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Effect of Improved Stoves on Wood Consumption, Particulate Matter, and Carbon Monoxide Production

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Introduction

In rural Central America, the dominant source of fuel for cooking is biomass (Cutz *et al*., 2016). This practice triggers two significant problems in the region: 1) health issues for users and household members; and 2) deforestation caused by the quantities of wood required to sustain the practice (Hanna *et al*., 2015; Khandker *et al*., 2015; Singh *et al*., 2014). Sustainable Harvest International (SHI), a USA-based nonprofit organization, has been developing and promoting different models of improved wood-conserving stoves in Panama, Belize, Nicaragua and Honduras since the year 2000 (Reed and Romero-Perezgrovas, 2015). These models have been built using local materials and incorporating local cooking cultures in the design. Dozens of improved stove models have been tested and extended in Central America since the 1980´s (Boy *et al*., 2000). Some exogenous improved models have proven successful in diminishing wood consumption and improving health of users. However, long-term adoption of these models has been low due to high costs, lack of training for maintenance and design failures resulting from a lack of understanding of local contexts and culinary traditions (Barnes *et al*., 1994). SHI locally designed models have been widely adopted on a long-term basis because they use local materials, are easy to build and maintain and have in keeping with local culinary traditions. Nonetheless, until now there has not been a systematic evaluation of the performance of these improved models on 1) wood consumption (kg); 2) particulate matter (PM ug/m^3) production and; 3) carbon monoxide (CO ppm) emissions when compared to the performance of traditional models. The objective of this research was to systematically compare the locally designed improved models to traditional stoves in field conditions on these specific three variables.

Materials and Methods

a) Data Collection

In collaboration with EARTH University (Costa Rica) and the Aprovecho Research Center (USA) and with the financial support of Cummins Inc., a systematic evaluation of two improved stove models – 'Damak' in Panama, and 'Mani' in Honduras – was performed. A total of 174 stoves were measured for CO and PM, including100 in Panama and 74 in Honduras. Of these 174 stoves, 92 were SHI-improved models, and 82 were traditional stoves. For the evaluation for CO and PM, a state-of-the-art portable Indoor Air Pollution Meter (IAP) 5000 series was utilized. For wood consumption, the surveyors measured mass using a balance, and registered the type and source of wood used in each household. Additional observations were registered, such as whether the stoves had soot presence and were well maintained; whether they were inside or outside of the house; and whether the main user was male or female, among other household characteristics. The total number of households surveyed for wood consumption was 157 using improved stoves and 100 using traditional stoves in Honduras, as well as 176 improved stoves and 99 traditional stoves in Panama.

b) IAP Meter

The Indoor Air Pollution Meter (IAP Meter) 5000 Series is a portable device used to quantify air emissions from cooking stoves by measuring indoor concentrations of CO ppm and PM ug/m^3. The CO concentration is measured through an electrochemical cell. The conductivity between two electrode changes in proportion to the concentration of CO. The PM sensor is composed of a laser and a light receiver, and works using optical light scattering. When smoke enters the sensing chamber, the light of the laser bounces off the particles of smoke into the receiver. As more smoke enters into the chamber more light reaches the receiver. This level of light has been calibrated against a laboratory standard nephelometer to relate the amount of reflected light to the concentration of smoke particles.

The IAP meter was placed between approximately 1.3 m to 1.5 m aside the stove, and 1.3 m to 1.5 m up from the floor, replicating a standard breathing position of the cook. Before running the tests, the meter operated for at least 10 minutes in a nearby location where direct smoke was not present, as background readings are necessary to determine the addition of IAP to the ambient air quality. Then, the meter was left running during a sampling period of 30 minutes at maximum cooking temperature.

c) Statistical Analysis

PM and CO averages were processed using analysis of variance (ANOVA) under the general and mixed model frameworks. To compare groups of means, different models were adjusted, and the best model, for each variable, was selected by the Likelihood Ratio Test-LRT. Data with values less than 0 were eliminated, as such 36 and 18 observations were eliminated, for a total of N=138 and N=156 for PM and CO respectively. A cube root transformation was necessary because the data did not fit normality assumption, following a positive asymmetry. Data were analysed with the software InfoStat professional (Di Rienzo *et al*. 2017), using the R interface (R Core Team, 2017).

