership on access to credit is 0.08, and a logit model of stove ownership on access to credit correctly predicts 62% of observations.

Additionally, we estimated the WAM and HAM models using variables that measure the length of time a child was breastfed and weight-for-height for the child's mother. The results are consistent with those reported here.¹⁵

6. Policy Simulations

Our results have several very interesting, practical implications. We begin by examining ARI in small children and then go on to look at what appear to be the broader health implications of firewood use.

If policies are narrowly aimed at reducing the health consequences of IAP then accelerating the adoption of a gas stove or otherwise seeking to reduce wood consumption may not be as effective as reducing smoke exposure by changing cooking behavior. In fact, changes in cooking practices can be as effective as eliminating wood use entirely in preventing ARI. In contrast, simulations of impact on weight and height for age suggest that eliminating the use of firewood could dramatically increase measured overall health.

6.1 Acute Respiratory Infection

We begin by using our empirical results to examine the effects of policies commonly proposed to mitigate the effects of cooking with wood on ARI. We consider the effects of attempts to reduce wood consumption by promoting the adoption of gas stoves and contrast these outcomes with policies that focus on changing cooking practices so as to reduce the smoke exposure of young children. In Guatemala there is a “dire shortage of information” about health effects of IAP, and women are frequently not

¹⁵ These variables were left out of the final version of the model because the mother's weight-for-height is not statistically significant and time-breastfed is likely measured with error and it also forces us to drop a significant number of observations.

aware of the link between IAP and health (Ahmed et al. 2005; WHO 2002). Hence, changes in cooking practices could be achieved through outreach and health awareness campaigns.

Our estimation results suggest that gas stove adoption should reduce the amount of wood used. They also suggest that this can be encouraged by improving access to credit, subsidizing gas stoves, or directly subsidizing LPG (Ahmed et al. 2005; Barnes et al. 2005; Duflo et al. 2008). However, our estimation results imply that these policies will have relatively small effects on gas stove adoption. We also find that IAP exposure can be reduced more effectively by not cooking inside the home and by discouraging child care givers from cooking with children present.

The results of policy simulations conducted using our estimates confirm these conclusions. We use our results to obtain predicted probabilities of stove ownership and predicted wood consumption as well as predicted probabilities of ARI. We use sample weights to project predicted sample effects to corresponding national amounts. We simulate the impact of granting universal access to credit for buying a stove, of price subsidies for gas stoves and LPG, and of a health awareness campaign that induces a change in cooking location to outside of the home or induces mothers to avoid cooking while children are under their care.

Simulation results indicate that improved access to credit and stove or LPG subsidies would increase stove ownership and reduce wood consumption, but would make practically no difference in the number of ARI cases¹⁶. For instance, universal access to credit would increase stove ownership by 4% and in turn decrease wood

¹⁶ Complete simulation results and methodology description are not included due to space considerations. They are available upon request.

consumption by 3%, but this translates into a reduction of less than 0.1% in the number of ARI cases. A 50% stove subsidy would increase stove ownership by 38% and decrease consumption of wood by almost 20%, but would reduce the number of children with ARI by only 0.6%. Similarly, a 50% subsidy of LPG would increase stove ownership by 11% and reduce wood consumption by 6%, but reduce ARI cases by only 0.2%.

A health awareness campaign that modifies cooking behavior could have a larger positive impact on respiratory health¹⁷. A campaign that changes the location of cooking to outside of the home in 50% of households would reduce the number of ARI cases by about 1%. A campaign that reduces the number of women who cook with children present could have a considerably bigger impact. Even if it only induces a behavior change in 10% of its target population, it would be more effective than universal access to credit or 50% subsidies for stoves or LPG, reducing the number of ARI cases by 0.7%. A 50% effective awareness campaign could decrease the number of children with ARI by close to 4%, more than five times the largest impact attainable with a subsidy, and at 100% effectiveness the number of ARI cases would decrease by almost 7%. To put this in perspective, consider that while firewood use plays a very important role in ARI, it is not the only cause. In fact, the model implies that if some method were found to completely eliminate its use, ARI cases would fall by approximately the same magnitude (7%)¹⁸.

¹⁷ We assume that such a campaign would not affect stove adoption or wood consumption, but instead would directly reduce exposure.

¹⁸ Recall that the roof and wall permeability interaction terms are negative and thus reduce the simulated impact on ARI of eliminating wood use. Since the two permeability coefficients are statistically insignificant, it might be argued that they should be left out of the simulation. Doing so increases the simulated impact of eliminating the use of firewood on ARI from 7% to 10.2%.

