Evaluation of the Efficacy and Effectiveness of the EcoStove for Reducing Indoor Air Pollution Exposures Among Nicaraguan Women

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ABSTRACT / EXECUTIVE SUMMARY

In 2002, CEIHD researchers conducted a study in Ciudadela de San Martin, Nicaragua, to evaluate the efficacy and effectiveness of two models of the EcoStove in reducing indoor air pollution (IAP). IAP exposure is widely accepted as a valid and reliable indicator of health risk. CEIHD evaluated the influence of stove type on kitchen air pollution levels and women's exposures to particle matter less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) through a randomized stove intervention trial. After the initial round of measurements among the 60 study participants, half the participating households received an entirely closed EcoStove while the others received a newer, slightly less expensive model with a semi-open design. The randomization was successful, with the two intervention groups proving very similar on all of the household variables and time-activity data collected.

Both the closed and semi-open EcoStove models achieve large reductions in indoor air pollution and exposure among Nicaraguan women cooking in enclosed kitchens. Adjusting for the effects of study group, duration of cooking, burning trash and average daily temperature, introduction of the closed Eostove was associated with an 86% reduction in $PM_{2.5}$ exposure, while the introduction of the semi-open model was associated with an 80% reduction. The difference between the effects of the two EcoStove models on $PM_{2.5}$ exposures was not significant (p-value = 0.285). However, the two EcoStove models did have significantly different effects on kitchen levels of $PM_{2.5}$ (p-value = 0.028), with the closed EcoStove reducing kitchen $PM_{2.5}$ levels by 94% and the semi-open EcoStove reducing kitchen $PM_{2.5}$ levels by 87%. The magnitude of the exposure reductions for both EcoStove models is expected to have great health benefits for Nicaraguan families. Since the health benefits will be multiplied by the amount of time the exposure reductions are maintained, an important next step would be to evaluate whether these reductions in exposure are sustained over time.

INTRODUCTION AND RATIONALE

Several recent studies have concluded that indoor air pollution (IAP) is a risk factor for acute respiratory infections, chronic obstructive lung disease, tuberculosis, lung cancer, low birth weight and cataracts. Much of the developing world relies on solid biomass fuels for cooking. The use of these fuels in simple, unvented cookstoves is the principle cause of elevated IAP levels. Improved biomass cooking stoves have the potential to reduce concentrations of pollutants in kitchens and thereby reduce harmful exposures. However, evaluation of such interventions has been very limited relative to the magnitude of this public health problem. Only a handful of studies have measured the reductions in exposures to harmful air pollutants achieved by improved cookstoves.

Since health risks often drive policy decisions, it is increasingly common that non-governmental organizations, funders and international agencies involved in the development of improved biomass stoves are interested in evaluation of the health benefits of their programs. This information can be used to make a compelling case for support from funding agencies and may also be useful in motivating families to invest in an improved biomass stove. However, making causal inferences about the health benefits of a specific stove design requires large study populations and expensive and complex data collection systems, even for the evaluation of a single health outcome. For example, an intervention study designed to detect whether acute lower respiratory infections (ALRI) are reduced among Guatemalan children due to improved stoves will require weekly visits to 500 children over a period of 12 to 18 months. Most of the health effects of IAP are less common diseases, some developing over several years, and would require much longer periods of observation than childhood ALRI. Stove programs do not typically have the resources to invest in long-term health studies, nor would this likely be a desirable use of resources, given the pressing need to promote and disseminate improved stoves.

Since population exposure to IAP is a valuable proxy for several health outcomes, a more practical approach to assessing health benefits of an improved stove project is to measure exposures to IAP among people in households with traditional and improved biomass stoves. The combined results of several epidemiological studies on the effects of solid fuel biomass smoke support the use of IAP exposure as an indicator of health risk. In addition, IAP exposures can be accurately measured using small sample sizes, such as 25 – 50 participants per study group. An evaluation of health benefits based on measured exposure reductions provides more useful information than a study attempting to establish causal links between environmental improvements and changes in disease incidence. For example, although the weight of evidence of roughly a dozen studies suggest ALRI incidence is 2.5 times higher among children exposed to IAP from solid biomass fuel combustion, the results of each individual study vary widely and were sometimes inconclusive. Thus, for stove program evaluation, assessing changes in human exposure to biomass smoke may not only be more practical and cost-effective than conducting a health-outcome study, it will also prove to be more accurate and comprehensive.

The characterization of health effects from indoor air pollution in developing countries is based on several studies among households that use solid fuel. Findings from the more numerous health studies of tobacco smoke and ambient air pollution are incorporated for supporting evidence. Four main categories of health effects are thought to result from indoor combustion of solid fuels in developing countries:

> Infectious respiratory diseases: acute respiratory infections in children and tuberculosis;
> Chronic respiratory diseases: chronic bronchitis, chronic obstructive pulmonary disease and lung cancer;
> Adverse pregnancy effects: stillbirth, low birth weight; and
> Other suspected health effects for which less evidence exists: blindness, asthma and heart disease.

The weight of evidence for these health effects has been discussed in detail in the literature (Smith 2000, Bruce 2000), and Appendix A provides a brief summary. The studies outlined have provided evidence of links between indoor air pollution and various diseases. The most common health effect estimates compare the difference between improved stoves or fuels and the traditional open fire. However, the exposure contrast in each study is different. Also, the reduction in exposure offered by a particular stove design may be less or more than the exposure contrasts in these studies. An understanding of the dose-response relationship between biomass smoke and each health outcome is required to extrapolate along the continuum of exposure levels associated with each fuel-stove combination. Therefore, the most useful kind of study relates specifically defined health outcomes to measured air pollution exposures, rather than a binary exposure variable. Although dose-response relationships between biomass smoke and the diseases it is thought to cause have not been established, it is reasonable to assume that the magnitude of health benefits will be related to the extent to which exposures are reduced.

Ezzati and Kammen conducted detailed exposure assessment and monitored acute respiratory infections (ARI) and acute lower respiratory infections (ALRI) symptoms every one to two weeks for two years in Kenya (Ezzati, 2001). Their analysis controlled for several confounding factors, such as sex, age, village type, number of people residing in the house, and smoking. They used these data to estimate a dose-response relationship between biomass smoke and ARI and ALRI using ordinary-least-squares regression. They estimated that children under five years of age with average PM_{10} exposures between 200 - 500 g/m^3 would have ARI symptoms during an additional 6% of the time, compared to those with exposures lower than 200 g/m^3 (p-value = 0.002). The fraction of time that a child had ARI was 5% in the lower exposure group, compared to 11% of the time in the next higher exposure group. The effect of a similar exposure increase among the 5 – 49 years age group resulted in an additional 2.7% of the time with ARI (p-value = 0.003). These same comparisons of fraction of time with illness were performed for ALRI, a more serious category of disease that includes pneumonia, but the effect estimates were insignificant. They also calculated odds ratios using logistic regression and found that the odds of having ARI was 2.42 (95%CI: 1.52-3.83) higher among the children under four years and 3.01 (95% CI: 1.59-5.70) times higher among people aged 5 – 49 years. Although the odds of ALRI were not significantly elevated among either age group in the 200 - 500 g/m^3 exposure category, the odds were significantly elevated at exposure levels above 500 g/m^3 and there was a trend of increasing risk with each higher exposure category.

While these types of exposure-response estimates provide a quantitative basis for estimating the health benefits of improved cooking stoves using information on exposure reductions, further evidence is required before such analyses can be performed with confidence for childhood pneumonia. In addition, exposure-response relationships have not even been explored for most of the suspected health outcomes of IAP in developing countries. When such models are developed, estimates of the total burden of disease averted by an improved stove intervention, which is most relevant to policy decisions, would also require information on prevalence and incidence of the specific diseases in the population. Burden of disease analyses would be useful for estimating the public health benefits of improved stoves, such as the EcoStove in Nicaragua.

STUDY OBJECTIVES

In January 2002, a CEIHD research analyst met with Proleña staff in Managua, Nicaragua, to plan a study that would assess and compare the indoor air pollution concentrations and human exposures associated with open fires and two competing models of the EcoStove, within the context of an ongoing World Bank/ESMAP/PROLEÑA project "Nicaragua – Pilot Commercialization of Improved Woodstoves". The planning, field staff recruitment, and study site selection took place over the next three days. The CEIHD research analyst coordinated field staff training, revisions of field data logs, refinement of the inclusion criteria for the study, and a brief pilot study using a continuous particle monitor over the following seven days. The CEIHD research analyst returned to the United States for the remainder of the study. The field staff, one Nicaraguan environmental scientist with a masters degree, one Guatemalan field work supervisor with experience conducting indoor air pollution research, and one local assistant, completed the study over the next five months.

Specific objectives discussed by CEIHD and Proleña during study preparation and incorporated into the study design include:

- To compare the performance of two competing EcoStove designs for reducing indoor concentrations and personal exposures to $PM_{2.5}$.
- To emulate, as much as possible, the non-experimental, real-life conditions under which people purchase improved stoves.
- To control for the influence of confounding factors that may bias the stove comparisons.

