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

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Abstract Biomass is the primary source of energy for cooking in rural Central America. The intensity of labour required to collect wood, levels of pollution resulting from incomplete burning, health problems linked to smoke inhalation, and pressure on forests are among the problems commonly associated with cooking with traditional stoves utilized in the region. Since the 1980s, improved stoves programs have been implemented in the region, but exogenous-developed models have had low adoption rates due to a lack of know-how for construction and repairs, expensive materials, and lack of understanding of local culinary traditions and culture. Sustainable Harvest International (SHI), a non-profit organization, has successfully developed two local improved stoves: the Damak model in Panama and the Mani model in Honduras. In both cases, anecdotal evidence of high rates of long-term adoption has been noted by SHI. Nonetheless, before this study, there has been no systematic evaluation of the efficiency of these two models in respect to 1) daily household wood consumption (kg); 2) particulate matter (PM₂.₅ ug/m³) concentration in the kitchen, and 3) carbon monoxide (CO ppm) concentration in the kitchen when compared to the traditional stoves used in rural households of both countries. The results presented herein were generated from a study using a random representative sample of 174 stoves and a portable Indoor Air Pollutant Meter manufactured by Aprovecho Research Center (ARC). An analysis of variance processed the data under the general and mixed model frameworks. The results showed that there was a statistically significant average decrease in wood consumption per day per stove for the improved models, as well as a statistically significant average decrease in personal exposure to particulate matter and carbon monoxide for the improved models when compared to those same measurements generated by traditional stoves.

Keywords: Central America, biomass, indoor air pollution, appropriate technology, deforestation

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1. Introduction

In rural Central America, the dominant source of fuel for cooking is biomass [1]. The traditional open cooking system, like the three-stone fire, is highly inefficient because it generates a great loss of energy and triggers three significant problems: 1) health issues for users and household members through the emission of smoke [2,3,4]; 2) pressure on the environment caused by the quantities of wood required to sustain the practice [5], and 3) the large quantities of labor (mainly women and children) needed to collect the required wood [6-7]. OLADE estimated that around 20 million people in Central America depended on wood for cooking in 2010 [8]. Blanco-Rodríguez estimated that around 4 million homesteads in Central America use an inefficient wood-stove technology for cooking food daily, with most of these people hailing from the lowest income levels, concentrated primarily in Guatemala Nicaragua, and Honduras [9]. The Central American Sustainable Energy Strategy 2020 proposed by the Central American Integration System [10] notes that: "Biomass resources constitute an intensively used resource in our region, representing around 38% of the Central American energy matrix, of which around 80% is wood that is used for cooking food.” According to FAO, 52% of global timber harvest is used for fuel [11], and Bailis [12] reports that between 27% and 34% of the global firewood harvest is unsustainable and that 275
It is estimated that indoor wood smoke emissions cause 4% of worldwide illnesses and annually lead to more than 2.1 million premature deaths of women and children [13]. The use of improved wood stoves can significantly reduce smoke-related problems and improve health conditions. The use of open fires produces an incomplete and uncontrolled combustion process, thus generating a significant amount of polluting smoke and particulate matter. According to Albakal [14], people using biomass for cooking are exposed to three to seven hours of cooking fires daily, thus risking direct body burns, the development of cardio-respiratory illnesses (e.g., acute childhood respiratory infections, chronic pulmonary disease, asthma, cancer, and pulmonary tuberculosis) and cataracts, all through the exposure to high levels of air pollutants. Culturally, firewood harvest and all related activities heavily rely on the investment of considerable time by children and women. As such, the implementation of improved stove models has an essential impact on diminishing health problems, including reducing the amount of wood employed (thus lowering deforestation in particular, environmental pressures in general, and time spent gathering fuelwood) and reducing the time spent cooking. Bailis [12] calculated that global emissions from firewood are 1.0–1.2 Gt CO₂e yr⁻¹ (1.9–2.3% of global emissions) and proposed that successful deployment and utilization of 100 million improved stoves around the globe could reduce this by 11–17%. Moreover, improved stoves also increase safety and result in a cleaner kitchen with less labor spent on housework.