6.2 Overall Health Effects

But what role does using wood as the primary fuel have on broader health measures? Are we missing something if we concentrate only on ARI, the most obvious consequence? To get an idea of the magnitude of the effect we perform a simple thought experiment. We use the FE models to calculate fitted values for WAM and HAM with sample values for all variables. Then we generate predicted values with the wood use dummy variable or wood-use quantity variables set equal to zero and calculate the change in predicted anthropometric measures. In addition to WAM and HAM, we calculate average weight-for-age and height-for-age z-scores (WAZ and HAZ) and measure severe malnourishment and stunting.¹⁹ The results summarized in Table 8 are remarkable.

WAM (HAM) measures weight (height) as a percentage of the median weight (height) from a U.S. Center for Disease Control (CDC) random sample of healthy infants and children. For instance, the first row of Table 8 shows that the average child in our younger sub-sample weighed in at 89% of the CDC sample median. The first row of panel (B) shows that average fitted values for the fixed-effects model are very close to the sample values. Simulation results in panel (C) suggest that if households stopped cooking with wood, weight-for-age for the average young child would climb by 8 to 9 percentage points for the full (0 to 15) sample and by 6 to 16 percentage points of the median for the younger sub-sample (0 to 5). The lower and upper bounds of these ranges

¹⁹ The standard score or “z-score” are normalized measures that express weight and height as $z = (x_i - \mu) / \sigma$, where x_i is the weight (height) of child “i” and μ and σ are the mean and standard deviation, respectively, drawn from the weight (height) distribution of an international reference sample of healthy children.

are defined by whether the wood-quantity or wood-dummy specification is used in the simulation.²⁰

These changes translate into a 0.6 - 0.7 rise in weight-for-age z-scores for the full sample and a 0.5 – 1.4 rise in weight-for-age z-scores for the younger sub-sample. Interestingly, the dichotomous definition of malnourishment²¹ and the density of the sample distribution in the neighborhood of the severe malnourishment cutoff signify that measured severe malnourishment would fall by between 65% and 87%. In fact, measured undernourishment would basically vanish.

The effects on HAM are also very significant, though less dramatic. Depending on whether the model includes wood quantity or the wood-use dummy, the height for age measure rises by between 0.4 and 1.4 percentage points for the full sample and between 1.3 and 3.3 percentage points for the younger one.

These effects seem small in comparison to weight impacts. Yet the distribution of the simulated impact means that increases in height-for-age z-scores would range between 0.1 and 0.3 for the full sample and 0.3 and 0.8 for the younger sub-sample. Furthermore, the density of the sample height-for-age z-score distribution in the neighborhood of the (HAZ = -2) cut-off has powerful implications here too. The proportion of the 0 to 15 population classified as severely stunted would fall by between 7.7% and 25.9%, while stunting among younger children would fall by between 22.6% and 54.4%.

²⁰ The estimations and simulation were repeated directly predicting weight and height with similar results. Also, substituting the frequently used 1990 U.K. reference growth charts (see Cole, et al., 1998) *increased* measured severe undernourished and stunting but did not substantially alter the magnitude of simulated impact of firewood use.

²¹ The international measure for severe child malnutrition is a z-score of more than 2 standard deviations below the international standard ($z < -2$).

7. Summary and Conclusions

Indoor Air Pollution caused by firewood has significant health consequences in the developing world, particularly for young children who suffer high rates of exposure when their mothers cook while caring for them. Research to date has focused on acute respiratory infections. Several policy options have been proposed to mitigate this effect of IAP, including policies that attempt to speed the transition to cleaner fuels such as LPG and policies aimed at reducing exposure rates by modifying cooking behavior. In this paper, we estimate econometric models to examine gas stove ownership and wood consumption decisions and to identify the major factors determining children's respiratory health in Guatemalan households.

Our results suggest that access to credit, the price of LPG, and the cost of gas stoves play a key role in determining whether households own a stove. They also indicate that stove ownership and the prices of wood, LPG, and other fuels affect households' wood consumption choices. The effects of wood consumption on ARI, however, are conditional on factors that determine exposure. Specifically, the amount of wood consumed, as such, does not have as significant an effect as when it is conditioned on the location of cooking and on a mother simultaneously cooking and caring for children.

If we ignore other possible health consequences of burning firewood and the policy focus is exclusively on reducing childhood ARI, our results suggest that policies that improve access to credit or subsidize the price of stoves or LPG are likely to be effective in increasing stove ownership and decreasing wood consumption in Guatemala, but that these policies would have very small effects on children's respiratory health. Policies which focus on modifying cooking behavior, such as a health awareness

campaign, can be more effective, particularly if they reduce the number of women who simultaneously cook and care for children.

We have also examined the relation between wood use and more general anthropometric measures of health. This analysis yields an interesting new finding. Our results strongly indicate that adverse health effects of burning wood in the home go well beyond acute respiratory infection and have much broader impacts.

