Determinants of exposure to household air pollution in rural Malawi

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Abstract

The very high exposure of people to airborne combustion products in developing nations who use solid fuels (mainly wood) as the only source of fuel for cooking, often in inefficient stoves and with poor ventilation is an important public health and environmental issue. A research study done by UNC's FUEL (Forest Use, Energy, and Livelihoods) Lab collected data on determinants of exposure to household air pollution in rural Malawi. The field study collected carbon monoxide (CO) and particulate matter ($PM_{2.5}$) for a period of 24 hours in each of the 108 households in the study. Additionally, they collected both personal (the primary cooks of the household wore the monitors) and area (placed in the primary cooking area) concentration measurements along with completing an in-depth questionnaire with the household owners.

The goal of the study was to do a multivariate regression analysis of household pollutant levels to see how different factors – the type of fuel, fuel quality, stove design, ventilation conditions, etc. – influence indoor air pollutant exposures. The study found that the interaction of ventilation, moisture content, stove type, income quintile, and household size in a multivariate regression model best explains the variance of household air pollutant concentrations. The identification of these determinants allows for further studies on targeted interventions that reduce pollutant concentrations and adverse health outcomes.

Acknowledgements

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Introduction

About half the world's population relies on biomass fuels as a means to meet their domestic energy requirements particularly for cooking (Barnes, 2014). The dependence on biomass fuel is the greatest in rural areas; specifically in African countries, it constitutes 70% of energy needs (Rumchev et. al, 2007). It is difficult to burn solid fuels in simple combustion devices without a sizable emission of pollutants. This leads to a substantial fraction of the fuel carbon being converted to products of incomplete combustion rather than compounds such as carbon dioxide that result from complete combustion (Zhang et al., 2000).

Products of incomplete combustion include, but are not limited to carbon monoxide (CO) and particulate matter (PM). The PM typically generated from fuel combustion is fine or ultrafine in size, but larger particles may result from ash and solid fuel fragments (Zhang et al., 2000). The size of the particulate matter is a determinant for assessing health impacts. Typically, a fine or ultrafine particle can easily travel within the respiratory tract leading to detrimental health effects. It is estimated that 4 million deaths occur annually due to indoor air pollution, or 2.7% of the global burden of disease (especially due to respiratory illness) (Lim et al., 2010). Global burden of disease refers to the lost healthy life years due to premature death and illness (Zhang et al., 2003). The Global Burden of Disease Project estimates that household air pollution (HAP) is responsible for 3.5 million deaths and smoke is attributed to 0.5 million deaths (Rosa et. al, 2014). Other than respiratory illness, HAP is linked to other adverse health outcomes such as low birth weight, inflammatory lung conditions, and cardiac events (Rosa et. al, 2014) (Lim et al., 2010). These adverse health outcomes are more serious for women who spend the predominant amount of time near the kitchen area.

The goal of the study is quantitatively assess the determinant exposure response relationship. To do this, certain determinants of exposure—including biophysical and behavioral causes—are reviewed for their effects on particle concentrations in up to date literature. It is particularly important to identify determinants of household air pollution in order to find effective mitigation and intervention strategies to reduced indoor air pollution. Not only is indoor air quality with regards to cookstove emissions an important health outcome, but it has implications on climate as well. Cookstove emissions contribute to the ever-increasing greenhouse gases and black carbon in the atmosphere (Rosa et. al, 2014). Additionally, using biofuels as a primary energy source may lead to deforestation, another contributor to greenhouse gas emissions.

Fuel type

Fuel type was found to be most important determinant of pollution in both Mehta et al. (2002) and Balakrishnan et al. (2002). In a 1996 study, it was shown that biomass fuels such as charcoal or fuel wood generally produced larger quantities of emissions than their fossil fuel equivalents such as kerosene (Zhang and Smith,1996). A study done in 2000 as a follow up found that emissions per unit delivered energy were less for liquid or gaseous fuels than in solid fuels due to the lower energy content of solid fuels and their subsequently low efficiency stoves (Zhang et al., 2000). Ranking common fuels by their increase in efficiency (and decrease in emissions) crop residues, brush, wood, and fuelwood were on the lower end whereas kerosene and gas were on the higher end (Zhang et al.,2000) (Smith, 1994).

With respect to just biomass fuels—wood crop residue, and dung—approximately two fifths of the world's households rely on biomass as their principal fuel type (Smith, 1994). Studies show that approximately 80% of the world's population exposure to particulate matter indoors is due to the emissions from biomass fuels—wood, crop residue, and dung (Chaudhuri et. al 2003). The use of biomass as the primary fuel source results in using a lower efficiency stove. In particular, wood burning stoves were found on average contribute 50 times more pollution during cooking in comparison to a gas stove (Smith, 1994).

Moisture content

Moisture content refers to the measure of the amount of water in a fuel, and is expressed as percent of the dry weight of the fuel. For a fire to burn more intensely, the moisture content of the fuel must be lower than the moisture content of the extinction of fire (Hoffa et al., 1999). The drier fuels burn more intensely than the wet because of less latent heat transfer; subsequently, the lower intensity fires of wet fuels produce more products of incomplete combustion including CO and $PM_{2.5}$ (Hoffa et al., 1999). Moisture content is also considered to be undesirable because it results in lower thermal emissions and has also been linked to higher emissions of aerosols or VOCs (McDonald et al. 2000). When using improved stoves that are capable of producing less CO and PM, the moisture content of the fuel used can lead to lower performance (Adler, 2010).

Stove Design

For the most part intervention studies for HAP are based on improved cookstove introductions into communities. In order for each stove type to be evaluated equally across the board on the same parameters, the Global Alliance for Clean Cookstoves developed an International Working Agreement (IWA) in 2012 on guidance for rating cookstoves. Cookstoves are rated based on four performance indicators: fuel use, total emissions, indoor emissions, and safety. To highlight progress in furthering improvement in cookstove design, each performance standard has multiple tiers of performance (valued from 0 to 4). Each stove type has up to four ratings for Tiers of Performance (one for performance indicator).

Many areas of the developing world are reliant on simple open-fire cookstoves that not only increase pollutant concentrations but cause adverse health outcomes for women and children. Burning biomass fuels in low efficiency stoves such as traditional, open-fire three stone stoves can emit smoke containing significant quantities of pollutants (Balakrishnan et al., 2004). Open fires and old-fashioned cookstoves emit 90% CO, the other 10% being a mix of VOCs, PAHs (polyaromatic hydrocarbons), metals, and variously sized particular matter (Adler, 2010). There's a strong need to improve stove efficiency as a method to increase combustion efficiency. The transition to more clean and efficient energy systems for cooking are also based on per capita incomes—the higher the more likely the switch (Balakrishnan et al., 2004). On the other hand, appliances that burn fossil fuels have higher combustion efficiencies and therefore generate insignificant amounts of CO (Zhang et al., 2003). Stoves that are not vented—have a flue or hood—do not take pollutants out of the living area (Smith et al. 2002). A Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) in Guatemala found that the use of stoves with chimneys reduced CO exposures by about

90% (Smith). Intervention studies for improved cook stoves found reductions in concentrations of CO and PM for kitchen level and personal concentrations (Bruce et al., 2004, Albalak et al.,2001, Cynthia et al.,2008, Rosa et. al, 2014).

Ventilation

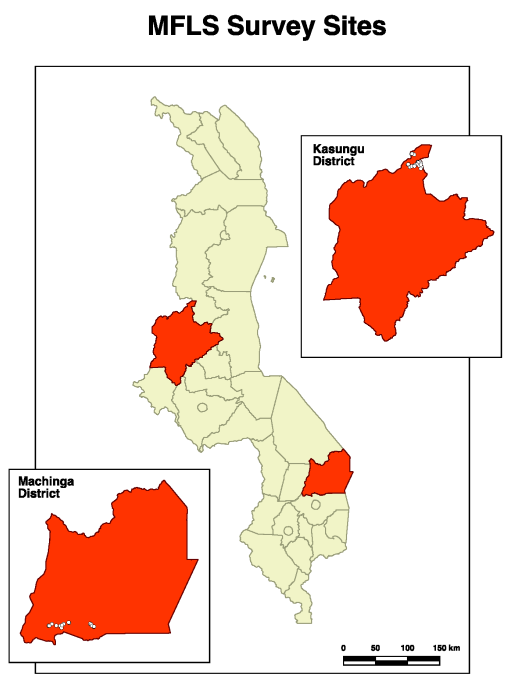
Kitchen ventilation (based on air exchange rates) and cooking location have profound impact on the level of household air pollutant concentrations (Rosa et al., 2014) (Ruth et al.,2013). A test kitchen study with biomass stoves found that increasing air exchange rates by opening windows and doors reduced $PM_{2.5}$ 1-hour concentrations by 93-98% compared to the closed kitchen and CO concentrations by 83-95% less (Grabow et al., 2013). Additionally, studies characterize ventilation as a function of the number of doors and windows open as in an indication of the air exchange rate. A study done by Rumchev et al. found a significant relationship between window area and concentration of CO and $PM_{2.5}$. The increase in window area was associated with reduction in the concentration of $PM_{2.5}$ and CO. Additionally, for $PM_{2.5}$, the increase in number of windows saw a reduction in $PM_{2.5}$ concentrations as well. It can be concluded from this study that using biofuels indoors in a poorly ventilated environment can cause an increase in air pollutants.