The adjusted model for average PM and CO

$$y_{ijklmnp} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \theta_m + \alpha\beta_{ij} + \beta\gamma_{jk} + \beta\delta_{jl} + \beta\theta_{jm} + b(\alpha)_{in} + \varepsilon_{ijklmnp}$$

Where $y_{ijklmnp}$ represents the observed response variable ($\sqrt[3]{COmean}$ or $\sqrt[3]{PMmean}$) in the *i*-1…., N country (*i* = Honduras, Panamá); in the *j*-1…, N wood stove model (*j* =traditional, efficient); in the *k* stove location (*k* =in, out); for the *l*-1…, N soot presence (*l* = Yes, No); for the *m*-1…, N type of user (*m* = men, women, multiple users); for the *n*-1…., N type of wood (*n* =1, …15), and in the *p*-1…., N repetition; μ is the model general mean; α_i is the fixed effect of the country; β_j is the fixed effect of the wood stove model; γ_k is the fixed effect of the wood stove location; δ_l is the fixed effect of the presence/absence of soot, and y θ_m is the fixed effect of the user. The model included different factor interactions, the model parameter $\alpha\beta_{ij}$ represents the fixed effect between country and wood stove model; $\beta\gamma_{jk}$ is the fixed of the interaction between wood stove model and stove location; $\beta\delta_{jl}$ is the fixed effect of the interaction between wood stove model and soot presence/absence; $\beta\theta_{jm}$ is the fixed effect of the interaction between wood stove model and type of user.

The last two terms of the model represent the random effects; $b(\alpha)_{in}$ is the random effect of the type of wood within the country, with a distribution of $N \sim \left(\mu, SC\sigma_{in}^{2}\right)$, where $SC\sigma_{in}^{2}$ is the estimated variance and covariance matrix for the effect of type of wood depending on the country. A variance for each country was estimated and only one covariance. The error term $\varepsilon_{ijklmnp}$, with a distribution of $N \sim \left(\mu, I\sigma_{ijl}^{2}\right)$, where $I\sigma_{ijl}^{2}$ is the variance matrix for each country, wood stove model and soot presence/absence combination, with covariance equal to cero.

Results

A statistically significant effect ($p<0.05$) was found on the average PM, between countries ($p<0.0001$), wood stove models ($p<0.0001$), type of user ($p=0.0066$), and the interaction country*wood stove model ($p=0.0280$)

Table 1. Average Particulate Matter (ug/m^3) estimated by the model including wood stove models and countries

	Honduras		Panama		N	Mean
Wood stove model	n	Mean	n	Mean		
Improved	14	2,6 c	46	440,7 b	60	91,1 b
Traditional	33	967,4 b	45	4057,7 a	78	2156,7 a
Mean	47	178,5 b	91	1634,7 a		

Different letters indicate significant differences ($p<0.05$)

A statistically higher average amount of CO was found in the traditional wood stoves in comparison to the improved wood stoves ($p<0.0001$). Improved stoves in Panama also showed a higher amount of average CO in comparison to Honduras ($p<0.0001$). Other significant effects by the adjusted models were not found.

Table 2. Average Carbon Monoxide (ppm) estimated by the model between wood stove models and countries

	Honduras		Panama		N	Mean
Wood stove model	n	Mean	n	Mean		
Improved	31	0,3 a	51	19,7 a	82	4,9 b
Traditional	27	20,1 a	47	52,3 a	74	33,7 a
Mean	58	5,0 b	98	33,4 a		

Different letters indicate significant differences ($p<0.05$)

Table 3. Average wood consumption (kg) per day by country and stove model

	Honduras		Panama			Mean
Wood stove model	n	Mean	n	Mean		
Improved	157	5.59	176	5.64	333	5.6
Traditional	100	10.9	99	11.52	199	11.21
Mean	257	8.24	275	8.58	532	8.4

Conclusions and Outlook

The three tested variables (wood consumption, CO and PM) had a statistically significant difference in favour of the locally designed improved stoves when compared to traditional stoves. This means less pressure for the households to get firewood, and improved health derived from a better air quality whilst cooking. There was a significant interaction between stove model and country, meaning there are big differences associated with the improved model (Damak for Panama and Mani for Honduras) and kitchen structure (Panama outside cooking facilities, Honduras inside cooking facilities). Locally designed and improved stove models have been adopted in the long term in both Honduras and Panama due to low costs, easy maintenance and respect for the culinary traditions of users. These factors should be considered for policy making.

Even with all these positive results we consider that it is necessary to perform tests in the laboratory to adequately analyse and compare the measurements of stove performance - including fuel consumption, CO, PM and black carbon, under controlled conditions. Additionally, protocols like the Water Boiling Test, which is a standardized and reproducible laboratory test, can be used to determine the thermal efficiency, specific fuel consumption, firepower and real-time emissions of CO_2, CO and PM. All the above are necessary to gain a deeper understanding of the performance of the locally designed improved stoves. To this end, such tests have already begun to be carried out with the Damak wood-stove at the Centre for Research and Development of Renewable Energies at EARTH University.

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