Finally, our analysis hints at another potentially very interesting finding, which deserves further attention in future research but lies outside the scope of this paper. Our results indicate that cooking with firewood in the home has an impact on traditional undernourishment measures. We cannot identify the mechanisms at work here, but they could be related to the effects that cooking with wood could have on the efficiency of nutrient absorption or directly on measured anthropometric indicators. There is a potential implication for policies to combat Third World childhood malnutrition, as measured by standard anthropometric indicators. If the impact of using firewood on these indicators has been ignored and they could therefore have been misinterpreted, then the problem they point to may have been, to some extent, misdiagnosed. To the extent that this is true, policies that focus on preventing malnutrition are mis-targeted.

References

- Ahmed, Kulsum, Yewand Awe, Douglas F. Barnes, Maureen L. Cropper, and Masami Kojima.** 2005. *Environmental Health and Traditional Fuel Use in Guatemala*. Washington, DC: World Bank.
- Alderman, Harold, John Hoddinott, and Bill Kinsey.** 2006. "Long Term Consequences of Early Childhood Malnutrition." *Oxford Economic Papers*, 58: 450-74.
- Amacher, Gregory S., William F. Hyde, and Keshav R. Kanel.** 1996. "Household Fuelwood Demand and Supply in Nepal's Tarai and Mid-Hills: Choice Between Cash Outlays and Labor Opportunity." *World Development*, 24: 1725-36.
- Barnes, Douglas F., Kerry Krutilla, and William F. Hyde.** 2005. *The Urban Household Energy Transition. Social and Environmental Impacts in the Developing World*. Washington, DC: Resources for the Future.
- Bruce, Nigel, and Rogelio Perez-Padilla.** 2000. "Indoor Air Pollution in Developing Countries: A Major Environmental and Public Health Challenge." *Bulletin of the World Health Organization*, 78: 1078-92.
- Cameron, A. Colin, and Pravin K. Trivedi.** 2005. *Microeconometrics. Methods and Applications*. New York: Cambridge University Press.
- Cebu Study Team.** 1992. "A Child Health Production Function Estimated From Longitudinal Data." *Journal of Development Economics*, 38: 323-51.
- Cogill, Bruce.** 2003. "Anthropometric Evaluation and Annual Monitoring Indicators." USAID, Food and Nutrition Technical Assistance Project. Washington, DC: USAID.

- Cole, T. J., J. V. Freeman, and M. A. Preece.** 1998. "British 1990 Growth Reference Centiles for Weight, Height, Body Mass Index and Head Circumference Fitted by Maximum Penalized Likelihood." *Statistics in Medicine*, 17(4): 407-29.
- Dasgupta, Susmita, Mainul Huq, M. Khaliquzzaman, Kiran Pandey, and David Wheeler.** 2004. "Indoor Air Quality for Poor Families: New Evidence from Bangladesh." World Bank Policy Research Working Paper 3393.
- Duflo, Esther, Micahel Greenstone, and Rema Hanna.** 2008. "Indoor Air Pollution, Health, and Economic Well-Being." *Surveys and Perspectives Integrating Environment and Society*, 1: 1-9.
- Edwards, John H.Y. and Christian Langpap.** 2005. "Startup Costs and the Decision to Switch from Firewood to Gas Fuel". *Land Economics*, 81(4): 570-86.
- Ezzati, Majid and Daniel M. Kammen.** 2002. "The Health Impacts of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs." Resources for the Future Discussion Paper 02-24.
- Heltberg, Rasmus.** 2005. "Factors Determining Household Fuel Choice in Guatemala." *Environment and Development Economics*, 10: 337-61.
- Heltberg, Rasmus, Thomas C. Arndt, and Nagothu U. Sekhar.** 2000. "Fuelwood Consumption and Forest Degradation: A Household Model for Domestic Energy Substitution in Rural India." *Land Economics*, 76: 213-32.
- Naeher, L.P., K.R. Smith, B.P. Leaderer, D. Mage, and R. Grajeda.** 2000. "Indoor and Outdoor PM_{2.5} and CO in High- and Low-Density Guatemalan Villages." *Journal of Exposure Analysis and Environmental Epidemiology*, 10(6): 544-51.

Pitt, Mark M., Mark R. Rosenzweig, and Md. Nazmul Hassan. 2006. “Short- and Long-Term Effects of Burning Biomass in the Home in Low-Income Countries.”

<http://www.pstc.brown.edu/~mp/papers/iapchild.pdf>

Pfaff, Alexander S.P., Shubham Chaudhuri, and Howard L.M. Nye. 2004.

“Household Production and Environmental Kuznets Curves - Examining the Desirability and Feasibility of Substitution.” *Environmental and Resource Economics*, 27: 187–200.

Smith, Kirk R., Sumi Mehta, and Mirjam Maeusezahl-Feuz. 2004. “Indoor Smoke from Solid Fuels.” In *Comparative Quantification of Health Risks: Global Burden of Disease due to Selected Major Risk Factors*, ed. Majid Ezzati, A.D. Rodgers, A.D. Lopez, and C.L. Murray, 1435-93. Geneva: World Health Organization.