A study (Albaklak et al., 1999) done in Bolivia measured PM_{10} concentrations in two different villages in Bolivia—one characterized by indoor cooking the other with outdoor cooking. The analysis of their pollutant concentrations of PM_{10} found that there were significant effects of indoor vs. outdoor cooking on the pollutant levels. Additionally, concentrations of PM_{10} were higher for indoor kitchen environments 1830

$\mu g/m^3$ in comparison to outdoor kitchen environments 280 $\mu g/m^3$. On the other hand, when smoke is released outdoors indoor levels can become high where a large population of households use solid fuels (Zhang et al.,2000). This is due to the re-entry of pollution back into households and is typically associated with cold winter weather with poor atmospheric dispersion (Zhang et al.,2000). Outdoor cooking "in the intervention was associated with a median reduction of 73% when compared to control households ($p<0.001$), 57% reduction when compared to indoor-cooking intervention homes ($p=0.02$). (Rosa et. al, 2014)

Methodology

Study Setting



The Forest Use, Energy and Livelihoods Lab (FUEL) collected data on determinants of exposure to household air pollution in Malawi as a part of the Malawi Forest and Livelihoods Survey (MFLS) from October to November of 2013. The sample of population was drawn from a household-level panel of 400 households that were selected using a stratified random sampling approach within the Machinga (N=18 villages) and Kasungu Districts (N=28 villages). These two districts were chosen as being representative of areas within

Malawi with high forest reliance and active forest co-management agreements. The districts are marked in red on the map entitled MFLS Survey Sites.

The villages of interest within the Machinga District are located adjacent to the Liwonde Forest Reserve, which is a significant source of fuelwood and charcoal. This area has good market access due to its proximity to three of Malawi's 15 largest urban centers (Balaka, Liwonde, and Zomba). The main agricultural crops of the region are maize and paddy rice. Households keep chickens and other small animals, but overall there is limited investment in livestock.

In comparison to the Machinga District, Kasungu has a lower population density. It is located approximately 300 kilometers north of Malawi's capital—Lilongwe; additionally, the villages of interest within the district are adjacent to the Chimaliro Forest Reserve, which has a significant source of fuelwood. Access to markets is limited in the region, but there are major markets due to international trade with Zambia. The main agricultural crops of the region are maize and tobacco; additionally, in the wetland areas (dambos) a variety of vegetables are grown. Unlike Machinga, Kasungu households invest in livestock including cattle and goats.

Approximately 108 households were randomly selected to be included in a rural Malawi study where they were studied for both personal (primary cooks wore monitors) and area (observations from kitchens or cooking area) household air exposures. A household is defined in this study as a group of people that regularly eat together. A primary cook is defined as those who cooked more than 50% of the meals in the household during the past 30 days. To measure the personal exposure within the home, the women—predominately the primary cooks of each household—were incentivized to partake in the study by being given a chitenge (a form of cloth). Each house chosen in the study responded to questions to describe their household demographics, assets, agricultural production, expenditures, access to forest resources, etc. The primary cooks also answered questions about household food consumption, kitchen design and ventilation, fuel use, cooking technology choices, indicators of health status, etc. The results from the questionnaires, in particular of relation to cooking, were used for this analysis.

Indoor air pollution measurements

The protocol of the study required collection of carbon monoxide (CO) and particulate matter ($PM_{2.5}$) for a period of 24 hours. The data collection was done in two parts —area exposure and personal exposure monitoring. The instruments for both the CO and $PM_{2.5}$ monitoring were mounted at a height of 1.5 meters on a tripod positioned 1 meter away from the stove. For the personal exposure monitoring, the CO monitor and the $PM_{2.5}$ monitor (including the pump and the filter) were placed in a side messenger bag or backpack for the women to hold.

Carbon monoxide was measured using a Lascar CO Data Logger (model EL-USB-CO) (Lascar Electronics, Salisbury, UK) at a sample rate of once a minute for a total of 24 hours. These monitors are accurate to ±6 ppm, with a range of 0 to 1000 ppm. To ensure accuracy, certain households were chosen to detect variance in measurements by placing three different monitors in the tripod. See Appendix A for all values of triplicates and their respective averages. The average value of the triplicates at each household was subsequently used for data analysis.

Particulate matter ($PM_{2.5}$) was collected on a 2μm polytetrafluoroethylene (PTFE) filter over the course of a 24-hour period. Each personal and area $PM_{2.5}$ filter was attached to a SKC AirChek XR5000 pump connected to a SKC Personal Environmental Monitor for $PM_{2.5}$ sampling (SKC, Inc., Eighty Four, PA, USA) that was calibrated to a flow rate of 2 (±0.5%) (L/min). The area pump was turned on once ever 6 minutes (i.e. 1 minute on, 5 minutes off, 240 cycles); whereas, the personal pump was continuously run. These filters were weighed prior to use, and weighed subsequently after the 24-hour study period in the household using a MX5 Microbalance (Mettler-Toledo, Inc., Columbus, Ohio) after being equilibrated for at least 24 hours in a Secador 1.0 Dessicator Cabinet (Bel-Art Products, Inc., Wayne, New Jersey) at 33% relative humidity.

Data Analysis

Processing emissions

The carbon monoxide (CO) measurements were averaged across the collected data points over the 24 hr. period to get the 24 hr.-period CO personal and area average concentrations measured in ppm (parts per million). Each of the carbon monoxide monitors used were corrected for their experimental correction factor—these calibration correction factors were found experimentally in the lab setting prior to using the monitors. See Appendix B for Carbon Monoxide correction factors.

Particulate Matter ($PM_{2.5}$) measurements were calculated using the net mass (measured in mg) gained in the Teflon filters (the difference between the mass prior to the study period and after the study period). The net mass values for filters were corrected for by the average net mass of the field blank filters—see Appendix *C* for field blank masses. To convert the net mass to a particulate matter concentration (μg /m^3), the following equation was used:

$$\frac{Mass\ of\ Filter \times 1000}{\frac{Pump\ Duration \times Pump\ Rate}{1000}} \qquad (1)$$

The pump duration (min) is the length of time that the pump was turned on, typically 240 minutes for the area pumps and 1440 min for the personal pumps. The pump rate (L/min) is the rate at which is air flowed into the filter, typically around 2 L/min for both the area and personal pumps. The $PM_{2.5}$ data proved to be problematic because there were negative concentrations and negative net gain in mass. Negative concentrations follow from negative masses as evident from equation (1). The second issue may be attributed to an error in weighing the filters. Additionally, personal $PM_{2.5}$ concentrations were larger than respective area $PM_{2.5}$ concentrations for certain households. To attempt to understand these varying values, the amount of black carbon (BC) in each filter was estimated using a Nexleaf algorithm, which takes a photo of the filter as an input and outputs the amount of black carbon that was in the air. The concentrations of BC (μg /m^3), were calculated the same ways at the $PM_{2.5}$.

Baseline characteristics

Initial data analysis was done to understand the variability of the particle concentrations of interest—area and personal $PM_{2.5}$ concentrations, area and personal CO concentrations, and area and personal BC concentrations. A t-test was done to identify the significance of the difference of means between area and personal concentrations. Additionally, initial plotting was completed to show the relationship between area and personal concentrations for CO, BC, and $PM_{2.5}$.

Using the cook and household survey data as well as relevant literature, certain parameters were chosen as a test to explain household air pollution exposures. These parameters include moisture content, fuel quantity, fuel type, stove type, income quintiles, household size, ventilation, and cooking experience. Moisture content (%) was obtained using an Ohaus MB23 Moisture Analyzer (Parsippany, NJ). The fuel quantity was calculated as the the sum of difference in the amount of fuel at the beginning and end of the 24 hr study period and the amount of fuel added in the study period. Fuel type is a categorical variable taking the value of 0 for low quality fuel wood, and 1 for high quality fuel wood. Stove type is a categorical variable taking the value of 0 for a 3 stone (traditional stove) and 1 for a non-traditional stove. Income quintile is a categorical variable taking the value of 0 for the lowest income bracket and 5 for the highest income bracket of the subset of households. Household size refers to the number of adult equivalents in each household—coded as 1 for each adult and 0.5 for each child. Ventilation is a categorical variable that takes the value of 0 for poorly ventilated kitchens and 1 for well ventilated kitchens—typically those with more windows and doors or those outdoors. Cooking experience is a continuous variable that refers to the number of years of cooking experience the primary cook has had in any household. T-tests and regressions were performed to see the significance of the relationship between each pollutant concentration and parameter.