One EcoStove model has a completely closed 1/8" steel stovetop griddle, on top of a stove body made of a mix of cement and pumice stone cast around a ceramic combustion chamber elbow. This will be referred to as the closed EcoStove. The second, slightly less expensive, newer model, has the same stove body, however with a smaller metal griddle on one side and one open pothole on the other side, allowing both direct contact between the fire and the pots and an opportunity for release of combustion emissions indoors if a pot is not placed over the pothole. This will be referred to as the semi-open EcoStove. Both EcoStove models have metal tube chimneys and ceramic elbow combustion chambers. Proleña hypothesized that switching to the semi-open model would involve a tradeoff between increased energy efficiency and increased indoor air pollution.

METHODS

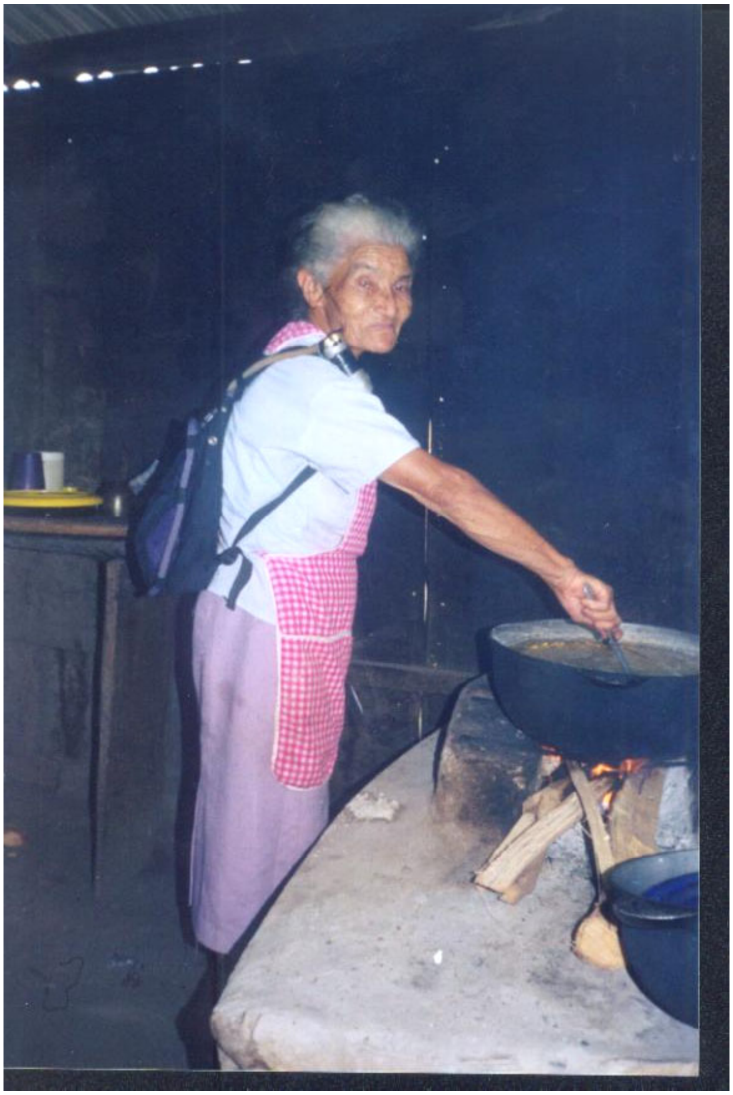
Study Site and Population

The search for an appropriate study site included visiting two communities in the capital city and three semi-rural communities within a 2-hour drive from Managua. In addition, the CEIHD research analyst met with representatives of the NGOs Handicap International and Plan International, and the governmental agency National Energy Commission (CNE). These groups, which are active in the region and perform work relevant to improved stoves, were informed of our study objectives and provided helpful tips on identifying our target and study populations. The CEIHD research analyst observed during visits to potential study sites that many household kitchens are only partially enclosed, often having one or two open sides and only two or three sides with walls. Since the air pollution levels in these kitchens may be more similar in magnitude to background outdoor air pollution levels, it would be more difficult to detect any true differences in air pollution exposures by stove type. The research analyst subjectively compared the potential study communities by the proportion of open kitchens.

The stove comparison study took place in Ciudadela de San Martín, a recently settled village approximately 2 Km from the town center of Tipitapa. The population was chosen for the almost exclusive use of biomass fuel and open fires for household cooking and the large proportion of indoor kitchens, as shown in the photo below. The community is located approximately 15 Km to the north of Managua and approximately at latitude: 12 08’ 36” N, longitude: 86 09’ 49” W, and elevation: 56 m above sea level) and has approximately 1000 homes. Typical homes are made of wooden planks for walls and corrugated iron for roofs and have dirt floors. Most of the homes have electricity.

Only participants with kitchens with walls on all four sides were recruited for the study, which would make the ventilation rates lower than in typical homes. Since the indoor emissions from cooking stoves would be more concentrated in these kitchens, this participant selection provided greater assurance that we would be able to detect any influence of stove type. However, this selection criterion made the air pollution levels less representative. The CEIHD fieldwork coordinator, Victorina López, selected the homes to create thirty pairs matched according to location (street block) and kitchen type. The kitchen types included: 1) inside a one-room dwelling including sleeping areas, 2) part of the main house, but with a partition separating the kitchen from other rooms, and 3) separate structures apart from living areas and bedrooms. Households with any kind of gas stove were excluded from the study.

Figure 1: Study Participant in Ciudadela de San Martin, Tipitapa, Nicaragua: Wearing $PM_{2.5}$ Exposure Monitoring Equipment and Cooking Over Traditional Open Fire



The field staff explained the concept of the EcoStove and the objectives of the study during participant recruitment. They also told the people about the burdens of carrying IAP equipment and having it operate in their homes during 24-hours for each of the two rounds of sampling. The field staff also informed the householders that they would receive a free stove as compensation for participation in the study, that participation was voluntary, and that they could leave the study at any moment without any consequences.

Study Design

CEIHD evaluated the influence of stove type on kitchen air pollution levels and women's exposures to particle matter less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) through a randomized stove intervention trial. $PM_{2.5}$, rather than the often measured courser particles (PM_{10}) or carbon monoxide, was chosen as the pollutant to be measured since it has most consistently been associated with respiratory and cardiovascular health effects. While CO is included in many studies of biomass smoke, this is more due to the availability of simple and inexpensive measurement methods, rather than evidence of health impacts found at the levels in developing country households. Prior to the first round of measurements, the field staff performed the randomization among the households pair-by-pair with the toss of a coin. One household from each matched pair was assigned to each of the competing EcoStove models: one with a closed stovetop and the other with a semi-open stovetop. Before the stoves were introduced, women's 24-hour average exposures to $PM_{2.5}$ were measured among the 60 participants cooking over open fires. Kitchen 24-hour average $PM_{2.5}$ concentrations were measured in roughly half of the homes.

After the first round of measurements, the field workers and Proleña staff coordinated the introduction of the EcoStoves according to the random assignments. The stoves were installed by Proleña in the same way they usually are. The principle cooks in the study households, who were all women, participated in a training session organized by Proleña. The objective of the training was to mimic the normal circumstance under which Proleña instructs women about the recommended ways of using and maintaining the stoves. The training included a discussion of appropriate pots to be used with the EcoStoves. People using open fires often cook with curved-bottom pots, while flat-bottom pots are essential to allow complete contact with the metal stovetop of the EcoStoves, which is necessary for increased energy efficiency. Several families were provided flat-bottom pots to encourage adoption of the EcoStoves.

The same air pollution measurements as in the pre-intervention round were repeated several weeks after the intervention. The average duration between introduction of the EcoStove and the post-intervention IAP measures was 34 days (St. Dev. = 12 days), with a minimum of 11 days and maximum of 69 days. These durations should have allowed enough time for the families to get comfortable with use of the new stoves.

Since an objective of this study was to emulate non-experimental, real-life conditions, there were no demands placed on the families to use only the improved stove. The extent to which the EcoStoves are adopted is a key component of the test of their ability to reduce IAP exposures. We also did not ask the families to discontinue other activities that produce air pollution, such as smoking and burning trash. Although no direct measurements of background air pollution levels were taken that would allow the contribution from the cooking stoves to be isolated, several other local sources were accounted for indirectly by questionnaire data that were included in the multivariable models. We decided not to use our limited resources to measure background air pollution levels because we expected that the contribution from other sources would be much less than that from cooking stoves and the randomization would make these background levels equal between the two study groups.

Measurements

Particle matter less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) was measured using SKC Personal Environmental Monitors (PEMs), which are designed to provide a 2.5 m cut-size by impaction at a flow rate of 4 liters per minute (LPM). Teflon filters with 2 m pore size were placed on top of support pads inside the $PM_{2.5}$ PEMs. These samplers were connected to personal pumps (BGI-400, BGI Inc. and SKC PCXR-4, SKC Inc.) set at a flow rate of 4 LPM. The field staff measured flows at the beginning and end of each 24-hour monitoring period with Matheson rotameters, which the CEIHD research analyst calibrated at Harvard School of Public Health and compared with a manual bubble tube, a primary standard, at the field site. To ensure that the calculated volumes of air that passed through the filters were accurate, the field workers checked each PEM for leaks after assembly. The leak test consists of measuring the difference in flow through a tube attached to the pump compared to the flow through the inlet of a PEM attached to the same tube. A large decrease in flow (more than 5 rotameter divisions) indicates a significant pressure drop, which would probably be due to a leak, since the pumps are flow controlled.