Smith, Kirk R., Jonathan M. Samet, Isabelle Romieu, and Nigel Bruce. 2000.

“Indoor Air Pollution in Developing Countries and Acute Lower Respiratory Infections in Children.” *Thorax*, 55: 518-32.

Strauss, John and Duncan Thomas. 1998. “Health, Nutrition, and Economic Development.” *Journal of Economic Literature*, 36: 766-817.

Thomas, Duncan, John Strauss, and Maria H. Henriques. 1990. “Child Survival, Height for Age, and Household Characteristics in Brazil.” *Journal of Development Economics*, 33: 197-234.

World Bank. 1999. *Fuel for Thought: Environmental Strategy for the Energy Sector*. Washington, DC: World Bank.

World Health Organization. 2002a. *The World Health Report 2002: Reducing Risks, Promoting Healthy Life*. Geneva: World Health Organization.

World Health Organization. 2002b. *Addressing the Links between Indoor Air Pollution, Household Energy and Human Health*. Based on the WHO-USAID Global Consultation On the Health Impact of Indoor Air Pollution and Household Energy in Developing Countries (Meeting report). Washington, DC 3-4 May 2000. Geneva: WHO.

Table 1 Summary Statistics

| <i>Variable</i> | <i>Description</i> | <i>Ages 0 - 5</i> | | <i>Ages 0 - 15</i> | |
|-------------------------------------|---|-------------------|------------------|--------------------|------------------|
| | | <i>Mean</i> | <i>Std. Dev.</i> | <i>Mean</i> | <i>Std. Dev.</i> |
| Children | | | | | |
| Respiratory Infection | Dummy = 1 if symptoms of respiratory infection reported | 0.46 | 0.50 | 0.46 | 0.50 |
| Height-for-age ^a | Height standardized by age | 93.12 | 6.22 | 92.61 | 5.88 |
| Weight-for-age ^a | Weight standardized by age | 89.02 | 14.27 | 88.08 | 14.97 |
| Age | Age in years | 2.43 | 1.71 | 4.69 | 3.07 |
| Female | Dummy = 1 if gender is female | 0.49 | 0.50 | 0.46 | 0.50 |
| Mothers | | | | | |
| Mother Cooks and Cares for Children | Dummy = 1 if mother both cooks and cares for children | 0.84 | 0.37 | 0.78 | 0.42 |
| Mother has No Education | Dummy = 1 if mother has no education | 0.41 | 0.49 | 0.43 | 0.50 |
| Mother's Age | Mother's Age in years | 29.10 | 7.39 | 31.39 | 7.77 |
| Mother is Household Head | Dummy = 1 if mother is head of household | 0.07 | 0.26 | 0.08 | 0.28 |
| Households | | | | | |
| Wood Use | Dummy = 1 if household used firewood | 0.80 | 0.40 | 0.87 | 0.34 |
| Wood consumption ^a | Monthly firewood consumption | 412.85 | 614.33 | 453.22 | 595.02 |
| Stove Ownership | Dummy = 1 if household owns gas stove | 0.41 | 0.49 | 0.37 | 0.48 |
| Cooking in Home | Dummy = 1 if cooking takes place inside the home | 0.35 | 0.48 | 0.34 | 0.47 |
| Roof Permeability | Dummy = 1 if roof permeable | 0.91 | 0.28 | 0.92 | 0.28 |
| Wall Permeability | Dummy = 1 if walls permeable | 0.17 | 0.38 | 0.17 | 0.37 |
| Price of Stove ^a | Estimated value of stove (GTQ) | 774.97 | 585.03 | 771.70 | 590.95 |
| Price of Wood ^a | Price firewood (GTQ/unit) | 0.51 | 2.08 | 0.46 | 1.51 |
| Price of Electricity ^a | Price electricity (GTQ/Kw) | 1.58 | 5.98 | 1.57 | 4.77 |
| Price of Coal ^a | Price coal (GTQ/lb) | 2.20 | 2.24 | 2.17 | 1.69 |
| Price of LPG ^a | Price LPG (GTQ/lb) | 6.53 | 12.10 | 6.62 | 10.82 |
| Price of Kerosene ^a | Price kerosene (GTQ/bottle) | 3.63 | 6.04 | 3.69 | 6.99 |
| No Credit | Dummy = 1 if no access to credit | 0.36 | 0.48 | 0.40 | 0.49 |
| Consumption ^a | Annual household consumption (GTQ) | 30,973 | 27,533 | 27,381 | 22,752 |
| Household Head Age ^a | Age head of household | 40.74 | 12.99 | 39.00 | 11.94 |
| Household size | Number of people in household | 5.93 | 2.31 | 6.84 | 2.48 |
| Rooms | Number of rooms in home | 1.86 | 1.21 | 1.90 | 1.21 |
| Rural | Dummy = 1 if rural household | 0.63 | 0.48 | 0.63 | 0.48 |

^a Natural logarithm of variable used for estimation.