Multivariable Regression Analysis

Multivariate regression model using STATA 12.1 was completed to identify which determinants (parameters) of exposure influence particle concentrations. The dependent variables of interest include the personal and area particulate matter concentrations, the personal and area carbon monoxide concentrations, and the personal and area black carbon concentrations. The independent variables – the determinants for household exposure—are the aforementioned parameters found from the household and cooking data.

$$Y_i = \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_p X_{ip} + \varepsilon_i$$

A multivariable regression model of this form is as shown above where Y_i is the dependent variable of interest, and X_{ip} are the independent variables with coefficients β_p for the *i*th observation. Each regression model also contains an error constant: ε_i.

Results

Table 1: Descriptive statistics for dependent variables

	Mean	Std. Dev	CV	Min	Max	Median	N
Area $PM_{2.5}$ (µg/m^3)	1502	2162	144%	2	11839	747	99
Personal $PM_{2.5}$ (µg/m^3)	407	277	68%	36	1830	361	96
Area CO (ppm)	22.8	23.6	103%	0.5	113.4	16.8	105
Personal CO (ppm)	2.7	1.9	73%	0.3	10.3	2.2	103
Area BC (µg/m^3)	104.8	72.1	69%	6.6	271.5	81.0	60
Personal BC (µg/m^3)	13.8	7.4	53%	6.3	43.9	11.0	85

Table 1 shows the mean, standard deviation, the coefficient of variance, minimum, maximum, medium and sample size of the set of air pollutant concentrations. The sample size (N) of Table 1, is lower than the number of households in the subset (108) due to the removal of outliers. Large outliers within the subsets of personal and area concentrations $PM_{2.5}$ were removed. Low-concentration filters of BC have biased estimates of BC mass because the study used Teflon filters instead of Quartz (which is the type of filter the Nexleaf algorithm is based on). Additionally, these filters drove the average ratio of BC to $PM_{2.5}$ ratios up. Subsequently, data was omitted when the BC mass was less than 0.0176 mg—or 150% of the blank filters average mass (0.0117 mg). Removing the low-mass filters stabilized the calculated average BC to $PM_{2.5}$ ratios for area and personal exposures. To view descriptive statistics for the original full data set, see Appendix D.

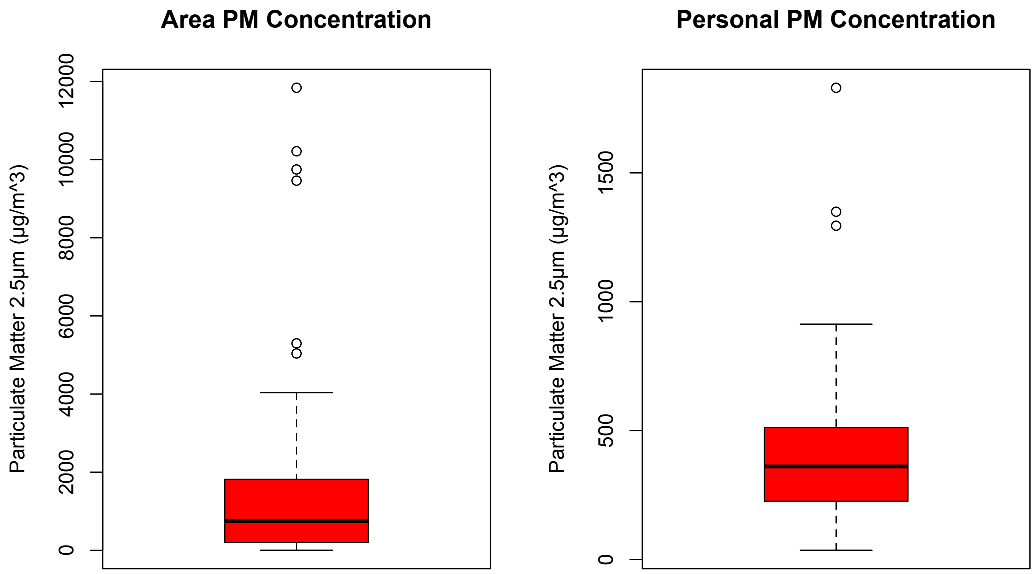


Figure 1: Graphical representation of the variability of $PM_{2.5}$ concentrations

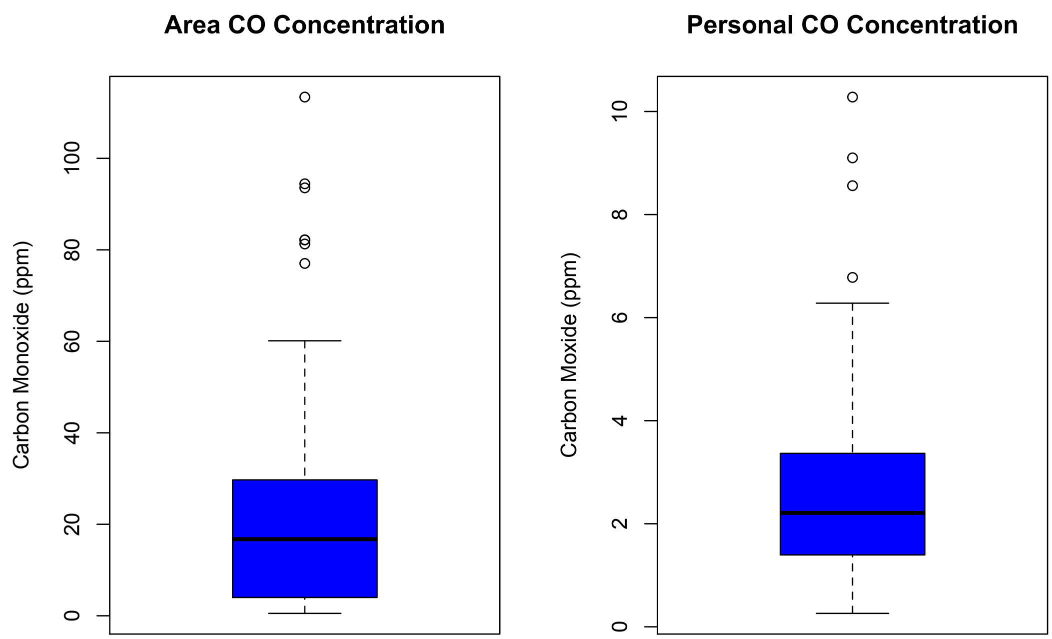


Figure 2: Graphical representation of the variability of CO concentrations

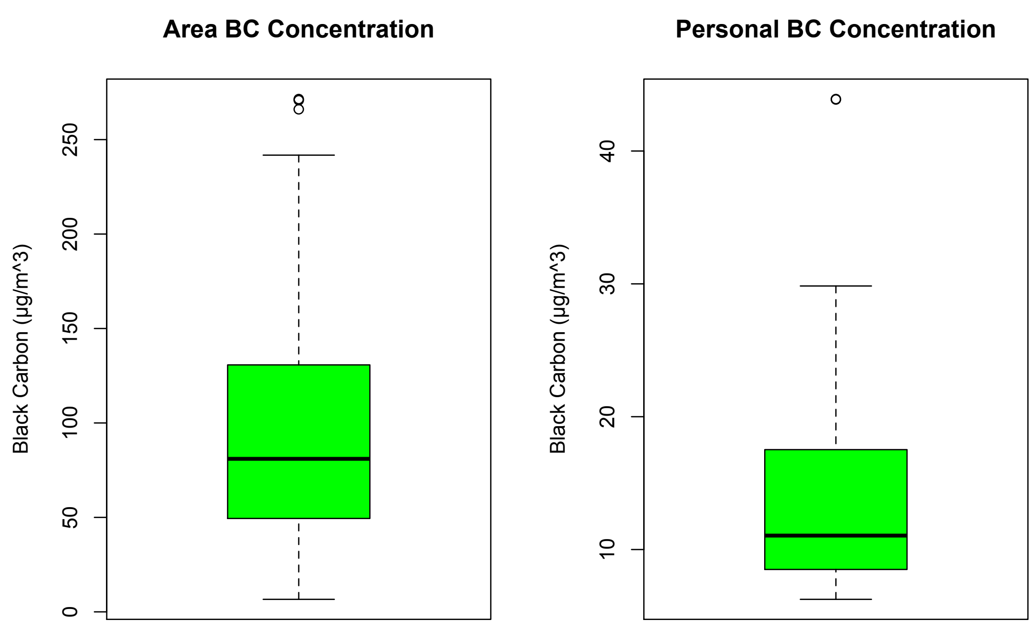


Figure 3: Graphical representation of the variability of BC concentrations

Figures 2, 3, and 4 above show boxplots of the area $PM_{2.5}$ concentration, area CO concentration, area BC concentration, personal $PM_{2.5}$ concentration, personal CO concentration, and personal BC concentration. These plots depict the spread of the distribution of each concentration subset by dividing each data point into its respective quartiles. The "whiskers" of each plot represent the 95% CI and the thick dark line represents the mean of the concentrations. Comparing the difference in means of the area and personal concentrations of $PM_{2.5}$, CO, BC shows that the difference is very statistically significant—the 95% confidence intervals do not overlap.