There has been a long history of development and adoption of improved wood-efficient stoves in Central America. Blanco-Rodríguez [9] cites the attempted establishment and use of twelve different efficient models in Guatemala alone and ten in Nicaragua, four in Honduras, and three in El Salvador and Costa Rica, respectively. Special mention should be given to the Lorena model (from the Spanish acronym lodo + arena, mud + sand), the most widespread model in the region (Guatemala, Honduras, and Nicaragua). It is also recognized as one of the first efficient stoves widely taken up in Latin America – specifically in Guatemala – during the 1970s. This model was subsequently further improved in Mexico under the name Patsari during the 1980s [15] and has become popular in the rural and peri-urban areas of the country. Many other types of improved stove models have been tested in the region, and recently, rocket stoves have started to be used in Guatemala, Nicaragua, and Honduras. Scientific literature and development agencies cite technical and policy reports consistently indicating that dozens of improved stove models have been tested and extended in Central America since the 1970s [16]. Although several of these models have been analyzed concerning wood consumption efficiency and emissions, little is known regarding the personal exposure to PM₂.₅ and CO in the Central American region under household conditions.

Sustainable Harvest International (SHI), a USA-based non-profit organization, has been developing and promoting different improved wood-conserving stoves in Panama, Belize, Nicaragua, and Honduras since 2000 [17]. These models have been built using local materials and incorporating local expertise and cooking cultures in the design. Some exogenous improved models have proven successful in diminishing wood consumption and improving users' health in these same countries. However, long-term adoption of these models has been low due to high costs, lack of maintenance training, and design failures resulting from a lack of understanding of local contexts and culinary traditions [18]. Improved Stove Models designed locally by SHI have been widely adopted long-term because they use local materials, are easy to build and maintain, and are in keeping with local culinary and cultural traditions. Nonetheless, until now, there has not been a systematic evaluation (in either household conditions or a controlled laboratory environment) of the performance of the SHI-improved models – compared to the performance of traditional stoves – regarding 1) daily household wood consumption (kg); 2) particulate matter (PM₂.₅ ug/m³) personal exposure during cooking and, 3) carbon monoxide (CO ppm) personal exposure during cooking. The objective of this research was to systematically compare the locally designed, improved models with traditional stoves in household conditions, focusing on these three specific variables.

2. Materials and Methods

2.1. Data Collection

In collaboration with EARTH University (Costa Rica) and Aprovecho Research Center (USA), a systematic evaluation of two improved stove models – 'Damak' in Panama and 'Mani' in Honduras – was performed (Figure 1, Figure 2). One hundred seventy-four households were sampled for CO and PM₂.₅ personal exposure while cooking, including 100 in Panama and 74 in Honduras. Of these 174 households, 92 use an SHI-improved model as the primary stove, and 82 used a traditional stove (Figure 3, Figure 4) as the primary stove. For the evaluation of CO and PM₂.₅, the ARC Indoor Air Pollution Meter (IAP) 5000 Series was utilized, as shown in Figure 5 [19]. For wood consumption (WC), 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 walls, ceiling, and other surfaces surrounding the woodstove had soot deposits (Figure 6), whether they were inside or outside of the house, and whether the primary user was male or female, among other household characteristics. The total number of households surveyed for wood consumption in Panama and Honduras was 174. Of that total, in Honduras, 40 used improved stoves, and 34 used traditional stoves. In Panama, 52 households primarily used improved stoves and 48 primarily used traditional stoves. The surveyed households in Honduras were in the departments of Yoro and Comayagua, and those surveyed in Panama were in the province of Coclé. All the surveyed communities in both countries were under the national poverty line but had high environmental value due to their location within the buffer zones of national parks and nature conservation areas.
Figure 1. “Damak” improved woodstove from Panama in the outside kitchen. The stove is made of bricks with a combustion chamber insulated from the stove body, the flames are in direct contact with the pot, and there is no chimney.