Table 2 Stove Ownership and Wood Use Models

| <i>Variable</i> | <i>Stove Ownership</i> | | <i>Wood Use</i> | |
|----------------------|---|--|--|---|
| | <i>Logit</i> (Dep. Var.: Stove Ownership) | <i>Logit</i> (Dep. Var.: Wood Use) | <i>Logit</i> (Dep. Var.: Wood Use) | <i>Tobit</i> (Dep. Var.: ln of Wood Qty.) |
| Constant | -15.01*** (1.04) | 8.89*** (1.67) | | 4.39*** (1.37) |
| No Credit | -0.62*** (0.09) | | | |
| Price of Stove | -2.53*** (0.11) | | | |
| Stove Ownership | | -2.68*** (0.20) | | -1.57*** (0.09) |
| Price of Wood | 0.42*** (0.05) | -1.19*** (0.12) | | -1.13*** (0.04) |
| Price of Electricity | -0.31*** (0.07) | -0.02 (0.07) | | -0.01 (0.04) |
| Price of Coal | -0.01 (0.13) | 0.13 (0.13) | | 0.06 (0.10) |
| Price of LPG | -0.81*** (0.07) | 0.014 (0.07) | | 0.01 (0.05) |
| Price of Kerosene | -0.04 (0.08) | -0.24** (0.10) | | -0.09 (0.06) |
| Consumption | 3.29*** (0.11) | -1.67*** (0.12) | | -0.79*** (0.06) |
| Age Household Head | | 1.11*** (0.21) | | 0.54*** (0.09) |
| Household Size | | 0.47*** (0.04) | | 0.21*** (0.01) |
| Ethnicity Dummies | | 7 Dummies | | |
| District Dummies | | 20 Dummies | | |
| Log likelihood | -1677.02 | -1034.37 | | -9455.37 |
| Observations | 5655 | 5124 | | 5151 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 3 Children's Respiratory Health

| <i>Variable</i> | <i>Wood Use</i> | | <i>Wood Consumption</i> | |
|--|----------------------|---------------------------------|-------------------------|---------------------------------|
| | <i>IV RE-Logit</i> | <i>IV FE-Linear Probability</i> | <i>IV RE-Logit</i> | <i>IV FE-Linear Probability</i> |
| Constant | -2.75 (1.83) | 0.68*** (0.24) | -2.97* (1.81) | 0.67** (0.27) |
| Mother Cooks and Cares for Children | | -0.42** (0.20) | | -0.21 (0.23) |
| Wood | 0.39 (0.51) | | -0.06 (0.10) | |
| Wood × Mother Cooks and Cares for Children | 0.43** (0.21) | 0.47** (0.21) | 0.07** (0.04) | 0.04 (0.04) |
| Wood × Age | 0.12 (0.09) | 0.02 (0.02) | 0.02 (0.01) | 0.002 (0.002) |
| Wood × Cooking in Home | 0.39** (0.16) | | 0.06** (0.03) | |
| Wood × Roof Permeability | -0.42 (0.38) | | -0.05 (0.07) | |
| Wood × Wall Permeability | -0.04 (0.17) | | -0.003 (0.03) | |
| Age | 0.34** (0.11) | 0.04** (0.02) | 0.36*** (0.09) | 0.05*** (0.02) |
| Age ² | -0.08*** (0.02) | -0.01*** (0.002) | -0.09*** (0.02) | -0.01*** (0.002) |
| Female | 0.05 (0.09) | -0.003 (0.01) | 0.05 (0.10) | -0.003 (0.01) |
| Mother's Age | -0.06 (0.05) | -0.01 (0.02) | -0.06 (0.05) | -0.01 (0.02) |
| Mother's Age ² | 6.7E-04 (7.8E-04) | 1.5E-04 (2.8E-04) | 7.2E-04 (8.0E-04) | 1.5E-04 (2.5E-04) |
| Mother has No Education | -0.17 (0.17) | 0.01 (0.04) | -0.17 (0.14) | 0.01 (0.04) |
| Mother is Household Head | -0.12 (0.23) | -0.18 (0.12) | -0.11 (0.19) | -0.16 (0.14) |
| Rural | 0.53*** (0.16) | | 0.57*** (0.18) | |
| Consumption | 0.35** (0.17) | | 0.26 (0.22) | |
| Household Size | -0.08*** (0.03) | | -0.05 (0.04) | |
| Rooms | -0.10 (0.07) | | -0.11* (0.06) | |
| Ethnicity Dummies | 7 Dummies | | 7 Dummies | |
| District Dummies | 20 Dummies | | 20 Dummies | |
| Log likelihood | -3876.09 | | -3897.52 | |
| Observations | 6542 | 6542 | 6576 | 6576 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 4 Children's Weight for Age - Ages 0 to 5