Relative to the WHO standards for $PM_{2.5}$ exposure guidelines—mean concentration of 24-hour period should not exceed 25 $\mu g/m^3$—the 95% CI of both the personal and area concentrations lie above this threshold. Similarly, the EPA National Ambient Air Quality Standards for $PM_{2.5}$ exposure guidelines—mean concentration of 24-hour period should not exceed 35 $\mu g/m^3$—our data lies above this as well. Relative to the WHO standards for CO exposure guidelines—mean concentration of 24 hour period should not exceed 7 mg/m^3 or 6.11 ppm—the 95% CI of personal and area concentrations of CO contains this threshold. However, the personal concentrations are closer in value to the mean WHO threshold.

- Personal PM and area PM relationship is statistically significant at the p(<0.05) level. R^2 value was 0.060.
- Area CO and personal Co are statistically significant at the ($p<0.001$) level R^2 value was 0.109.
- Area BC and personal BC are statistically significant at the ($p<0.05$) level R^2 value was 0.112

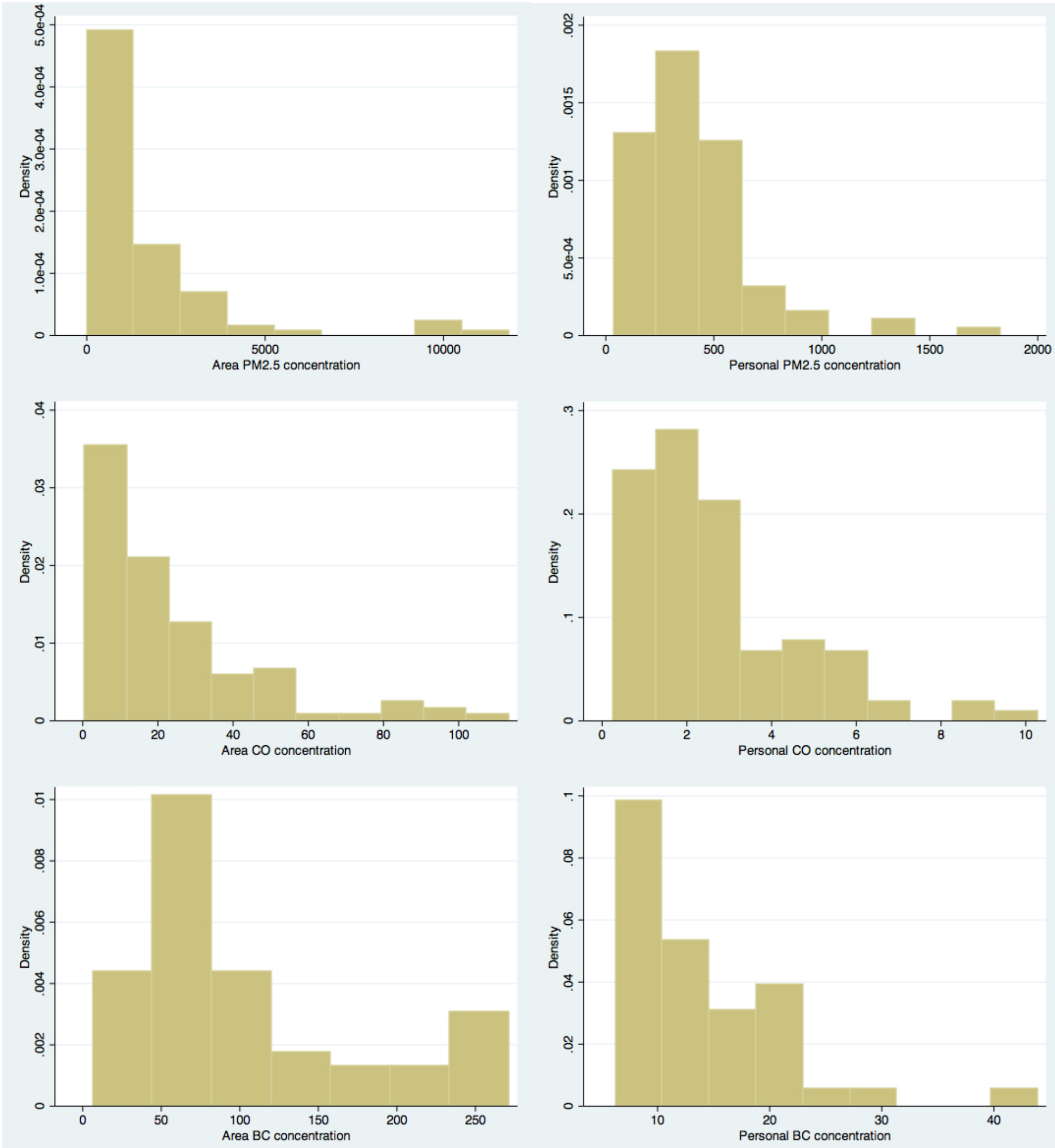


Figure 4: Descriptive statistics for dependent variables (histogram distributions)

Figure 3 above shows the distributions of area $PM_{2.5}$ concentration, personal $PM_{2.5}$ concentration, area CO concentration, personal CO concentration, area BC concentration, and personal BC concentration. Looking at these plots, each particle concentration subset follows a log normal distribution. Therefore, a log transformation of each specific particle concentration will closely follow a normal distribution. These log-transformed subsets are used for the multivariate regression analysis. A table of descriptive statistics for the log-transformed values can be seen in the Appendix.

Profile of study populations

Table 2: Descriptive statistics for categorical independent variables

	N	% of subset
Stove type	108	
0 = traditional 3 stone	96	88.9%
1 = non-traditional	12	11.1%
Fuel type	105	
0 = low quality fuel wood	25	23.8%
1 = high quality fuel wood	80	76.2%
Ventilation	107	
0 = poorly ventilated	30	28.1%
1 = well ventilated	77	78.5%

Table 2 describes the sample size N and percentage of subset for the categorical independent variables for the multivariate regression model including stove type, fuel type, and ventilation. The subset of households in the study, had 88.9% traditional 3-stone stoves, 76.2% use of high quality fuel, and 78.5% had well ventilated kitchen.

Table 3: Comparison of means test for categorical independent variables

	Area $PM_{2.5}$ Conc. (μg/m^3)	**Personal $PM_{2.5}$ Conc. (μg/m^3)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. (μg/m^3)**	**Personal BC Conc. (μg/m^3)**
Stove type						
0 = 3 stone traditional	1544 (2272)	396 (276)	21.3 (22.7)	2.6 (1.8)	100.4 (70.8)	13.7 (7.5)
1 = non-traditional	1166 (872)	493 (276)	35.0 (27.8)	3.6 (2.5)	152.4 (76.3)	14.5 (5.8)
Fuel type						

0 = low quality fuel wood	1399 (2232)	424 (399)	19.3 (24.0)	2.2 (1.3)	95.3 (67.3)	12.9 (8.1)
1 = high quality fuel wood	1531 (2166)	405 (227)	24.1 (23.8)	2.8 (2.0)	106.4 (70.0)	14.1 (7.3)
Ventilation						
0 = poorly ventilated	1130 (1043)	411 (289)	26.3 (27.3)	3.0 (1.9)	105.0 (64.1)	16.3 (9.6)
1 = well ventilated	1623 (2394)	409 (276)	22.0 (22.7)	2.6 (1.9)	105.1 (75.8)	13.0 (6.5)

Significance of difference of means based on t test of unequal variance Pr (T>t)
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

Table 4 above shows the means for the categorical independent variables in the multivariate regression model including stove type, fuel type, and ventilation. In addition, the significance for the difference of means (assuming unequal variances) of each subset is noted in the categorical variable heading. There was no significant difference between the mean values of the categorical variable, meaning that the 95% CI of each coded value of the categorical variable (i.e. 0 or 1) significantly overlapped.