The sampling equipment, weighing approximately 3 pounds, was carried inside backpacks by the women and hung in the kitchens. The PEMs were cleaned with distilled water and/or alcohol on a daily basis and the impactor plates were wiped clean and oiled between samples to prevent particle bounce. The field worker or fieldwork supervisor visited the homes during the 24-hour periods monitoring to verify that the women were wearing the monitors and that they were functioning properly. The standard location of the equipment in all kitchens was 1.25 meters off the floor and 1 meter from the outer perimeter of the stove and at least 1.5 meters from all doors and windows.

The Teflon filters were weighed using a Mettler MT5 microbalance at Harvard School of Public Health before and after sampling for determination of $PM_{2.5}$ mass.

CEIHD included several observations and questionnaire items on time activity patterns and housing characteristics in the IAP exposure assessment (EA) survey. Participants completed a time activity table for each 30-minute period over the 24-hour measurement session with help from the field workers. This time activity table included whether or not the participant was cooking and whether or not the fire was lit during each 30-minute period. Also included was whether the participant or participant's neighbors were burning trash and whether the participant (active) or somebody else close to the participant (passive) was smoking cigarettes. These measures were included in order to be able to control for their influence on IAP exposures when comparing the stove types. These items were also evaluated as predictors of kitchen concentrations and personal exposures for the potential calibration of a simple questionnaire that would allow easier access to information on changes in exposure. The usefulness of each item for the calibrated questionnaire will be indicated by the amount of variability in air pollution concentrations and exposures explained.

Meteorological data were collected by the weather station at the Managua airport. These were daily average data and included: temperature, humidity, atmospheric pressure, wind direction, wind speed, and precipitation. Fieldwork for this study took place mostly during the dry season, from January to May 2002.

Analysis

Air pollution levels and exposures associated with the two EcoStoves can be compared directly between the two study groups or by comparing the changes in exposure associated with the introduction of each EcoStove. Although the two types of improved stove were randomly assigned, the small sample size allows a large role for chance in producing differences between the two groups. Direct comparisons of measurements between the two groups are susceptible to confounding by any factors that by chance are associated with the assigned improved stove type and independently with pollution levels and/or exposures. However, by comparing the changes in air pollution from before to after the stove intervention between the two groups, the analysis is less susceptible to the influence of any factors that differ between homes. Also, by taking into account the baseline IAP levels, given that the IAP levels pre- and post-intervention are correlated among homes, the unexplained variability is reduced and the probability of detecting any true differences between the closed and semi-open EcoStoves is increased.

Since the research team monitored in the same kitchens before and after installation of the improved stoves, the comparison of the EcoStoves to the traditional open fire cannot be confounded by any factors that are constant within homes over the duration of the study. Although the comparisons between open fires and EcoStoves may be influenced by time-varying characteristics, we considered that the effects of these characteristics on air pollution levels should be minimal over the duration of this study relative to the expected influence of the improved stoves. In addition, any time-varying factors that we measured in the study can be controlled for in the multivariable analyses.

A remaining concern, however, is the extent to which the two study groups adopt and properly use the improved stoves, which may be related to differences in the stoves or differences in the participants. Since we collected data on the amount of continued open fire use after the improved stove intervention, we could compare the efficacy of the two EcoStove designs with their real-world effectiveness.

Efficacy
To measure the efficacy of each stove design, we subtracted the effect of open fire use post-intervention, in order to estimate what the IAP levels and exposures would be if people completely substituted an EcoStove for the open fire. In these models (which include a variable for duration of open fire use post-intervention), the effect estimate for each EcoStove design represents how well the stoves would reduce IAP if they were fully adopted.

Effectiveness
The efficacy of the Ecostoves can then be compared to their real-world effectiveness. In these models (which do not include a variable for duration of open fire use post-intervention), the effect estimate for each type of Ecostove demonstrates the actual benefit to the participants of being given an Ecostove, which depends on how much and how effectively they use that stove. The comparison of stove efficacy and effectiveness can help policy makers to determine how well each stove design meets the needs of the cooks and to predict the real-world results of stove interventions relative to stove performance under research protocols that require use of a specific stove. A significant gap between effectiveness and efficacy would indicate that acceptability or adoption of a particular stove has been limited.

RESULTS

The two randomized intervention groups are very similar on all of the household variables and time-activity data collected (see Table 1). This indicates that a good balance was achieved and that the randomization was successful. In addition, the weather conditions on the days that the $PM_{2.5}$ samples were collected were similar between the two groups. Given these results, we assume that the distribution of all other unmeasured variables that may influence kitchen concentrations and exposures were similar between the two groups.

Although there are no statistical differences at the traditional $p = 0.05$ level, these statistical tests are not sensitive enough to detect small differences between groups that can confound the relation between stove type and IAP. Using a p-value significance level of less than 0.25 to indicate differences between study groups that have more potential to bias the IAP concentration and exposure comparisons between stove groups, kitchen volume, reported time spent cooking, reported time spent burning garbage, reported time neighbor burnt garbage, and time exposed to passive tobacco smoke met this criterion. However, in order for these factors to bias the results, they would also have to be independent predictors of exposure and/or kitchen concentration. In the multivariable analyses, these potential confounding biases will be removed by statistical adjustment, assuming that the variables have been measured accurately.

As shown in Table 2 (see also Figure 2 below), personal $PM_{2.5}$ exposures and kitchen concentrations were high during the pre-intervention round of sampling. Although the concentrations were 25 % higher (p-value = 0.3706) and the women's exposures were 9% higher (p-value = 0.7476) in Group 2 compared with Group 1, these differences are consistent with random variability. The standard deviations were similarly high in both groups.

Table 1: Univariate Comparisons of Baseline Data by Randomized Group before Intervention

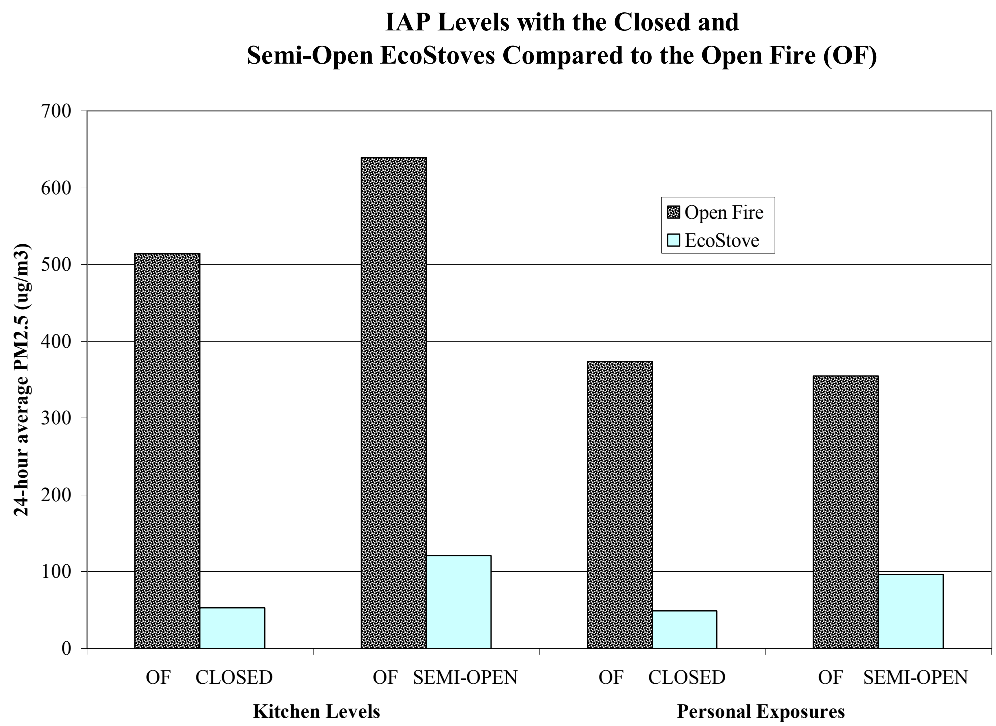
Continuous Variables	**Group 1 (n=30)**		**Group 2 (n=30)**		
	Average	**St. Dev.**	**Average**	**St. Dev.**	**p-value**
Kitchen Volume (m^3)	16.38	7.80	19.65	11.04	0.2339*
Time Fire Lit (hr)	9.9	3.9	10.7	3.7	0.4349
Time Cooking (hr)	6.9	2.5	6.0	2.2	0.1843
Time Active Smoking (hr)	0.1	0.2	0.2	0.7	0.6983*
Time Passive Smoking (hr)	0.9	2.1	0.8	1.2	0.1311*
Burning Garbage (hr)	0.2	0.4	0.3	0.6	0.2037*
Neighbor Burning Garbage (hr)	1.1	2.3	0.3	0.6	0.2096*
Reports Moderate Smoke Levels (hr)	5.4	3.1	4.7	3.3	0.3643
Reports High Smoke Levels (hr)	3.1	2.9	3.7	2.7	0.4281
Avg. Daily Temperature (C)	27.4	0.8	27.2	0.8	0.2734
Avg. Daily Wind Speed (mph)	4.2	0.6	4.3	0.6	0.8037
Avg. Daily % Relative Humidity	63.0	3.8	62.9	3.8	0.9197
Categorical Variables	**N**	**%**	**N**	**%**	**Chi-Square p-value**
Kitchen Type					
One Room House	7	23	8	27	0.7656
Separate Room	10	33	9	30	0.7814
Separate Building	13	43	13	43	1.0000
Kitchen with Outside Door	21	70	23	77	0.5593

* Indicates that Kruskal-Wallis non-parametric test was performed due to violation of normality assumption.