Figure 2. “Mani” improved woodstove from Honduras inside the kitchen. The stove is made of bricks with an adobe outer shell, there is no direct flame contact with the pots, and a chimney is included.

Figure 3. Traditional woodstove from Panama. The stove is made of stones and a metal base, and the flames are in direct contact with the pot.
Figure 4. Traditional woodstove from Honduras. The stove is made out from sand and clay, does not include a chimney, and has no direct flame contact to the pot. When tortillas are prepared, they receive the heat directly from the plancha.

Figure 5. Portable Indoor Air Pollution Meter (IAP) 5000 Series after measuring of a Mani improved stove model inside a kitchen in Honduras. The stove is made of bricks, and an adobe cover utilizes a chimney and has no direct flame contact to the pot.

Figure 6. Soot presence on the walls near the cookstove from a traditional woodstove in Honduras inside the kitchen.
2.2. Personal Exposure While Cooking

The Indoor Air Pollution Meter (IAP Meter) 5000 Series [19] (Figure 5) is a portable device used to quantify air emissions from cooking stoves by measuring indoor concentrations of CO ppm and PM$_{2.5}$ ug/m$^3$. The CO concentration is measured through an electrochemical cell. The conductivity between the two electrodes 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 scatters into the receiver. As more smoke enters the chamber, more light reaches the receiver. This level of light was calibrated at ARC at the time of the meter’s manufacture against a standard laboratory nephelometer to relate the amount of scattered light to the concentration of smoke particles in the absence of a site-specific gravimetric calibration.

The IAP meter was placed between approximately 1.3 m to 1.5 m aside from the stove, and 1.3 m to 1.5 m up from the floor, replicating the standard breathing position of the cook following the Berkley [20] guidelines. Before running the tests, the meter operated for at least ten 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,' a period in which the cook was actively cooking and present near the meter. In Panama, the primary household user decided the 'maximum cooking temperature' based on the temperature that he or she perceived as ready for cooking rice (the staple food). The exact process was carried out in Honduras, but with tortillas and/or beans (the country’s staple food) instead of rice.

2.3. Statistical Analysis

PM$_{2.5}$, CO, and WC averages were processed using analysis of variance (ANOVA) under the general and mixed model frameworks. Different models were adjusted to compare groups of means, and the best model for each variable was selected by the Likelihood Ratio Test -LRT. Measurements with negative values were eliminated. As such, 36, 18, and 28 observations were eliminated, for a total of N=138 and N=156 for PM$_{2.5}$ and CO, respectively, and N=148 for wood consumption. A cube root transformation was necessary because the data did not fit the normality assumption, following a positive skew. Data were analysed with the software InfoStat [21], using the R interface [22].

The adjusted model for average PM$_{2.5}$, CO, and WC

\[ y_{ijklmp} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \theta_m + \epsilon_{ijklmp} \]

Where $y_{ijklmp}$ represents the observed response variable ($\sqrt[3]{\text{COmean}}, \sqrt[3]{\text{PM}_{2.5}\text{mean}}, \sqrt[3]{\text{WCmean}}$) in the $i^{th}$ country ($i =$ Honduras, Panama); in the $j^{th}$ woodstove model ($j =$ traditional, efficient); in the $k^{th}$ stove location ($k =$ indoor, outdoor); for the $l^{th}$ soot deposits on the walls of the house ($l =$ yes, no); for the $m^{th}$ type of user ($m = \text{men, women, multiple users}$); for the $n^{th}$ type of wood ($n = 1, \ldots, 15$), and in the $p^{th}$ repetition; $\mu$ is the model general mean; $\alpha_i$ is the fixed effect of the country; $\beta_j$ is the fixed effect of the woodstove model; $\gamma_k$ is the fixed effect of the woodstove location; $\delta_l$ is the fixed effect of the presence/absence of soot, and $\theta_m$ 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 effect of the interaction between woodstove model and stove location; $\beta\delta_{jl}$ is the fixed effect of the interaction between woodstove model and soot presence/absence; $\beta\theta_{jm}$ is the fixed effect of the interaction between woodstove model and type of user. The last two terms of the model represent random effects, $b(\alpha)_{m}$ is the random effect of the type of wood within the country, has a distribution of $N \sim (\mu, SC\sigma^2_m)$, where $SC\sigma^2_m$ is its estimated variance matrix, with a covariance equal to zero. The random error term $\epsilon_{ijklmp}$, has a distribution of $N \sim (\mu, I\sigma^2_U)$, where $I\sigma^2_U$ is the variance matrix for each country/woodstove combination, with a covariance equal to zero.