Table 4: Descriptive statistics for continuous independent variables

	Mean	Std. Dev	CV	Min	Max	Median	N
Moisture content (%)	11.4	6.4	56%	1.4	43.4	9.9	106
Fuel quantity (kgs)	17.5	19.8	113%	0.5	159.9	12.6	106
Household Size (# adult equivalents)	4.5	2.0	44%	1	11	4	107
Fuel quantity by household size (kgs/ adult equiv)	4.5	7.9	176%	0.2	80.0	3.1	105
Cooking experience (years)	25.0	14.7	59%	1	67	24	107

Table 4 above shows the mean, standard deviation, the coefficient of variance, minimum, maximum, medium and sample size of each continuous independent variable of interest—moisture content, fuel quantity, household size, fuel quantity by household size, and cooking experience.

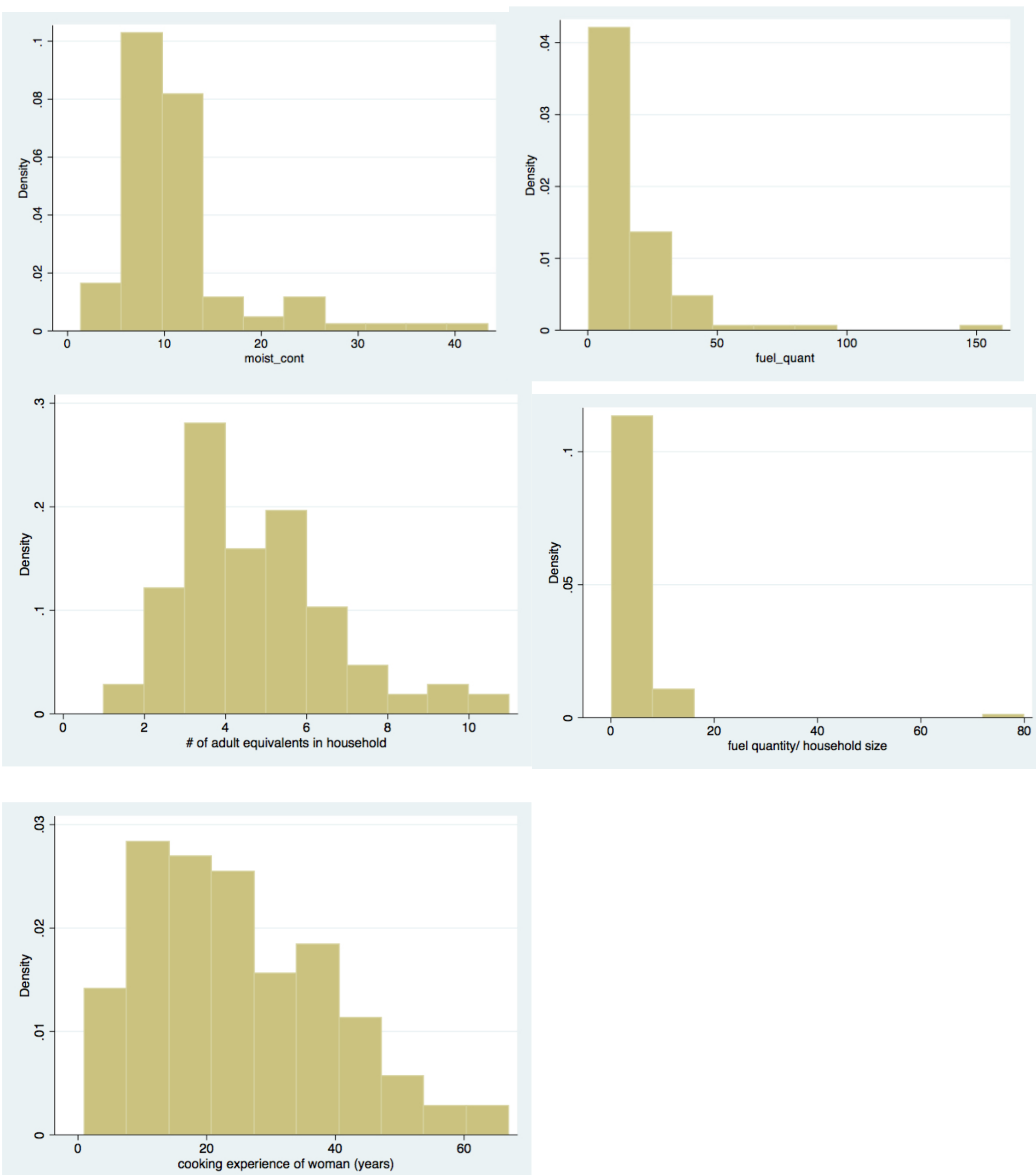


Figure 5: Histogram distributions for continuous independent variables

The figures above show the distributions of the continuous independent variables (from left to right, top to bottom) moisture content (%), fuel quantity (kgs), household size (# adult equivalents), fuel quantity by household size, and cooking experience (years). Looking at these plots, each particle concentration subset follows a log normal distribution. A log transformation of each independent variable will closely follow a normal distribution. Therefore, when completing the multi-regression analysis, the log-transformed values will be used.

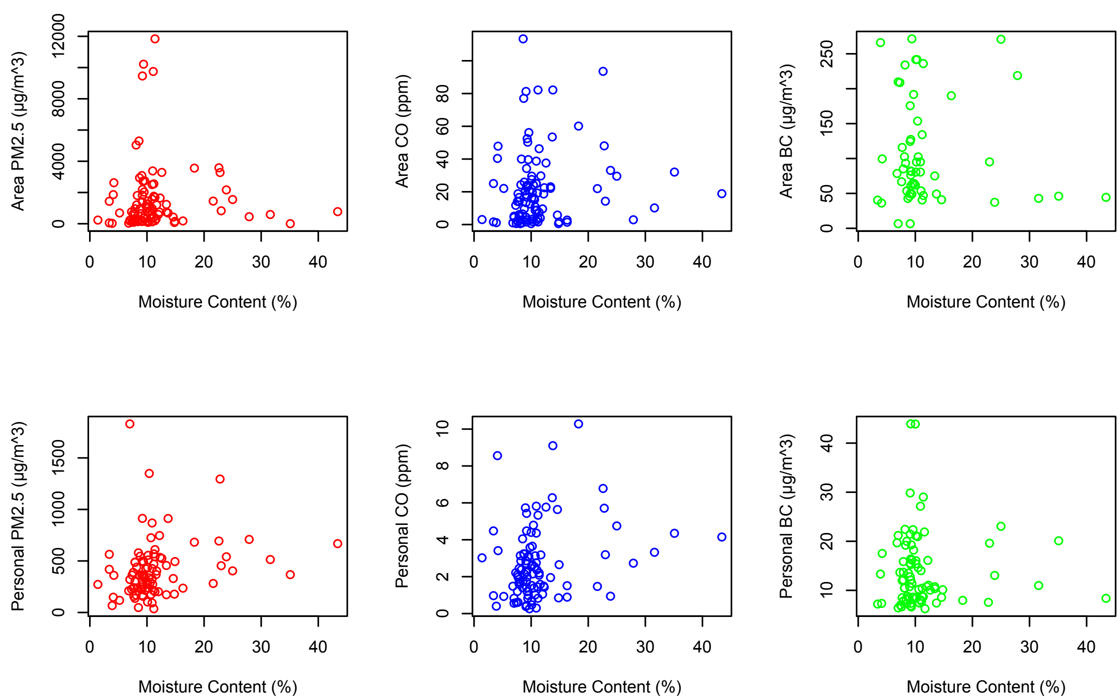


Figure 6. Dependence of particle concentrations on moisture content

The figures above show plots of the area $PM_{2.5}$ concentration, area CO concentration, area BC concentration, personal $PM_{2.5}$ concentration, personal CO concentration, and personal BC concentration as a function of moisture content. Basic correlation testing found a statistically significant relationship between moisture content and personal $PM_{3.5}$ concentrations as well as with personal CO concentrations at the p(<0.05) level.