Crude (Unadjusted) Results

According to the random assignments made prior to the first round of measurements, Group 1 received the closed EcoStove, while Group 2 received the semi-open EcoStove. The personal and kitchen $PM_{2.5}$ levels were roughly an order of magnitude lower in both groups during the post-intervention round (Figure 2).

Figure 2:



The average kitchen concentrations decreased from 514 to 53 g/m^3 with introduction of the closed stovetop EcoStove in Group1, while the average levels decreased from 639 to 121 g/m^3 with introduction of the semi-open EcoStove in Group 2. The average women's exposure to $PM_{2.5}$ decreased from 374 to 49 g/m^3 with introduction of the closed EcoStove in Group1, while the average exposure decreased from 355 to 96 g/m^3 with introduction of the semi-open EcoStove in Group 2. The reductions in kitchen concentrations and women's exposures in both groups were highly significant, regardless of statistical modeling approach. Due to one equipment failure and one dropout (refusal), only 28 of the 30 personal exposure measurements for women cooking over semi-open EcoStoves were collected. Since the kitchen measurements were taken among a convenience sample of households during each round, the randomization was somewhat sacrificed and not all of the same homes were sampled pre- and post-intervention.

Table 2: $PM_{2.5}$ Kitchen Concentrations and Personal Exposures Before and After Improved Stove Intervention

	Kitchen Concentrations			Personal Exposures		
	N	Avg.	St. Dev.	N	Avg.	St. Dev.
Pre-Intervention						
Group 1: Open fire	19	514	388	30	374	456
Group 2: Open Fire	17	639	426	30	355	313
Linear Regression*	p-value = 0.6839			p-value = 0.7311		
Post-Intervention						
Group 1: Closed EcoStove	20	53	30	28	49	30
Group 2: Semi-Open EcoStove	14	121	90	30	95	126
Linear Regression*	p-value = 0.0055			p-value = 0.0244		

* Linear regression models test whether log-transformed kitchen concentrations and personal exposures are different between study groups.

It appears from the crude (unadjusted) comparison of the two competing EcoStove models that both kitchen concentrations (p-value = 0.0055) and women's exposures (p-value = 0.0244) are significantly lower among the households randomly assigned to the closed EcoStove. However, these crude (unadjusted) comparisons do not take into account other variables that may confound or modify the relationship between EcoStove model and the air pollution measures, such as kitchen volume, time spent cooking, trash burning, and passive smoking. These comparisons also do not take into account the kitchen levels and exposures at baseline, which would control for other differences among homes prior to introduction of the stoves.

The time participants reported cooking was 1.4 hours less on average post-intervention compared to the open fire use pre-intervention (p-value = 0.0004). The time the fire was reported lit was also 2.9 hours less post-intervention compared to open fire use only (p-value < 0.0001). The reductions in reported time cooking and reported time the fire was lit were roughly the same between the two intervention groups. These finding are contrary to the notion that EcoStoves, although more fuel-efficient than open fires, take longer to cook. One interpretation of the shorter cooking times may be that the EcoStove design allows people to cook more items simultaneously. However, it is important to note that these findings are based on reported stove use and should be validated with observational data.

Univariate Analyses of Predictors of Kitchen Levels and Personal $PM_{2.5}$ Exposures

The CEIHD research analysts then began to evaluate the univariate (unadjusted) relationships between women's exposure to $PM_{2.5}$ and household characteristics, time-activity patterns, and weather data. The first priority was to understand the potential influences of the variables that were less balanced between the two groups at baseline, which were kitchen volume, reported time spent cooking, reported time spent burning trash, reported time neighbor burned trash, and reported time exposed to passive tobacco smoke. The CEIHD research analyst ran least squares linear regression models for each of these variables with personal exposures and then kitchen concentrations as the outcomes.

The plots of residuals versus predicted values from these regression models indicated violations of the homogeneous variance and normality assumptions for linear regression.[1] The CEIHD researcher log-transformed the concentration and exposure data to make the residuals more normal and the variance more constant across the predictors. This strategy was successful. It is important to note that this transformation of the independent variable alters the interpretation of the parameter estimates from the regression models. With a log-transformed outcome, the model is multiplicative, rather than additive, and the parameter estimates for each predictor are interpretable as percent changes, rather than changes in absolute value of the concentrations and exposures. Fortunately, this agrees with the physical models for many of the effects being evaluated. For example, the steady state model for calculation of concentrations (C, $\mu g/m^3$) from emissions (E, μg/hour), volume (V, m^3), and air exchange rate (S^{-1}, hr) is $C = E * S / V$. This multiplicative model relates to three predictor variables included in the regressions models, namely kitchen volume, kitchen ventilation indicators (air exchange rate), and stove type (emissions).

With this transformation of the dependent variable, the interpretation of the β estimates as percent changes in exposures or kitchen levels requires the following formula:

$$\% \text{ Change in Exposure} = (e^{\beta} - 1) * 100.$$

Housing Characteristics

According to the equation above for calculating concentrations based on emissions, there should be an inverse relationship between kitchen volume and concentrations. Although each 1 m^3 increase in kitchen volume was associated with a 1.9% decrease in kitchen concentrations, this was not statistically significant (ß = p-value = 0.3391). Although each 1 m^3 increase in kitchen volume was associated with a 0.3% decrease in women's exposures to $PM_{2.5}$, this effect was also non-significant ($p = 0.7954$).

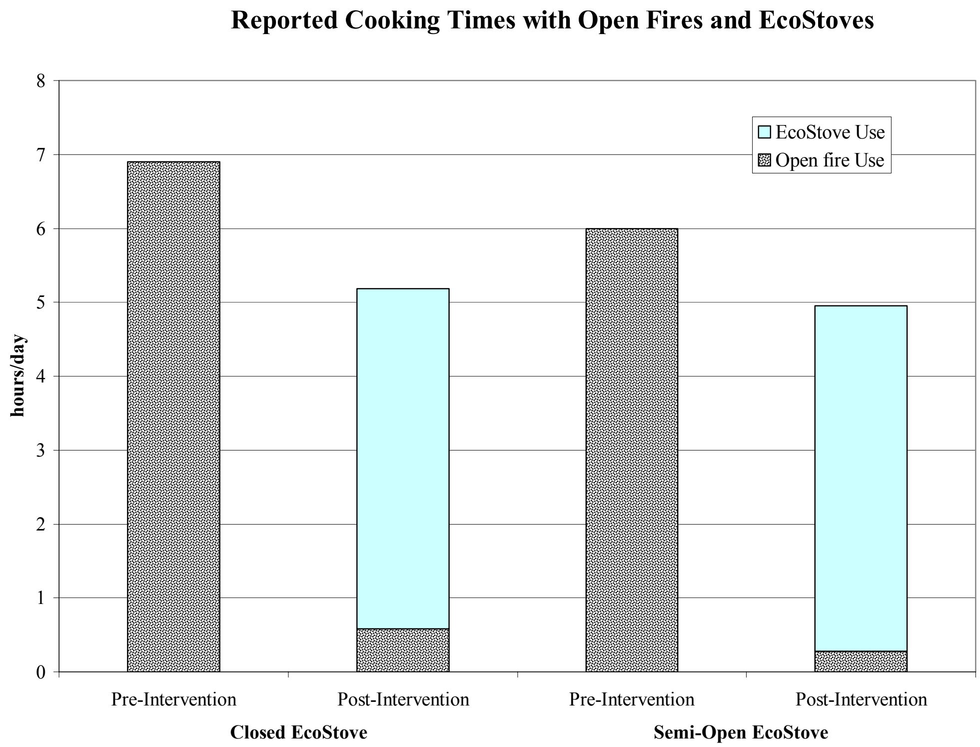
Stove Use

Since the time activity questionnaires distinguished between when the study participant was cooking from the total time that the stove was lit, these variables were analyzed separately. Although time spent cooking over an open fire pre-intervention was associated with slightly higher $PM_{2.5}$ exposures, it was not a significant predictor (ß = 0.0358, p-value = 0.5052). After excluding the pre-intervention measurements, time spent cooking with EcoStoves was also not a significant predictor of exposure (ß = 0.0757, p-value = 0.1518). However, excluding the pre-intervention measurements, each hour of reported open fire use post-intervention was associated with a 16% increase in kitchen levels of $PM_{2.5}$ (ß = 0.1449, p-value = 0.0306).