| <i>Variable</i> | <i>Wood Use</i> | | <i>Wood Consumption</i> | |
|--|------------------------|----------------------|-------------------------|----------------------|
| | <i>IV RE</i> | <i>IV FE</i> | <i>IV RE</i> | <i>IV FE</i> |
| Constant | 4.44*** (0.06) | 4.56*** (0.09) | 4.44*** (0.06) | 4.57*** (0.11) |
| Mother Cooks and Cares for Children | | 0.16 (0.10) | | 0.03 (0.09) |
| Wood | -0.03 (0.02) | | -0.01** (0.004) | |
| Wood × Mother Cooks and Cares for Children | -0.01** (0.006) | -0.19* (0.10) | -0.002** (0.001) | -0.01 (0.02) |
| Wood × Age | -0.01*** (0.004) | -0.01** (0.006) | -0.001* (0.0006) | -0.001 (0.0007) |
| Wood × Cooking in Home | -0.01* (0.004) | | -0.001* (0.0008) | |
| Wood × Roof Permeability | 0.002 (0.01) | | 0.002 (0.002) | |
| Wood × Wall Permeability | 0.1E-03 (0.006) | | 0.001 (0.001) | |
| Age | -0.06*** (0.01) | -0.06*** (0.01) | -0.06*** (0.01) | -0.06*** (0.01) |
| Age ² | 0.01*** (0.001) | 0.01*** (0.001) | 0.01*** (0.001) | 0.01*** (0.001) |
| Female | 0.01*** (0.003) | 0.01*** (0.005) | 0.01*** (0.003) | 0.01*** (0.005) |
| Mother's Age | -0.004** (0.002) | -0.003 (0.005) | -0.003 (0.002) | -0.003 (0.007) |
| Mother's Age ² | 0.7E-03** (0.3E-03) | 0.5E-03 (0.8E-03) | 0.6E-03* (0.3E-03) | 0.5E-03 (1.1E-03) |
| Mother has No Education | -0.01** (0.005) | 0.01 (0.02) | -0.01** (0.004) | 0.01 (0.02) |
| Mother is Household Head | -0.01* (0.008) | -0.08 (0.06) | -0.02* (0.008) | -0.09 (0.07) |
| Rural | -0.02*** (0.01) | | -0.02*** (0.005) | |
| Consumption | 0.02*** (0.01) | | 0.02*** (0.005) | |
| Household Size | -0.01*** (0.001) | | -0.007*** (0.001) | |
| Rooms | 0.01*** (0.002) | | 0.01*** (0.002) | |
| Ethnicity Dummies | 7 Dummies | 7 Dummies | 7 Dummies | 7 Dummies |
| District Dummies | 20 Dummies | | 20 Dummies | |
| Observations | 5798 | 5798 | 5831 | 5831 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 5 Children's Weight for Age - Ages 0 to 15

| <i>Variable</i> | <i>Wood Use</i> | | <i>Wood Consumption</i> | |
|--|------------------------|----------------------|-------------------------|-----------------------|
| | <i>IV RE</i> | <i>IV FE</i> | <i>IV RE</i> | <i>IV FE</i> |
| Constant | 4.32*** (0.05) | 4.56*** (0.08) | 4.25*** (0.06) | 4.54*** (0.07) |
| Mother Cooks and Cares for Children | | 0.09 (0.07) | | 0.08 (0.06) |
| Wood | -0.02 (0.02) | | -0.003 (0.003) | |
| Wood × Mother Cooks and Cares for Children | -0.01** (0.005) | -0.10 (0.07) | -0.002** (0.001) | -0.01 (0.01) |
| Wood × Age | -0.01*** (0.002) | -0.01*** (0.003) | -0.001*** (0.0003) | -0.001*** (0.0004) |
| Wood × Cooking in Home | -0.01** (0.005) | | -0.002*** (0.001) | |
| Wood × Roof Permeability | 0.003 (0.01) | | 0.001 (0.002) | |
| Wood × Wall Permeability | -0.004 (0.005) | | -0.0002 (0.0009) | |
| Age | -0.01*** (0.002) | -0.01*** (0.003) | -0.01*** (0.002) | -0.01*** (0.003) |
| Age ² | 0.001*** (0.0002) | 0.001*** (0.0002) | 0.001** (0.0001) | 0.001** (0.0002) |
| Female | 0.01** (0.003) | 0.01** (0.003) | 0.01** (0.003) | 0.01** (0.003) |
| Mother's Age | -0.002** (0.001) | -0.002 (0.005) | -0.002 (0.002) | -0.001 (0.004) |
| Mother's Age ² | 0.5E-03** (0.2E-03) | 0.3E-03 (0.7E-03) | 0.4E-03* (0.2E-03) | 0.2E-03 (0.7E-03) |
| Mother has No Education | -0.01*** (0.003) | 0.01 (0.02) | -0.01** (0.004) | 0.01 (0.02) |
| Mother is Household Head | -0.01* (0.008) | -0.04 (0.06) | -0.02* (0.008) | -0.01 (0.04) |
| Rural | -0.02*** (0.003) | | -0.02*** (0.004) | |
| Consumption | 0.03*** (0.01) | | 0.03*** (0.006) | |
| Household Size | -0.01*** (0.001) | | -0.01*** (0.001) | |
| Rooms | 0.01*** (0.002) | | 0.01*** (0.002) | |
| Ethnicity Dummies | 7 Dummies | 7 Dummies | 7 Dummies | 7 Dummies |
| District Dummies | 20 Dummies | | 20 Dummies | |
| Observations | 9867 | 9867 | 9923 | 9923 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 6 Children's Height for Age - Ages 0 to 5