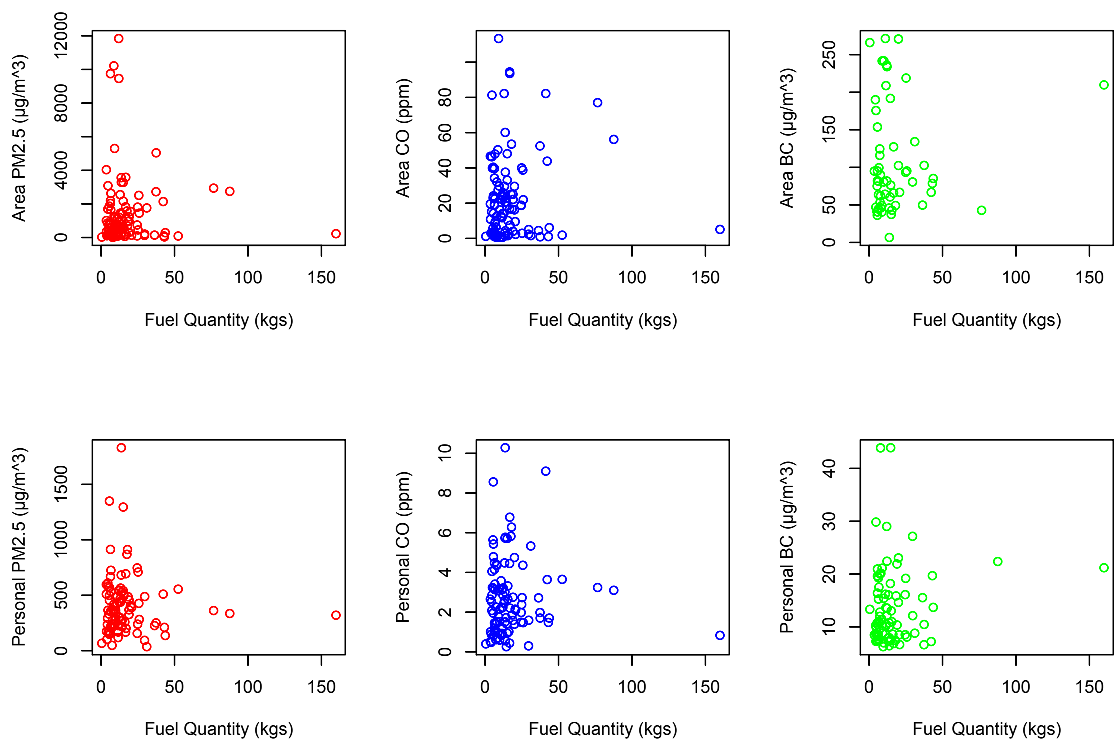


Figure 7: Dependence of particle concentrations on fuel quantity

The figures above show plots of the area $PM_{2.5}$ concentration, area CO concentration, area BC concentration, personal $PM_{2.5}$ concentration, personal CO concentration, and personal BC concentration as a function of fuel quantity. Basic correlation testing between exposures and fuel quantity found no significant relationship for any of the six measured exposures.

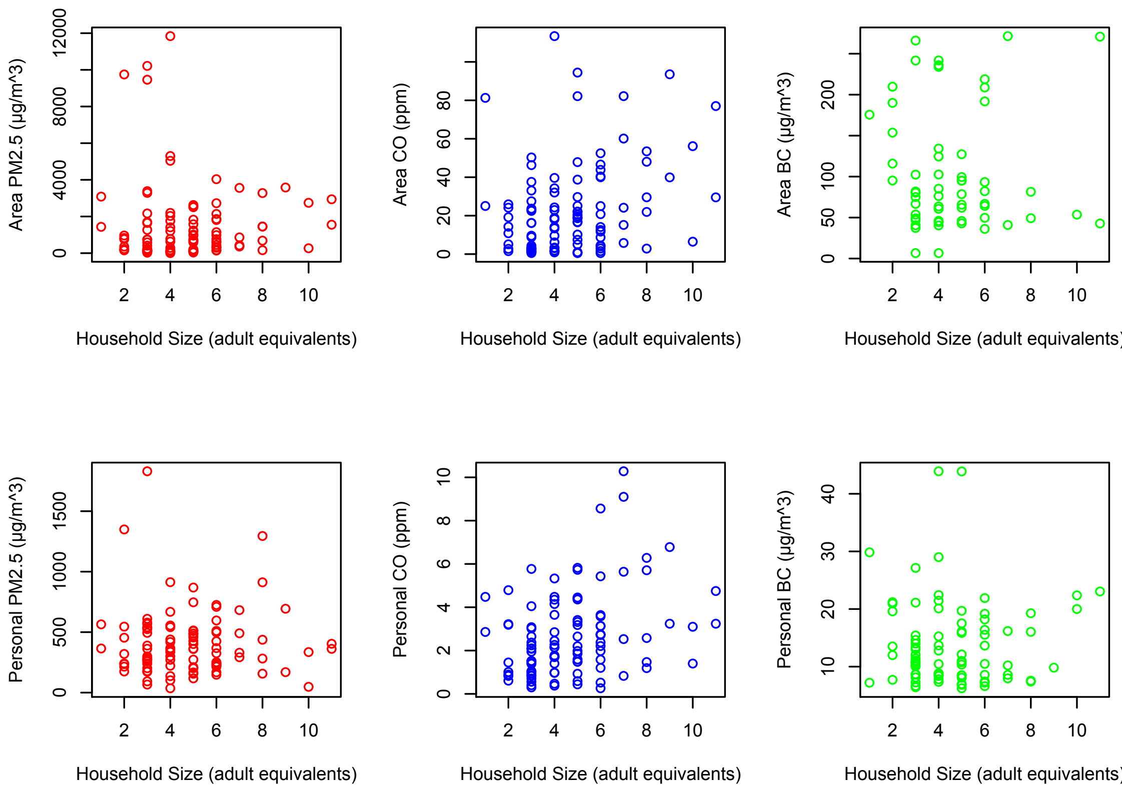


Figure 8: Dependence of particle concentrations on household size

The figures above show plots of the area $PM_{2.5}$ concentration, area CO concentration, area BC concentration, personal $PM_{2.5}$ concentration, personal CO concentration, and personal BC concentration as a function of household size. Basic correlation testing found a statistically significant relationship between household size and area and personal CO concentrations at the p(<0.01) level.

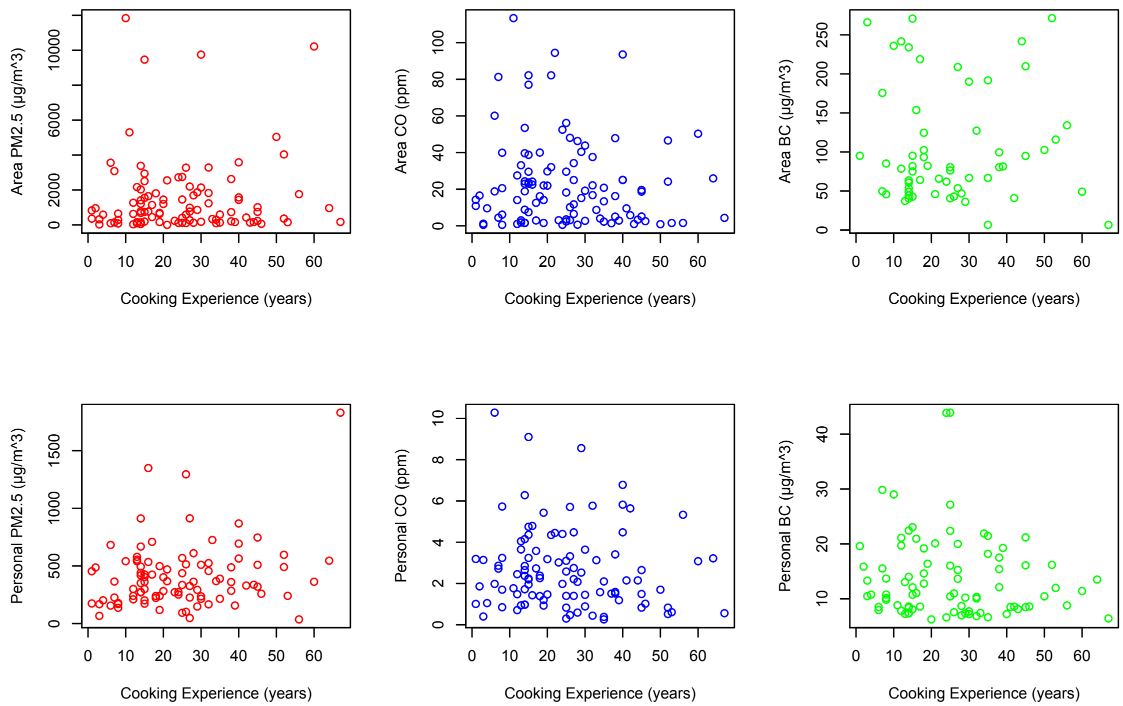


Figure 9 Dependence of particle concentrations on moisture cooking experience

The figures above show plots of the area $PM_{2.5}$ concentration, area CO concentration, area BC concentration, personal $PM_{2.5}$ concentration, personal CO concentration, and personal BC concentration as a function of cooking experience. Basic correlation testing found a statistically significant relationship between cooking experience size and personal $PM_{2.5}$ concentrations at the p(<0.05) level.