[1] Residuals (R) are the differences between the observed values (OBS) and predicted (PRED) values from the regression models. For example, the residuals for a concentration (C) model would be: $R = C_{obs} – C_{pred}$.

The women with the closed EcoStoves reported cooking over the open fire for 33 minutes per day on average, compared to 16 minutes per day among the women who received partially open EcoStoves. As shown in Figure 3 below, these durations of open fire use are very short compared to EcoStove use on the same days and open fire use pre-intervention. The data on open fire use post-intervention are highly skewed because most women in both groups did not report any open fire use after they received their EcoStoves. A non-parametric Kruskal-Wallis test failed to find a statistical difference between reported durations of cooking over the open fire post-intervention between the two groups (p-value = 0.2816).

Figure 3:



Other Sources of Air Pollution

The second most important source of air pollution, after cooking stoves, was burning of waste materials. Each hour participants reported that they themselves burned trash was associated with a 140% increase in personal exposures (ß = 0.8744, p-value = 0.0014) and a 129% increase in kitchen levels (ß = 0.82806, p-value = 0.0398).

Each hour of active smoking by the participants was associated with a non-significant 46% increase in kitchen concentrations (ß = 0.3793, p-value = 0.2446). Although active smoking by the participants was associated with a 7% increase in personal $PM_{2.5}$ exposures, this relationship was also non-significant (ß = 0.0649, p-value = 0.7941).

In univariate linear regression models, passive smoking (other person smoking near the participant) was neither a significant predictor of women's exposure (ß = -0.0502, p-value = 0.5141) nor of kitchen concentrations of $PM_{2.5}$ (ß = 0.0862, p-value = 0.4950). However, since passive smoking was somewhat different between the two groups at baseline and it has a potentially strong influence on kitchen concentrations, this variable is a candidate for inclusion in multivariable models.

The amount of time the participants reported sensing moderate smoke levels was associated with an 11% increase in personal exposures (ß = 0.10612, p-value = 0.0012) and a 17% increase in kitchen concentrations (ß = 0.1529, p-value = 0.001). The amount of time the participants reported sensing high smoke levels was associated with associated with a 30% increase in personal exposures (ß = 0.26063, p-value < 0.0001) and a 27% increase in kitchen concentrations (ß = 0.2400, p-value = 0.0002).

Meteorological Conditions

In the univariate analysis, daily average temperature was associated with a 32% decrease in personal exposures (ß = -0.39134, p-value <0.0001) and a 40% decrease in kitchen levels of $PM_{2.5}$ (ß = -0.5141, p-value < 0.0001). Daily average relative humidity was associated with a 4% increase in personal exposures (ß = 0.3887, p-value = 0.066) and a 2% increase in kitchen levels of PM2.5 (ß = =0.0198, p-value = 0.5302).

Other

The CEIHD research analyst then tested for the effects of all other household, time-activity-location, and weather variables on personal exposures in univariate analyses. The significant or nearly significant (p-value <0.25) predictors of the natural logarithm of women's $PM_{2.5}$ exposures include relative humidity, temperature, total time reported high smoke levels, time reported moderate smoke levels, reported time participant burnt trash, reported time fire lit, and reported time cooking.

Multivariable Models

EcoStove Efficacy for Reducing $PM_{2.5}$ Exposures

The CEIHD research analyst began the model selection by building a "kitchen sink" model including the variables necessary to compare the study groups and stove types, all the variables not well-balanced between the two groups at baseline (p-value < 0.25), and all the variables even weakly associated with exposures (p-value < 0.25). The "kitchen sink" model for women's exposures included round (0 for pre-intervention and 1 for post-intervention), randomization group (0 for those that received the close EcoStove), the interaction of round and group, kitchen volume (m^3), amount of time spent cooking, amount of time cooking over the open fire post-intervention, amount of time somebody else smoked in the participant's house, amount of time participant burned trash, amount of time neighbor burned trash, average ambient temperature, and average relative humidity. The interaction between round and study group estimates the difference in exposure reductions among the women who received semi-open EcoStoves relative to the exposure reductions among the women who received the closed EcoStoves. Since this model included a variable for the amount of time cooking over the open fire post-intervention, the effect is stove type is a measure of efficacy for reducing IAP.

Although the variable for study group was the least significant predictor (β = -0.033, p-value = 0.8763), it was kept in the model to respect the analysis plan that would compare the IAP changes in the two intervention arms by controlling for baseline IAP levels. Kitchen volume was the next least significant variable in the model (ß = -0.004, p-value = 0.6122) and the first to be eliminated in the backwards elimination procedure. Relative humidity was the next least significant variable (β = 0.005, p-value = 0.7873). The rest of the variables were significant at the p-value = 0.25 level. However, time exposed to passive smoking and neighbors burning trash were removed because they were both associated with decreases in exposure, contrary to expectations, due to single outliers. The following predictors remained in the model after backwards elimination and removal of statistical outliers: study round, study group, the interaction of round and group, reported cooking time, reported amount of time using the open fire after the EcoStove intervention, reported amount of time participants burned trash, and average daily temperature.

This main effects model was then compared to a mixed effects model with the same main effects and with the addition of a random effect for intercept. This model accounts for the correlation among repeated measures within each home. The precision of the model was improved with this approach. The results of this refined version of the model for women's exposures are presented in Table 3. Controlling for the effects of study group, cooking time, duration of open fire use post-intervention, trash burning by participants, and ambient temperature, the introduction of closed EcoStoves resulted in an 89% $((e^{-2.174} - 1) * 100)$ reduction in women's exposures, whereas the introduction of the semi-open EcoStoves resulted in an 83% $((e^{-2.174 + 0.391} - 1) * 100)$ exposure reduction. The interaction term for estimating the differential reduction in exposure offered by the semi-open compared to closed EcoStoves indicates a small difference between the stove types, though not statistically significant (p-value = 0.158).

Table 3: Linear Mixed-Effects Model to Estimate EcoStove Efficacy for Reducing Women's Exposures to $PM_{2.5}$ (Full Set of Predictors)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-1.317 (-6.850, 4.216)		0.636
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-2.174 (-2.771, -1.578)	-88.6 (-93.7, -79.4)	< 0.0001
Group (Group 2 OF vs. Group 1 OF)	0.081 (-0.366, 0.528)	8.4 (-30.6, 69.6)	0.717
Round*Group (Differential Change wi Semi-Open vs. Change with Closed ES	0.391 (-0.157, 0.938)	47.8 (-14.5, 155.5)	0.158
Cooking Time (hr)	0.045 (-0.032, 0.122)	4.6 (-3.1, 13.0)	0.247
Open fire use post-intervention (hr)	0.196 (0.040, 0.352)	21.7 (4.1, 42.2)	0.015
Trash burning by participants (hr)	0.334 (-0.096, 0.764)	39.7 (-9.2, 114.7)	0.125
Avg. Daily Temp (deg C)	0.233 (0.032, 0.434)	26.2 (3.3, 54.3)	0.024

* Reference is Group 1 with open fire (OF) during pre-intervention round.

The CEIHD research analyst then started with this full set of predictors of women's $PM_{2.5}$ exposure and began to work towards a more parsimonious model, while observing changes in effect estimates to maintain unbiased stove comparisons. Since the least significant predictor of exposure was study group, this variable was eliminated first. Removing this variable is tantamount to assuming that the randomization procedure was successful and that it is not necessary to adjust for differences in exposure at baseline. Table 2 and Figure 2 demonstrate that exposures were very similar between groups prior to the EcoStove intervention. Reported hours of cooking during the 24-hour sampling periods, which was the next least significant predictor (p-value = 0.2635), was then excluded from the model without any important influence on the other effect estimates. This model resulted in an insignificant β estimate for reported hours burning trash near the home (β = 0335, p-value = 0.1149). Removal of this variable did not significantly alter the estimates of the effects of stove types.

Table 4: Linear Mixed-Effects Model to Estimate EcoStove Efficacy for Reducing Women's Exposures to $PM_{2.5}$ (Parsimonious Model)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-0.860 (-6.314, 4.595)		0.754
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-2.342 (-2.907, -1.778)	-90.4 (-94.5, -83.1)	< 0.0001
Round*Group (Differential Change wi Semi-Open vs. Change with Closed ES	0.467 (0.046, 0.887)	59.5 (4.7, 142.8)	0.030
Open fire use post-intervention (hr)	0.210 (0.055, 0.365)	23.4 (5.7, 44.1)	0.009
Avg. Daily Temp (deg C)	0.231 (0.031, 0.432)	26.0 (3.1, 54.0)	0.025

* Reference is Group 1 with open fire (OF) during pre-intervention round.