| <i>Variable</i> | <i>Wood Use</i> | | <i>Wood Consumption</i> | |
|--|-----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|
| | <i>IV RE</i> | <i>IV FE</i> | <i>IV RE</i> | <i>IV FE</i> |
| Constant | 4.50 ^{***} (0.02) | 4.60 ^{***} (0.04) | 4.50 ^{***} (0.02) | 4.60 ^{***} (0.04) |
| Mother Cooks and Cares for Children | | 0.02 (0.02) | | -0.004 (0.02) |
| Wood | -0.002 (0.009) | | -0.0001 (0.001) | |
| Wood × Mother Cooks and Cares for Children | -0.01 ^{***} (0.002) | -0.03 (0.02) | -0.001 ^{***} (0.0004) | 0.0002 (0.005) |
| Wood × Age | -0.01 ^{***} (0.002) | -0.008 ^{***} (0.003) | -0.001 ^{***} (0.0002) | -0.002 ^{***} (0.0003) |
| Wood × Cooking in Home | -0.003 (0.002) | | -0.001 [*] (0.0003) | |
| Wood × Roof Permeability | -0.003 (0.01) | | -0.0002 (0.0008) | |
| Wood × Wall Permeability | -0.004 [*] (0.002) | | -0.0005 (0.0004) | |
| Age | -0.03 ^{***} (0.002) | -0.03 ^{***} (0.003) | -0.03 ^{***} (0.002) | -0.03 ^{***} (0.003) |
| Age ² | 0.01 ^{***} (0.003) | 0.01 ^{***} (0.0004) | 0.01 ^{***} (0.0002) | 0.01 ^{***} (0.0003) |
| Female | 0.002 (0.002) | 0.002 (0.002) | 0.002 (0.001) | 0.002 (0.002) |
| Mother's Age | -0.0003 ^{**} (0.0005) | -0.002 (0.002) | -0.7E-03 (0.001) | -0.003 (0.002) |
| Mother's Age ² | 0.1E-03 (0.8E-07) | 0.4E-03 (0.4E-03) | 0.8E-07 (1.0E-07) | 0.4E-03 (0.4E-03) |
| Mother has No Education | -0.01 ^{***} (0.002) | -0.004 (0.008) | -0.01 ^{***} (0.002) | -0.002 (0.01) |
| Mother is Household Head | -0.001 (0.003) | -0.02 (0.02) | -0.002 (0.004) | -0.02 (0.02) |
| Rural | -0.01 ^{***} (0.002) | | -0.005 ^{***} (0.002) | |
| Consumption | 0.01 ^{***} (0.002) | | 0.01 ^{***} (0.002) | |
| Household Size | -0.003 ^{***} (0.0005) | | -0.003 ^{***} (0.0004) | |
| Rooms | 0.004 ^{***} (0.0009) | | 0.004 ^{***} (0.001) | |
| Ethnicity Dummies | 7 Dummies | 7 Dummies | 7 Dummies | 7 Dummies |
| District Dummies | 20 Dummies | | 20 Dummies | |
| Observations | 5798 | 5798 | 5831 | 5831 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 7 Children's Height for Age - Ages 0 to 15