Regression Analysis

Table 5: Multivariate regression analysis using stove type, fuel type, fuel quantity, ventilation, and moisture content as inputs. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models.

	Area $PM_{2.5}$ Conc. ($\mu g/m^3$)	**Personal $PM_{2.5}$ Conc. ($\mu g/m^3$)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. ($\mu g/m^3$)**	**Personal BC Conc. ($\mu g/m^3$)**

Stove type (1= non-traditional)	0.372 (0.48)	0.229 (0.21)	0.823 * (0.42)	0.220 (0.24)	0.442 (0.34)	0.008 (0.19)
Moisture content (%)	0.132 (0.32)	0.301 ** (0.14)	0.374 (0.29)	0.218 (0.16)	0.031 (0.20)	0.070 (0.13)
Fuel type (1 = high quality fuel wood)	0.117 (0.37)	0.026 (0.17)	0.236 (0.34)	0.222 (0.19)	0.189 (0.24)	0.089 (0.12)
Fuel quantity (kg)	-0.025 (0.22)	-0.041 (0.10)	-0.057 (0.20)	-0.002 (0.11)	0.035 (0.13)	0.087 (0.08)
Ventilation (1= well ventilated)	-0.136 (0.37)	-0.015 (0.16)	-0.213 (0.34)	-0.223 (0.19)	-0.071 (0.23)	-0.251 * (0.13)
Error Constant	6.189 (0.96)	5.193 (0.43)	1.572 (0.88)	0.222 (0.49)	4.154 (0.62)	2.252 (0.38)
R^2 value	0.0134	0.0708	0.0749	0.0647	0.0573	0.0766

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

Looking at the first regression in Table 5, using stove type, fuel most used, fuel quantity, ventilation, and moisture content as inputs, the model demonstrates that use of a non-traditional stove has a positive and weakly significant effect on area CO exposures. Moisture content has a positive and significant effect on personal $PM_{2.5}$ exposures; therefore, as moisture content increases so does the exposure concentration. Improved ventilation has a negative and weakly significant effect on personal BC exposures.

Table 6: Multivariate regression analysis using stove type, fuel type, fuel quantity, household size, ventilation, and moisture content as inputs. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models.

	Area $PM_{2.5}$ Conc. (μg/m^3)	**Personal $PM_{2.5}$ Conc. (μg/m^3)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. (μg/m^3)**	**Personal BC Conc. (μg/m^3)**
Stove type (1= non-traditional)	0.357 (0.48)	0.249 (0.22)	0.757* (0.43)	0.149 (0.24)	0.581 (0.36)	0.031 (0.20)

Moisture content (%)	0.119 (0.32)	0.319** (0.15)	0.323 (0.29)	0.165 (0.16)	0.033 (0.20)	0.086 (0.13)
Fuel type (1 = high quality fuel wood)	0.099 (0.38)	0.051 (0.17)	0.167 (0.35)	0.152 (0.19)	0.229 (0.24)	0.103 (0.13)
Fuel quantity (kg)	-0.037 (0.22)	-0.023 (0.10)	-0.107 (0.20)	-0.054 (0.11)	0.057 (0.13)	0.092 (0.079)
Ventilation (1= well ventilated)	-0.136 (0.37)	-0.015 (0.16)	-0.209 (0.34)	-0.218 (0.19)	-0.021 (0.23)	-0.246* (0.13)
Household size (# adult equivalents)	0.083 (0.36)	-0.117 (0.16)	0.353 (0.33)	0.368** (0.18)	-0.289 (0.23)	-0.062 (0.13)
Error Constant	6.147 (0.98)	5.251 (0.44)	1.380 (0.89)	0.019 (0.49)	4.411 (0.65)	2.283 (0.39)
R^2 value	0.0140	0.0768	0.0870	0.1088	0.0883	0.0797

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

Table 6's model looked at the influence adding household size to the original list of determinants. This model finds that household size has a positive and significant effect and personal CO exposures, meaning that the increase in the number of adult equivalents in a household corresponds to an increase in personal CO exposures. A similar model was run considering fuel quantity as a function of household size, but found no statistically significant effect (See Appendix).

Table 7: Multivariate regression analysis using stove type, fuel type, fuel quantity, household size, ventilation, income quintiles, and moisture content as inputs. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models. The coefficients and significance for the income quintiles are relative to the base 1 quintile.

	Area $PM_{2.5}$ Conc. (µg/m^3)	**Personal $PM_{2.5}$ Conc. (µg/m^3)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. (µg/m^3)**	**Personal BC Conc. (µg/m^3)**

Stove type (1= non-traditional)	0.230 (0.48)	0.293 (0.22)	0.779* (0.43)	0.150 (0.24)	0.594 (0.38)	0.049 (0.20)
Moisture content (%)	0.066 (0.32)	0.312* (0.15)	0.259 (0.30)	0.149 (0.16)	0.052 (0.21)	0.087 (0.14)
Fuel type (1 = high quality fuel wood)	0.028 (0.39)	0.021 (0.17)	0.003 (0.36)	0.098 (0.20)	0.247 (0.24)	0.101 (0.14)
Fuel quantity (kg)	0.001 (0.22)	-0.0342 (0.11)	-0.078 (0.21)	-0.009 (0.12)	0.033 (0.14)	0.083 (0.08)
Ventilation (1= well ventilated)	-0.005 (0.37)	-0.053 (0.17)	-0.233 (0.34)	-0.232 (0.19)	0.013 (0.25)	-0.252* (0.14)
Household size (# adult equivalents)	0.236 (0.36)	-0.114 (0.17)	0.467 (0.34)	0.406** (0.19)	-0.265 (0.25)	-0.063 (0.13)
Income quintiles						
2	-1.013* (0.52)	0.202 (0.25)	-0.292 (0.46)	-0.353 (0.25)	-0.0284 (0.33)	0.064 (0.19)
3	-0.743 (0.48)	0.113 (0.22)	-0.500 (0.44)	-0.187 (0.24)	0.092 (0.31)	0.16 (0.16)
4	-1.257*** (0.48)	0.251 (0.23)	-0.091 (0.45)	0.0202 (0.24)	-0.286 (0.31)	0.072 (0.16)
5	-1.059** (0.49)	0.061 (0.24)	-0.687 (0.46)	-0.322 (0.26)	-0.041 (0.33)	0.039 (0.18)
Error Constant	6.746 (0.99)	5.211 (0.46)	1.751 (0.94)	0.102 (0.51)	4.406 (0.71)	2.242 (0.40)
R^2 value	0.1045	0.0945	0.1190	0.1491	0.1201	0.0934

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

The regression in Table 7 adds income quintile to the list of determinants. The multivariate regression was calculated based on the income quintile 1 (the lowest income bracket). With respect to quintile 1, quintile 5 (the highest income bracket) has a negative and significant effect on area $PM_{2.5}$ concentrations; quintile 2 has a negative and weakly significant effect on area $PM_{2.5}$ concentrations; and quintile 4 has a negative and very significant effect on area $PM_{2.5}$ concentrations.

Table 8: Multivariate regression analysis using stove type, moisture content, ventilation, household size, and income quintiles. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models. The coefficients and significance for the income quintiles are relative to the base 1 quintile.