3. Results and Discussion

3.1. Indoor/outdoor and Improved/traditional Woodstoves

The present analysis resulted in the study of 174 woodstoves, 74 from Honduras and 100 from Panama. The distribution of these woodstoves into traditional and improved models and how many of them were of indoor or outdoor use is indicated in Table 1. There was a roof over all stoves that were used outside. In Honduras, 54 % of the studied woodstoves were of the improved model, with the number of improved model woodstoves studied in Panama standing at 52 %. Due to cultural practices and climate conditions, all studied woodstoves in Honduras were indoor, while 85% of the studied woodstoves in Panama were outdoor.

| Table 1. The number of households with indoor/outdoor and improved/traditional woodstove models |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Improved        | Traditional     | Improved        | Traditional     |
| Outdoor                        | 40              | 34              | 45              | 40              |
| Indoor                         | 40              | 34              | 7               | 8               |
| Total                          | 40              | 34              | 52              | 48              |
|                                 | 174             | 174             | 174             |

3.1.1. Presence of Soot

Table 2 shows the results about the presence of soot according to country and woodstove type. Honduras shows a low soot presence for improved woodstoves, while all traditional woodstoves generated soot deposits, whereas in Panama, soot was present indistinctly in...
improved woodstoves, and traditional stoves had a marked generation of soot deposits. A statistically significant association (p<0.05) was registered between the woodstove type and the presence/absence of soot in both countries.

Table 2. Soot presence for each country and woodstove type

| Woodstove Type | Honduras | Panama | Total |
|----------------|----------|--------|-------|
| Improved       | Traditional | Improved | Traditional |
| No             | 36        | 0      | 27    | 3     | 66    |
| Yes            | 4         | 34     | 25    | 45    | 108   |
| Total          | 40        | 34     | 52    | 48    | 174   |

3.1.2. User Type

The type of primary user, i.e., man, woman, multiple (man and woman, man and children, woman and children), is reported in Table 3. In Honduras, only women and multiple were reported as primary users; in the case of Panama, all three primary user types were recorded. For both improved stoves and traditional stoves, the proportion of user types was similar.

Table 3. User type according to country and woodstove type

| User | Honduras | Panama | Total |
|------|----------|--------|-------|
| Man  | Improved | Traditional | Improved | Traditional |
|      | 0        | 0       | 8      | 9     | 17    |
| Woman| 30       | 26      | 25     | 31    | 112   |
| Multiple | 10     | 8       | 19     | 8     | 45    |
| Total | 40       | 34      | 52     | 48    | 174   |

3.1.3. Wood Species

Fifteen different species of wood were registered for this study. Out of that total, eleven were present in Panama and seven in Honduras (Table 4). Guabo or Guama (Inga spp.), Laurel (Cordia alliodora), and Nance (Byrsonima crassifolia) were used in both countries. Nance was the most used wood in Panama, and Roble (Quercus acuta) was the most used wood in Honduras.