The inclusion of the variable for reported durations of open fire use post-intervention causes the term for the interaction between round and study group to be a comparison of the two EcoStove models assuming equal open fire use. The inclusion of this variable also causes the term for round (post-intervention versus pre-intervention) to be an estimate of exposure reductions offered by EcoStoves relative to the traditional open fire after eliminating the influence of open fire use post-intervention. Since the stove comparisons in the models from Tables 3 and 4 relate to exclusive use of the EcoStoves, the parameter estimates provide information on the efficacy of the EcoStoves for reducing IAP exposure. With these models we can estimate the proportion of $PM_{2.5}$ exposures attributable directly to the EcoStoves. In other words, we can estimate the exposures that would occur if people completely substituted the EcoStove for the traditional open fire. The model can be expressed:

$$\ln(\text{exposure}) = ß_0 + ß_1\text{*round} + ß_2\text{*group} + ß_3\text{*round*group} + ß_4\text{*hours of cooking} + ß_5\text{*hours open fire use post-intervention} + ß_6\text{*hours burning trash} + ß_7\text{*temperature},$$

Filling in ß estimates from the exposure efficacy model with the full set of variables (Table 3) and assuming the average hours of cooking among households with the closed EcoStove (5.18 hours), zero hours of open fire use post-intervention, zero hours of trash burning, and the average temperature during the study (25.75 ºC), we estimate for the closed EcoStove:

$$\ln(\text{exposure}) = (-1.317) + (-2.174 * 1) + (0.081 * 0) + (0.391 * 0) + (0.045 * 5.18) + (0.196 * 0) + (0.334 * 0) + (0.231 * 25.75),$$

Exponentiating both sides of the equation, we have:

$$\text{exposure} = e^{(-1.317 + (-2.174 * 1) + (0.081 * 0) + (0.391 * 0) + (0.045*5.18) + (0.196*0) + (0.334*0) + (0.231 * 25.75))} = 15\ \mu g/m^3,$$

which is the amount of exposure attributable to the closed EcoStove, assuming no open fire use and no trash burning by the participants.

The same estimate for the semi-open EcoStove is calculated:

$$\ln(\text{exposure}) = (-1.317) + (-2.174 * 1) + (0.081 * 1) + (0.391 * 1) + (0.045 * 4.95) + (0.196 * 0) + (0.334 * 0) + (0.231 * 25.75),$$

Exponentiating both sides of the equation, we have:

$$\text{exposure} = e^{(-1.317 + (-2.174 * 1) + (0.081 * 1) + (0.391 * 1) + (0.045*4.95) + (0.196*0) + (0.334*0) + (0.231 * 25.75))} = 23\ \mu g/m^3,$$

which is the amount of exposure attributable to the semi-open EcoStove, assuming no open fire use and no trash burning by the participants. Though this exposure is higher than that attributed to the closed EcoStove, recall that the difference was not statistically significant.

Filling in ß estimates from the parsimonious exposure reduction efficacy model (Table 4) and assuming zero hours of open fire use post-intervention and the average temperature during the study, we estimate women's exposure at 16 $\mu g/m^3$. The same assumptions produce an estimate of 25 $\mu g/m^3$ for exposure among women cooking exclusively with the semi-open EcoStoves. Note that these estimates differ slightly because the parsimonious model does not control for hours of cooking, burning trash, nor study group as in the model with the full set of predictors.

EcoStove Effectiveness for Reducing $PM_{2.5}$ Exposures

The models for personal exposure discussed below exclude the variable for open fire use post-intervention and therefore estimate the effectiveness of EcoStoves for reducing IAP under real-life conditions. This type of model is an "intention-to-treat" analysis, which refers to the evaluation of the effect of allocating people to a treatment group rather than the actual effect of using the treatment.[2]

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[2] Typical analyses of randomized trials use the "intention-to-treat" rule, in which subjects are compared based on their assigned treatment, regardless of compliance. Estimates of intervention effects based on this rule are likely to be biased because noncompliance causes assigned improved stove to become a misclassified version of used improved stove. On the other hand, noncompliers tend to differ from compliers with respect to exposure risk, and hence the analyses of the effect of use of a particular stove may be confounded. In the case of the two EcoStoves, we assume that the difference in compliance between the two groups is more likely due differences in the EcoStoves rather than the cooks.

Table 5: Linear Mixed-Effects Model to Estimate EcoStove Effectiveness for Reducing Women's Exposures to $PM_{2.5}$ (Full Set of Predictors)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-1.005 (-6.627, 4.617)		0.722
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-1.997 (-2.602, -1.392)	-86.4 (-92.6, -75.1)	< 0.0001
Group (Group 2 OF vs. Group 1 OF)	0.093 (-0.359, 0.546)	9.7 (-30.2, 72.6)	0.681
Round*Group (Differential Change with Semi-Open vs. Change with Closed ES)	0.312 (-0.267, 0.890)	36.6 (-23.4, 143.5)	0.285
Cooking Time (hr)	0.058 (-0.019, 0.134)	6.0 (-1.9 14.3)	0.136
Trash burning by participants (hr)	0.341 (-0.096, 0.778)	40.6 (-9.2, 117.7)	0.124
Avg. Daily Temp (deg C)	0.218 (0.014, 0.422)	24.4 (1.4, 52.5)	0.037

* Reference is Group 1 with open fire (OF) during pre-intervention round.

Adjusting for the effects of study group, duration of cooking, burning trash and average daily temperature, the introduction of the closed EcoStove was associated with an 86% reduction in $PM_{2.5}$ exposure, while the introduction of the semi-open model was associated with an 80% reduction. The difference between the effects of the two EcoStove models on $PM_{2.5}$ exposures was not significant (p-value = 0.285).

A similar process of backward selection as for the efficacy model was used to derive a more parsimonious model for the "intention-to-treat" (effectiveness) analyses. The same variables were eliminated as neither significant predictors of exposures nor confounders of the relationship between stove types and exposures.

Table 6: Linear Mixed-Effects Model to Estimate EcoStove Effectiveness for Reducing Women's Exposures to $PM_{2.5}$ (Parsimonious Model)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-0.376 (-5.947, 5.195)		0.893
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-2.179 (-2.754, -1.603)	-88.7 (-93.6, -79.9)	< 0.0001
Round*Group (Differential Change with Semi-Open vs. Change with Closed ES)	0.402 (-0.029, 0.834)	49.5 (-2.9, 130.3)	0.067
Avg. Daily Temp (deg C)	0.214 (0.009, 0.418)	23.9 (0.9, 51.9)	0.041

* Reference is Group 1 with open fire (OF) during pre-intervention round.

Adjusting for the effect of average daily temperature, introduction of the closed EcoStove was associated with an 89% reduction in $PM_{2.5}$ exposure, while the introduction of the semi-open model was associated with an 83% reduction. The difference between the effects of the two EcoStove models on $PM_{2.5}$ exposures was almost significant at the traditional p-value < 0.05 level (p-value = 0.067). However, note that this model may be less correct than the full model, since it does not control for the differences in kitchen $PM_{2.5}$ levels between the study groups at baseline.

EcoStove Efficacy for Reducing Kitchen $PM_{2.5}$ Levels

The CEIHD research analyst took a similar approach to building a model for kitchen concentrations. The "kitchen sink" model included the variables necessary to compare the study groups and stove types, all the variables not balanced between the two groups at baseline (p-value < 0.25), and all the variables even weakly associated with kitchen concentrations (p-value < 0.25). The significant or nearly significant predictors of kitchen concentrations are temperature, total time reported high smoke levels, time reported moderate smoke levels, reported time participant burned trash, reported time participant smoked, reported time fire lit, reported time cooking, and reported time using open fire post-intervention. The "kitchen sink" model for kitchen concentrations included round (0 for pre-intervention and 1 for post-intervention), randomization group (0 for those that received the closed EcoStove), the interaction of round and group, time during which the fire was lit, time cooking over the open fire post-intervention, amount of time participants reportedly burned trash, reported amount of time neighbors burned trash, reported time participant smoked, reported time exposed to passive tobacco smoke, and average daily temperature. A random effect for intercept was added to this main effects model to account for correlation among the repeated measures.

As with the models for personal exposures, backwards elimination was the main technique used to remove unimportant independent variables. After smoking, study group was the next variable to be removed on the basis of statistical significance. Although removal of study group was found to change the ß estimate for the interaction between group and round from 1.00 to 0.844, the decision was made to exclude this from the model since kitchen $PM_{2.5}$ levels were not measured in all of the same homes pre- and post-intervention. Temperature was found to be a negative confounder of the relationship between round and kitchen concentrations. Round represents the overall comparison of both EcoStove models together with the open fire. Reported hours using the open fire post-intervention was found to be a negative confounder of the relationship between the round and study group interaction and kitchen levels. After removing variables that were not significant predictors of kitchen $PM_{2.5}$ (p-value < 0.05) and that did not alter the effect estimates of stove type by more than 10%, the model for EcoStove efficacy remained with the following independent variables: round, interaction of round and group, reported amount of time using open fire post-intervention, and average daily temperature. The results of this model are found in Table 7.