| <i>Variable</i> | <i>Wood Use</i> | | <i>Wood Consumption</i> | |
|--|-----------------------|----------------------|-------------------------|-----------------------|
| | <i>IV RE</i> | <i>IV FE</i> | <i>IV RE</i> | <i>IV FE</i> |
| Constant | 4.46*** (0.02) | 4.59*** (0.04) | 4.48*** (0.02) | 4.59*** (0.04) |
| Mother Cooks and Cares for Children | | 0.02 (0.02) | | 0.005 (0.03) |
| Wood | -0.008 (0.006) | | -0.002* (0.001) | |
| Wood × Mother Cooks and Cares for Children | -0.004** (0.002) | -0.02 (0.02) | -0.001** (0.0003) | -0.0002 (0.005) |
| Wood × Age | -0.001 (0.001) | -0.001 (0.001) | -0.0002* (0.0001) | -0.0003** (0.0001) |
| Wood × Cooking in Home | -0.005*** (0.002) | | -0.001*** (0.0003) | |
| Wood × Roof Permeability | -0.004 (0.004) | | -0.001 (0.001) | |
| Wood × Wall Permeability | -0.005** (0.002) | | -0.001 (0.0004) | |
| Age | -0.02*** (0.001) | -0.02*** (0.001) | -0.02*** (0.001) | -0.02*** (0.001) |
| Age ² | 0.001*** (0.0001) | 0.001*** (0.0001) | 0.001** (0.0001) | 0.001** (0.0001) |
| Female | 0.003*** (0.001) | 0.003** (0.001) | 0.003*** (0.001) | 0.003*** (0.001) |
| Mother's Age | -0.0003** (0.0005) | -0.001 (0.002) | 0.0001 (0.0005) | -0.001 (0.001) |
| Mother's Age ² | 0.1E-03 (0.8E-07) | 0.2E-03 (0.3E-03) | 0.4E-07 (0.7E-07) | 0.2E-03 (0.2E-03) |
| Mother has No Education | -0.01*** (0.001) | -0.007 (0.008) | -0.01*** (0.002) | -0.01 (0.01) |
| Mother is Household Head | -0.001 (0.003) | 0.01 (0.01) | -0.002 (0.003) | 0.01 (0.01) |
| Rural | -0.01*** (0.001) | | -0.005*** (0.002) | |
| Consumption | 0.01*** (0.002) | | 0.01*** (0.002) | |
| Household Size | -0.003*** (0.0004) | | -0.003*** (0.0004) | |
| Rooms | 0.004*** (0.0007) | | 0.004*** (0.001) | |
| Ethnicity Dummies | 7 Dummies | 7 Dummies | 7 Dummies | 7 Dummies |
| District Dummies | 20 Dummies | | 20 Dummies | |
| Observations | 9867 | 9867 | 9923 | 9923 |

Note: *, **, *** indicate parameter significance at $\alpha = 10\%$, 5% , and 1% respectively

Table 8 Impact of Wood Burning on Weight for Age and Height for Age

| <i>Variable</i> | <i>AGE</i> <i>0 to 5</i> | <i>AGE</i> <i>0 to 15</i> | <i>AGE</i> <i>0 to 5</i> | <i>AGE</i> <i>0 to 15</i> |
|--|--------------------------------|------------------------------|-----------------------------------|------------------------------|
| (A) | Observed Sample Values | | | |
| Weight for Age Percentile (WAM) | 89.02 (14.27) | 88.08 (14.97) | 89.02 (14.27) | 88.08 (14.97) |
| Height for Age Percentile (HAM) | 93.12 (6.22) | 92.61 (5.88) | 93.12 (6.22) | 92.61 (5.88) |
| Weight for Age Z-Score (WAZ) | -1.05 (1.24) | -1.04 (1.15) | -1.05 (1.24) | -1.04 (1.15) |
| Height for Age Z-Score (HAZ) | -1.73 (1.55) | -1.76 (1.41) | -1.73 (1.55) | -1.76 (1.41) |
| Severe Undernourishment (% with WAZ<-2) | 21% | 18% | 21% | 18% |
| Severe Stunting (% with HAZ<-2) | 44% | 44% | 44% | 44% |
| | <i>Wood Use Dummy in Model</i> | | <i>Wood Use Quantity in Model</i> | |
| (B) | Model Fit | | Model Fit | |
| Predicted WAM from model | 88.75 (12.30) | 87.71 (12.32) | 88.75 (12.30) | 87.71 (12.32) |
| Predicted HAM from model | 93.08 (5.54) | 92.55 (4.94) | 93.08 (5.54) | 92.55 (4.94) |
| Predicted WAZ from model | -1.07 (1.06) | -1.07 (0.93) | -1.07 (1.06) | -1.07 (0.93) |
| Predicted HAZ from model | -1.74 (1.38) | -1.78 (1.18) | -1.74 (1.38) | -1.78 (1.18) |
| Predicted Severe Undernourishment (%) | 16.8% | 11.8% | 16.8% | 11.8% |
| Predicted Severe Stunting (%) | 43% | 43% | 43% | 43% |
| (C) | Simulations | | Simulations | |
| Predicted WAM with no wood | 104.85 (14.60) | 97.13 (12.63) | 94.88 (12.32) | 95.89 (12.38) |
| Predicted HAM with no wood | 96.34 (5.19) | 93.87 (4.82) | 94.28 (5.24) | 92.96 (4.86) |
| Predicted WAZ with no wood | 0.31 (1.26) | -0.36 (0.96) | -0.55 (1.06) | -0.45 (0.94) |
| Predicted HAZ with no wood | -0.92 (1.30) | -1.46 (1.15) | -1.44 (1.31) | -1.68 (1.16) |
| Severely Undernourished with No Wood (%) | 2% | 2% | 6% | 2% |
| Predicted Stunting No Wood (%) | 20% | 32% | 33% | 39% |

Standard errors in parentheses.