Table 4. The number of households using wood species of firewood in Honduras and Panama

| Wood species                  | Honduras | Panama |
|-------------------------------|----------|--------|
| Acacia (Acacia mangium)       | 0        | 6      |
| Café (Coffea arabica)         | 0        | 1      |
| Encino (Quercus corrugata)    | 9        | 0      |
| Frijolillo (Lonchocarpus minimiflorus) | 0     | 1      |
| Guabo/Guama (Inga spp.)      | 3        | 3      |
| Laurel (Cordia alliodora)     | 1        | 10     |
| Macano (Diplphysa americana)  | 0        | 2      |
| Matillo (Matabya scrobiculata) | 0     | 6      |
| Nance (Byrsonima crassifolia) | 7        | 67     |
| Pino octxo (Pinus octx)        | 13       | 0      |
| Pinta mozo (Vismia baccifera) | 0        | 2      |
| Poró (Cochloperum vitifolium) | 0        | 1      |
| Roble (Quercus acuta)         | 32       | 0      |
| Roble (Tabebuia rosea)        | 0        | 1      |
| Tatascán (Senna guatemalensis) | 9      | 0      |
| Total                         | 74       | 100    |

3.1.4. Particulate Matter (PM)

Statistically significant effects were found for mean PM$_{2.5}$ values, type of user (p=0.0066) (Table 5), the interactions country*woodstove model (p=0.0280) (Table 6), and woodstove model*soot presence/absence (p=0.0001) (Table 7). Kitchens with multiple cooks engaged in the cooking effort made less smoke, possibly because more time was spend tending the fire. In Honduras, the improved Mani stove had the lowest PM$_{2.5}$ emissions, most likely because it was the only stove to utilize a chimney. Within a wide safety margin to account for the inaccuracy of making PM$_{2.5}$ measurements with the ARC light scattering based sensor, the average PM$_{2.5}$ exposure when using the Mani stove was most likely below the ultimate WHO guideline for 24 hr PM$_{2.5}$ exposure (10 ug/m$^3$, [23]). Although the exposure measurement was not conducted for 24 hours, the 30-minute high-power cooking period is likely the highest exposure period since the cook is usually not present during the long duration smouldering events that are commonly associated with high emissions rates. Even though the stoves in Panama mainly were used in the outdoor settings, where there are likely higher ventilation rates than in the indoor settings, the users were still exposed to more PM$_{2.5}$. This finding implies that if the study had evaluated more users in Panama that cooked indoors, the difference between user's exposure in Panama and Honduras would have been even higher.

Table 5. Average Particulate Matter$_{2.5}$ (ug/m$^3$) means estimated by the model according to users

| User | n | Mean |
|------|---|------|
| Man  | 17 | 791.5 a |
| Woman| 83 | 686.1 a |
| Multiple | 38 | 521.7 b |

Different letters indicate significant differences (p<0.05).

Table 6. Average Particulate Matter$_{2.5}$ (ug/m$^3$) means estimated by the model according to the country*woodstove model interactions

| Country | Woodstove Model | Improved | Traditional |
|---------|-----------------|----------|-------------|
| Honduras| N Mean n Mean   | 14 2.6c 46 440.7b | 60 91.1b |
| Panama  | N Mean n Mean   | 33 967.4b 45 4057.7a | 78 2156.7a |
| Mean    | N Mean n Mean   | 178.5b 1634.7a | 2156.7a |

Different letters indicate significant differences (p<0.05).

Table 7. Average Particulate Matter$_{2.5}$ (ug/m$^3$) means estimated by the woodstove model*soot presence/absence interactions

| Absence | Presence | N Mean | n Mean | N Mean |
|---------|----------|--------|--------|--------|
| Improved| N Mean n Mean | 34 76.2c 26 107.2c | 60 91.1b |
| Traditional| 2 4354.7a 76 860.1b | 78 2156.7a |
| Mean    | N Mean | 1089.5 a 362.5 a | 2156.7a |

Different letters indicate significant differences (p<0.05).

It is interesting to compare the Mani woodstove from Honduras and the Patsari woodstove from Mexico, both indoor-style stoves. The mean results for PM$_{2.5}$ for the Mani model are 2.6 ug/m$^3$ for a 30-minute highest temperature cooking monitoring period (vs. 967.4 ug/m$^3$ mean for the traditional Honduran woodstove model for a 30-minute cooking period). In contrast, the improved Mexican Patsari model registers 115 ± 59 ug/m$^3$ [15] for a 24-hour monitoring period, suggesting a diminished
particulate matter production for the improved Honduran model.