Table 7: Linear Mixed-Effects Model to Estimate EcoStove Efficacy for Reducing Kitchen Levels of $PM_{2.5}$ (Parsimonious Model)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-0.967	Variable	0.812
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-2.841 (-3.655, -2.028)	-94.2 (-97.4, -86.8)	<0.0001
Round*Group (Differential Change with Semi-Open vs. Change with Closed ES)	0.837 (0.170, 1.505)	131.0 (18.5, 35.4)	0.016
Open fire use post-intervention (hr)	0.171 (-0.086, 0.428)	18.6 (-8.2, 53.4)	0.182
Avg. Daily Temp (deg C)	0.255 (-0.049, 0.559)	29.0 (-4.8, 74.9)	0.096

* Reference is Group 1 with open fire (OF) during pre-intervention round.

The model in Table 7 indicates that exclusive use of the closed EcoStoves would result in a 94% reduction in kitchen $PM_{2.5}$ concentrations, whereas the exclusive use of the semi-open EcoStoves would result in an 86% reduction. The interaction term for estimating the differential reduction in exposure offered by the semi-open compared to the closed EcoStove was significant in the efficacy model ($\beta = 0.837$, p-value = 0.016), suggesting that the reduction in kitchen levels of $PM_{2.5}$ offered by the closed EcoStove is significantly greater than the semi-open EcoStove. It is important to note that these analyses do not control for differences between the groups at baseline. Also, these are estimates of the effects of the EcoStoves controlling for open fire use post-intervention, which is what may be expected if people completely substituted the EcoStoves for the open fires.

EcoStove Effectiveness for Reducing Kitchen $PM_{2.5}$ Levels

Table 8: Linear Mixed-Effects Model to Estimate EcoStove Effectiveness for Reducing Kitchen Levels of $PM_{2.5}$ (Parsimonious Model)

Variable	**β estimate (95% CI)**	**Predicted Percent Change (95% CI)**	**p-value**
Intercept	-1.659 (-9.763, 6.445)		0.680
Stove/Group Combination*			
Round (Group 1 Closed ES vs. Group 1 OF)	-2.775 (-3.564, -1.985)	-93.8 (-97.2, -86.3)	<0.0001
Round*Group (Differential Change with Semi-Open vs. Change with Closed ES)	0.728 (0.086, 1.370)	107.1 (8.9, 293.5)	0.028
Avg. Daily Temp (deg C)	0.281 (-0.019, 0.580)	32.4 (-1.9, 78.6)	0.065

* Reference is Group 1 with open fire (OF) during pre-intervention round.

The model in Table 8 provides estimates of the actual effect of having EcoStoves on kitchen levels of $PM_{2.5}$, without subtracting the effect of continued open fire use. The effect estimate for round indicates that the introduction of the closed EcoStoves resulted in a 94% reduction in kitchen levels, whereas multiplication of the effect estimates for round and the round-by-group interaction indicate that the semi-open EcoStove is associated with an 87% reduction ($(e^{-2.775} * e^{0.728} - 1) * 100\% = -87\%$). The interaction term for estimating the differential reduction in kitchen $PM_{2.5}$ levels offered by the semi-open compared to the closed EcoStove was significant in the stove effectiveness model ($\beta = 0.728$, p-value = 0.028), which takes into account the fact that some women in the study did not completely switch to the EcoStove.

As with the exposure comparisons, these results suggest the possibility that the closed EcoStove reduces IAP somewhat better than the semi-open model. However, the difference between the EcoStoves was not statistically significant for the exposure models taking into account the study group differences at baseline and the differences between study group could not be taken into account in the kitchen analyses, since different households were monitored pre- and post-intervention, due to logistical constraints.

Table 9: Comparison of Estimates of EcoStove Efficacy and Effectiveness in Reducing Personal Exposures and Kitchen Levels of $PM_{2.5}$

Model	**Efficacy**		**Effectiveness**	
	Pers. Exposure	**Kitchen Levels**	**Pers. Exposure**	**Kitchen Levels**
Closed	89%	94%	86%	94%
Semi-Open	83%	86%	80%	87%

In this intervention, the effectiveness of both EcoStoves in reducing both personal exposures and kitchen concentrations of $PM_{2.5}$ was very similar to their estimated efficacy. This indicates that, at least initially, the EcoStove was successfully adopted in the study homes.

DISCUSSION

The most comparable and widely disseminated improved biomass cook stove in Central America is the improved plancha from Guatemala. A study by Albalak *et al*. in the western highlands of Guatemala found that, compared to open fire kitchens, indoor concentrations of $PM_{3.5}$ were 45% lower in homes with gas (LPG) stoves and open fires, and 85% lower in homes with the improved plancha. However, this study included regular surveillance for stove deterioration, and the research team repaired stoves that had cracked or were leaking smoke. The IAP levels in the Guatemalan study were much higher in an absolute sense than in this Nicaraguan study, which is partially due to the more enclosed households in the colder Guatemalan highland region. In Guatemala, the open fire households had 24-hour average kitchen levels of particulate matter smaller than 3.5 microns ($PM_{3.5}$) of 1930 $\mu g/m^3$ and the improved plancha kitchens had average $PM_{3.5}$ levels of 330 $\mu g/m^3$, while in Nicaragua open fire kitchens had $PM_{2.5}$ levels of 573 $\mu g/m^3$, closed EcoStove kitchens had 53 $\mu g/m^3$ $PM_{2.5}$, and semi-open EcoStove kitchens had 121 $\mu g/m^3$ $PM_{2.5}$. Since the IAP levels in open fire kitchens in Guatemala were much higher, the IAP levels in the improved stove households in Nicaragua and Guatemala are not directly comparable. Comparing the percent reductions in IAP, the EcoStove performed only slightly better than the improved plancha

There are many differences between the studies that should be considered when comparing the performance of the Guatemalan and Nicaraguan improved stoves. While the goal of the Albalak *et al*. study was to determine whether the plancha could be used to reduce concentrations for a health study if the stoves were maintained over time by the study team, the goal of the EcoStove study is to measure the impact of an improved stove under real life conditions. The Guatemala study also did not directly measure personal exposure, as was done in Ciudadela de San Martin. In addition, the improved planchas had been used for several years, roughly ranging from two to four years, whereas the EcoStoves in this study had been used for only an average of 34 days before the IAP assessment. Another difference is that the Albalak *et al*. study evaluated the ability of stoves to maintain reductions in concentrations over time by repeating measurement six times over an eight month period, whereas the EcoStove evaluation compared the tradition open fire to newly installed stoves. While $PM_{3.5}$ was measured by Albalak *et al*., the present study measured $PM_{2.5}$. This should make little difference, since the vast majority of wood smoke particles are less than 1 micron in diameter.

The evidence suggests that the closed EcoStove may offer greater IAP reductions, and therefore greater health benefits, compared to the improved plancha and semi-open EcoStove. However, given the differences between the Albalak *et al*. study and the EcoStove IAP evaluation and the lack of statistical significance in the exposure comparisons between the EcoStove models in the present study, we cannot make strong conclusions regarding which stove is most effective at reducing IAP levels and exposures. At the low cost of about \$35 compared to approximately \$120 for the improved plancha, the EcoStove has greater potential as a widespread public health intervention.

CONCLUSIONS

The randomized intervention design allowed for efficient comparison of stove types with minimal influence of confounding factors.
Comparisons of the changes in IAP levels and exposures over time, acknowledging the correlation between IAP levels within households, allowed detection of small differences between the two EcoStove models.
Both the closed and semi-open EcoStove models achieve large reductions in indoor air pollution and exposure among Nicaraguan women cooking in enclosed kitchens.
Although the data suggest the possibility that the closed EcoStove model reduces women's $PM_{2.5}$ exposures by a greater amount than the semi-open model, these comparisons are not conclusive.
The reduction in kitchen levels of $PM_{2.5}$ were significantly greater with the closed EcoStove than semi-open EcoStove.
Although open fire use after the intervention did not change the results of the stove comparisons, even the very small amount of reported open fire use did have a significant effect on $PM_{2.5}$ exposures and would be a concern if it increased over time.
The magnitude of these exposure reductions is expected to have great health benefits for Nicaraguan families. Given data on the local incidence or prevalence of diseases related to biomass smoke, these health benefits could be roughly estimated. Since the IAP levels in Nicaragua were lower than those in other developing countries where epidemiological studies of biomass smoke have been conducted, extrapolations of health risks may require careful consideration of the assumptions involved. Since the health benefits will be multiplied by the amount of time the exposure reductions are maintained, an important next step would be to evaluate whether these reductions in exposure are sustained after potential stove deterioration. Repetition of the same data collection protocol is recommended within one to two years.

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APPENDIX A: Literature Review of Health Impacts of Indoor Air Pollution

Indoor air pollution from the solid fuel use in household stoves is a risk factor for several important diseases. Five of these air pollution related diseases – ischaemic heart disease, lower respiratory infections, chronic obstructive pulmonary disease, tuberculosis, and cancers of the respiratory tract – are among the ten leading causes of death globally (Murray and Lopez 1997).

The most detailed estimates of the health impacts have been calculated for India (Smith 2000). Household solid fuel causes an estimated 500,000 premature deaths per year in women and children under 5 in India. This disease burden is almost as large as the national disease burden of poor water and sanitation and greater than the national burden of major health concerns such as malaria, tuberculosis, tobacco, AIDS, heart disease, and cancer (Murray and Lopez, 1996). Extrapolating this estimate to the total number of people cooking with solid fuels in the developing world, the global impact is estimated at about 2 million deaths per year. This is similar in magnitude to the World Health Organization estimates of about 2.5 million (WHO, 1997).