3.1.5. Carbon Monoxide (CO)

Table 8 shows that statistically significant differences were found for the CO means between countries (p<0.0001) and woodstove models (p<0.0001). Users of the Mani stove in Honduras were found to have had less exposure than the WHO 24 hr guideline (5.7 ppm, [23]). Although the exposure measurement was not conducted for 24 hours, the 30-minute high-power cooking period is likely the highest exposure period since the cook is usually not present during the long duration smouldering events that are commonly associated with high emissions rates. The adjusted model found no other significant effects.

Table 8. Average Carbon Monoxide (ppm) means estimated by the model between countries and woodstove models

|                | Table of Values | Panama       | Mean  | N  | Traditional | Improved | Mean  | N  |
|----------------|----------------|--------------|-------|----|-------------|----------|-------|----|
|                |                | Honduras     |       |    |             |          |       |    |
| 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).

3.1.6. Wood Consumption

Table 9 shows that the average mean is statistically different for wood consumption for a country (p<0.0001). Moreover, there was a statistical difference between traditional and improved mean by stove type (p<0.0001). For the calculations, the model considered 148 stoves of a total of 174.

Table 9. Average Wood Consumption per household per meal (kg) means estimated by the model between countries and wood stove models

|                | Table of Values | Panama       | Mean  | N | Traditional | Improved | Mean  | N |
|----------------|----------------|--------------|-------|---|-------------|----------|-------|---|
|                |                | Honduras     |       |   |             |          |       |   |
| Traditional    | 48             | 9.1          | 52    | 5.57 | 100        | 7.39 a   |       |   |
| Improved       | 34             | 7.62         | 40    | 4.58 | 74         | 6.07 b   |       |   |
| Mean           | 82             | 8.39 a       | 92    | 5.08 b |          |          |       |   |

Different letters indicate significant differences (p<0.05).

Between Panama and Honduras, there was an average decrease in wood consumption. One possible explanation is that in Panama, the Nance wood (which mainly was commonly used by cooks in this study) is planted mainly by farmers as an energy and food crop, but in Honduras, the Roble wood (and other woods found to be most frequently used in this study) is primarily collected in the forest. One would expect that more time would be spent travelling to the forest and foraging for wood than harvesting from a plantation and that the users in Honduras are more careful with the Roble wood that is more difficult to obtain. Another possible explanation for the increased wood consumption in Panama is that rice is the staple food, whereas, in Honduras, it is maize tortillas. It may be that rice takes more energy to prepare than maize tortillas because it requires a longer cooking time.

4. Conclusions and Policy Implications

The three tested variables (WC, CO, and PM$_{2.5}$) had a statistically significant difference in favour of the locally designed improved stoves compared to traditional stoves. This result means less labour for the households to get firewood, less pressure on their surrounding natural environment, and improved health derived from better air quality while cooking. There was a significant interaction between the stove model and country, meaning there are significant differences due to the geographic location of the stove and the culinary traditions of each country.

Considering these positive results, we acknowledge necessary to perform tests in the laboratory to adequately analyse and compare the measurements of stove performance - including WC, CO, PM$_{2.5}$, and black carbon, under controlled conditions so that we can understand why the improved stoves performed better than the traditional stoves. Protocols like the Water Boiling Test, 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$_{2.5}$. The Controlled Cooking Test can be used in the laboratory setting to understand why cooks like to use the stove. Efforts in the laboratory are necessary to gain a deeper understanding of the locally designed improved stoves' performance and inform the stove design community and policymakers about how to design and deploy stoves that reduce emissions and fuel consumption during household use. To this end, such tests have already begun to be carried out with the Damak woodstove at the Centre for Research and Development of Renewable Energies at EARTH University.

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