Acute Respiratory Infections (ARI) in Children Under 5 Years

ARI is the disease category accounting for the largest burden of disease globally, accounting for 9% global ill health. Among children less than 5 years of age, an estimated three to five million deaths annually are caused by ARI, 75 % of which are pneumonia. Among several other important risk factors, indoor air pollution from solid fuel combustion has been found to be associated with childhood ARI.

The relationship between ALRI and indoor air pollution from cooking with polluting fuel/stove combinations has been examined in at least 16 epidemiological studies. Six out of nine case-control studies from developing countries report significantly elevated odds ratios, ranging from 2.2 to 9.9. An odds ratio is an estimate of the relative risk or the ratio of the risks of developing a disease between people at two different exposure levels. The non-significant results, however, could be explained in two of the studies by the lack of significantly reduced air pollution exposures in the "improved" stove households. Three out of four of the cohort studies performed report significantly elevated relative risks, ranging from 2.2 to 6.0. One case-fatality study of hospitalized patients in Nigeria reported a significant odds ratio of 12.2 ($p<0.0005$). Two case-control studies of Navajo children found elevated odds ratios of 4.8 (1.7,12.9) for cooking with wood and 7.0 (0.9,57) for PM_{10} levels above 65 g/m^3. The average odds ratio from published studies is approximately 2.5 for exposure to IAP from biomass combustion, indicating that children exposed to biomass smoke are roughly 2.5 times more likely to develop ALRI.

Chronic Bronchitis and Chronic Obstructive Pulmonary Disease in Women

It has been estimated that chronic obstructive pulmonary disease (COPD) will rise from the twelfth to the fifth leading cause of disease burden by 2020 (Murray 1996). COPD is characterized by progressive and incompletely reversible airflow obstruction. Chronic bronchitis (CB) is characterized by inflammation of the lining of the bronchial tubes, and severe cases of CB may progress to COPD. In developed countries, over 80% of cases of these respiratory illnesses are caused by smoking. However, in many parts of the developing world, these diseases occur at high rates even though smoking is uncommon.

The impacts of biomass and coal smoke on CB and COPD have been reported by numerous studies in developing countries. Reviews by Smith (2000) and Bruce *et al*. (2000) have focused on studies looking at COPD and biomass smoke. Epidemiological investigations have also examined the effects of coal smoke. In Nepal (Pandey 84), Ladakh (Norboo 91), Pakistan (Qureshi 94) and China (???), COPD prevalence has been found to be similar or even greater among women than men, even though men do most of the smoking. The conclusion has been that men are getting COPD from smoking, whereas women are getting COPD mostly from cooking with polluting fuels, in addition to environmental tobacco smoke (ETS) and other exposures. A significantly increased relative risk for COPD (1.329, $p < 0.01$) was found among indoor coal use households in Shanghai (Tao 1992). Coal heating was also found to be an important risk factor for decreased pulmonary function in Beijing (Xu 1991). Smith has recommended, based on eight published studies of COPD prevalence, that a range of odds ratios from 2-4 is most appropriate for calculating the disease burden of IAP in solid-fuel-using households.

There are many related respiratory conditions for which disease burdens cannot be quantified due to limited causal evidence and understanding of impacts. *Cor pulmonale*, a serious heart condition secondary to COPD, has been observed in women with chronic exposure to biomass smoke (Padmavati 1959). Interstitial lung disease has been attributed to long-term exposures to biomass smoke (Dhar 1991, Ramge 1988). Strong evidence exists for more mild impacts, such as reduce lung function, reduced local non-specific immune function, and cough and other respiratory symptoms. Although these measures of health impact do not identify specific diseases, the health burdens are great.

Lung Cancer

While there have been relatively few studies examining the lung cancer risks from biomass smoke, there have been numerous studies of lung cancer focusing on coal-burning households, particularly in China. Epidemiological studies have not found an association between biomass smoke and lung cancer, most likely due to inadequate sample sizes, exposure misclassification and short study durations. However, exposure to the products of biomass combustion is still considered a potential risk for lung cancer for three reasons: (1) Many of the pollutants found in large quantities in biomass smoke are known and suspected carcinogens; (2) Previous lung diseases, such as COPD, which are also aggravated by biomass smoke, are associated with an increased lung cancer risk; (3) In contrast, the relationship between lung cancer in women and exposure to coal smoke has been examined in more than 20 studies in China studies, all of which found significant associations (Smith 1994). As a group, these studies provide strong evidence for a relative risk between 3-5 for cooking and/or heating indoors with coal.

Tuberculosis

Two published epidemiological studies of biomass-using households in India provide strong evidence that biomass smoke increases the burden of tuberculosis. Results of the 1992-1993 Indian National Family Health Survey indicated that women over 20 years in biomass-using households were three times more likely to report TB compared to households using cleaner fuels (Mishra 1999). This study is particularly strong due to the large sample size of 90,000 households and the fact that the authors measured and adjusted for several potentially confounding factors, such as socioeconomic status. The other Indian study found that men and women using wood or dungcakes for household fuels had 2.5 times more clinically confirmed TB (Gutpa 1997). These findings are particularly concerning as TB is on the rise in many developing countries due the HIV and drug-resistance.

Although *Mycobacterium tuberculosis* is the cause of pulmonary tuberculosis, the risk of disease upon exposure to the bacteria may be modified by an individual's resistance to infection. Exposure to tobacco smoke has been shown to decrease cellular immunity, antibody production and local bronchial immunity and increase the incidence of tuberculosis (Altlet 1996). The similarities between biomass fuel smoke and tobacco smoke make a strong case for increased tuberculosis risk in households using biomass. In addition, animal studies have shown that woodsmoke decreases respiratory immunity (Zellikoff 1994, Thomas 1999).

Low Birth Weight and Perinatal Conditions

Several studies have linked ambient air pollution to reduced birth weight (Wang 1997, Ritz 1999, Bobak 1999, Bobak 2000). In addition, a study in Guatemala found that babies born to women using wood fuel, compared to those using gas or electricity, weighed 63 gm less. This finding was significant ($p=0.049$) after adjusting for potential socioeconomic and maternal confounders (Boy 1998). Low birth weight is a risk factor for several important childhood diseases, including diarrhea and ARI (Walsh 1993), and probably effects health into adulthood (Barker 1997). Therefore, the magnitude of the public health impacts of decreased birth weight from solid fuel pollution is potentially very large.

Only one study, which found a 50% excess risk of stillbirth in India (Mavalankar 1991), has directly studied perinatal mortality as an outcome of biomass fuel use. Evidence from studies of urban ambient air pollution, however, suggests that this risk is probably real. A time series study in Mexico City found that, using a 3-5 day lag period, a 10 g/m^3 increase in ambient $PM_{2.5}$ was associated with a 6.9% (2.5-11.3) higher infant mortality rate (Loomis 1998). A US study found an odds ratio of 1.10 (1.04-1.16) for perinatal mortality when comparing high (mean 44.5 g/m^3) and low (mean 23.6 g/m^3) exposure groups (Woodruff 1997). Among normal birth weight infants, they also found 40% increased respiratory mortality (OR 1.40, 1.05-1.85) and 26% increased sudden infant deaths (OR 1.26, 1.14-1.39) in the high exposure group. Although there may be important toxicological differences between urban ambient pollution and solid fuel smoke, adverse effects at the concentrations found in outdoor air are worrying, considering the significantly higher (10's to 100's of times) levels typically found in developing country kitchens.

Asthma

Various sources and pollutants have been linked to increased frequency and severity of asthma attacks among sensitized people. Studies from Kenya (Mohamed 1995), Malaysia (Azizi 1995), China (Xu 1996) and Turkey (Guneser 1994) have measured associations between asthma and indoor air pollution from solid-fuel combustion. There is evidence of asthma risk for both wood and coal smoke.

Cataract

A case control study in India found 60% increased risk of cataract among people using biomass fuel (Mishra 2000). Analysis of the Indian National Family Health Survey found increased partial blindness among biomass households (OR = 1.3), but no significantly increased risk of total blindness (Mishra 2000). Evidence that these epidemiological findings are not spurious, smoke is a known eye irritant for women cooking with biofuels (Ellegard 1997) and has been shown to damage the lens of rats and cause cataracts (Shalini 1994, Rao 1995). There is also evidence that ETS exposure is associated with cataracts (West 1992).

Heart Disease

Highly sophisticated studies of large populations have linked ambient air pollution (Dockery 1993, Borja-Aburto 1998) and ETS (Glantz 1995, Steenland 1998) to heart disease. This is the focus of much ambient air pollution epidemiological research in developed countries. Although this body of evidence strongly suggests that there may be cardiac effects of exposure to solid fuel combustion emissions, no known studies have been conducted in these settings. Smith tentatively recommends applying conservative risk estimates from studies of ambient air pollution to the levels typical IAP exposures in developing countries. Using an estimate of 160 g/m^3 for the average exposures in India, he derives a range of risk from 10% to 40% increased heart disease.