	Area $PM_{2.5}$ Conc. (μg/m^3)	**Personal $PM_{2.5}$ Conc. (μg/m^3)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. (μg/m^3)**	**Personal BC Conc. (μg/m^3)**
Stove type (1= non-traditional)	0.242 (0.48)	0.301 (0.22)	0.763* (0.42)	0.152 (0.25)	0.623 (0.38)	0.060 (0.19)
Moisture content (%)	0.180 (0.31)	0.360** (0.14)	0.326 (0.29)	0.206 (0.16)	0.012 (0.21)	0.043 (0.13)
Ventilation (1= well ventilated)	-0.008 (0.36)	-0.079 (0.17)	-0.249 (0.33)	-0.251 (0.19)	0.033 (0.25)	-0.222* (0.13)
Household size (# adult equivalents)	0.242 (0.33)	-0.101 (0.15)	0.421 (0.31)	0.421** (0.17)	-0.257 (0.25)	-0.017 (0.12)
Income quintiles						
2	-0.937* (0.49)	0.211 (0.23)	-0.232 (0.46)	-0.278 (0.24)	0.008 (0.33)	0.078 (0.18)
3	-0.790* (0.47)	0.111 (0.22)	-0.465 (0.44)	-0.272 (0.24)	-0.109 (0.31)	0.19 (0.16)
4	-1.301*** (0.47)	0.260 (0.22)	-0.073 (0.45)	0.023 (0.24)	-0.244 (0.31)	0.057 (0.16)
5	-1.222** (0.47)	-0.005 (0.22)	-0.718 (0.43)	-0.401 (0.25)	0.066 (0.35)	0.006 (0.17)
Error Constant	6.542 (0.88)	5.027 (0.41)	1.470 (0.81)	0.020 (0.46)	4.767 (0.67)	2.549 (0.34)
R^2 value	0.1180	0.1197	0.1273	0.1552	0.0744	0.0647

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

The regression in Table 7 considers only the independent variables those statistically significant effects on the dependent variables. This model shows that moisture content has a positive and statistically significant effect on personal $PM_{2.5}$ concentrations. The use of a non-traditional stove has a positive and weakly significant effect on area CO concentrations. With respect to income quintile 1, quintile 5 (the highest income bracket) has a negative and significant effect on area $PM_{2.5}$ concentrations; quintile 2 has a negative and weakly significant effect on area $PM_{2.5}$ concentrations; quintile 3 has a negative and weakly significant effect on area $PM_{2.5}$ concentrations; and quintile 4 has a negative and very significant effect on area $PM_{2.5}$ concentrations. Household size has a positive and significant effect on personal CO concentrations. A well-ventilated kitchen has a negative and weakly significant effect on personal BC exposures.

Discussion

This study attempts to identify determinants of exposure for household air pollution by quantitatively associating survey—household and cook—data with area and personal concentrations of CO, $PM_{2.5}$, and BC. Determinants of interest in the study include fuel quantity, fuel type, stove type, ventilation, moisture content, income quintile, cooking experience, and household size. Using different combinations of the aforementioned determinants, multivariate regression analysis is done to best explain the variance of household air pollutant concentrations the best.

Although the sample size of the study was large (N = 108), there was a plethora of missing values for each variable; therefore, the results can be accurately extrapolated to other geographical areas or population. However, these results have implications for improving health outcomes as they relate to concentrations of personal particulate matter and black carbon. By targeting interventions and mitigation strategies in the subset of households on reducing moisture content and improving ventilation within the cooking environment—there could be potential reductions in particle concentrations. The subsequent decrease in concentrations could reduce adverse health effects such as respiratory illness in the main cooks/women of the households. In addition, the overall positive (but only relatively significant effect on personal $PM_{2.5}$ concentrations) of using a non-traditional stove demonstrates that the existing infrastructure for “improved” or stoves that are not 3 stone, may not have the intended effect of reducing pollutant concentrations.

The regression models run did not find a statistically significant effect of fuel type on particle concentrations. Balakrishnan et al. 2002 and Hu et. al, 2004 both found that fuel type was one of the main determinants of exposure. Perhaps the reason for lack of statistically significance, is the subset of households used in the data analysis were not

Future studies should address seasonal variation of exposure and explore other determinants of exposure. There are three distinct seasons in Malawi (wet, dry, and cold) that may alter cooking practices such as cooking indoors vs. outdoors as well as the presence of fuel source. Additionally, the change in season may influence the moisture content of the fuel and storing mechanisms. To better characterize personal exposures—especially the time spent way from cooking—future studies can incorporate time activity association especially for $PM_{2.5}$ exposures.

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Appendix

A. List of all carbon monoxide monitor triplicates

Household ID	Area Avg	Area Max	Area Min	Pers Avg	Pers Max	Pers Min
141	2.0	53.6	0.0	0.3	75.3	0.0
141	3.3	63.1	0.0	0.3	75.3	0.0
141	1.8	53.9	0.0	0.3	75.3	0.0
Average	**2.4**	**56.9**	**0.0**	**0.3**	**75.3**	**0.0**

440	7.5	130.0	0.0	2.4	75.2	0.0
440	8.9	117.0	0.0	2.4	75.2	0.0
440	10.1	146.4	0.0	2.4	75.2	0.0
Average	**8.8**	**131.1**	**0.0**	**2.4**	**75.2**	**0.0**
335	9.6	74.5	1.0	3.1	153.6	0.0
335	8.4	81.6	0.0	3.1	153.6	0.0
335	8.1	62.7	0.0	3.1	153.6	0.0
Average	**8.7**	**72.9**	**0.0**	**3.1**	**153.6**	**0.0**
161	22.2	167.2	0.0	1.9	127.1	0.0
161	21.7	178.5	0.0	1.9	127.1	0.0
161	25.3	174.1	0.0	1.9	127.1	0.0
Average	**23.1**	**173.3**	**0.0**	**1.9**	**127.1**	**0.0**
303	96.9	400.5	0.0	6.8	329.6	0.0
303	92.2	395.0	0.0	6.8	329.6	0.0
303	91.5	443.1	0.0	6.8	329.6	0.0
Average	**93.6**	**412.9**	**0.0**	**6.8**	**329.6**	**0.0**
277	46.1	230.0	0.0	0.5	107.8	0.0
277	48.7	242.9	0.0	0.5	107.8	0.0
277	45.0	217.8	0.0	0.5	107.8	0.0
Average	**46.6**	**230.2**	**0.0**	**0.5**	**107.8**	**0.0**
205	3.3	56.6	0.0	2.7	62.6	0.0
205	2.6	55.7	0.0	2.7	62.6	0.0
Average	**2.9**	**56.1**	**0.0**	**2.7**	**62.6**	**0.0**
222	1.4	70.7	0.0	2.7	195.3	0.0
222	1.4	49.1	0.0	2.7	195.3	0.0
222	1.8	63.7	0.0	2.7	195.3	0.0
Average	**1.6**	**61.1**	**0.0**	**2.7**	**195.3**	**0.0**

B. Calibration factors of carbon monoxide (CO) Monitors

Monitor Serial Number	Correction factor
12248	1.028370288
12306	1.060630508
12354	1.006566742
12451	0.981310826
12483	1.045800826
12488	1.020449593
12514	1.009032944
12529	1.019597315
12534	1.002669326
12554	1.020845777
12557	1.011870578
12558	1.041816519
12563	1.024578862
12570	1.009420311

12575	1.003876652
12591	1.032626427
12592	0.971935511
12714	1.07106599
12757	1.081332448
127456	1.088529393

C. Filter Blank values

Date Deployed	Filter Mass (ug)
N/A	0.003
10/24/13	0.005
11/8/13	0.026
11/15/13	0.002
11/19/13	0.007
11/24/13	-0.001

D. Descriptive statistics for dependent variables: The table below shows the mean, standard deviation, the coefficient of variance, minimum, maximum, medium and sample size of the set of air pollutant concentrations without outliers removed.

	Mean	Std. Dev	CV	Min	Max	Median	N
Area $PM_{2.5}$ (μg/m^3)	1771	3308	187%	2	26879	754	102
Personal $PM_{2.5}$ (μg/m^3)	438	477	109%	4	4250	360	99
Area	22.8	23.6	103%	0.5	113.4	16.8	105

CO (ppm)							
Personal CO (ppm)	2.7	1.9	73%	0.3	10.3	2.2	103
Area BC (μg/m³)	80.5	75.9	94%	0.0	406.0	49.1	99
Personal BC (μg/m³)	12.8	7.6	59%	0.0	43.9	10.5	96

E. Descriptive statistics for dependent variables based on logarithmic transformation distribution The table below shows the mean, standard deviation, the coefficient of variance, minimum, maximum, medium and sample size of the set of air pollutant concentrations.

	Mean	Std. Dev	Min	Max	Median	N
Area $PM_{2.5}$ (μg/m³)	6.46	1.47	0.88	9.4	6.62	99
Personal $PM_{2.5}$ (μg/m³)	5.81	0.66	3.58	7.51	5.89	96
Area CO (ppm)	2.45	1.36	-0.66	4.63	2.81	105
Personal CO (ppm)	0.72	0.78	-1.33	2.33	0.79	103
Area BC (μg/m³)	4.41	0.76	1.89	5.60	4.40	60
Personal BC (μg/m³)	2.51	0.46	1.83	3.78	2.40	85

F: Multivariate regression analysis using stove type, fuel type, fuel quantity by household size, ventilation, and moisture content as inputs. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models.

	Area $PM_{2.5}$ Conc. (μg/m³)	Personal $PM_{2.5}$ Conc. (μg/m³)	Area CO Conc. (ppm)	Personal CO Conc. (ppm)	Area BC Conc. (μg/m³)	Personal BC Conc. (μg/m³)

Stove type (1= non-traditional)	0.367 (0.47)	0.217 (0.21)	0.822* (0.42)	0.234 (0.24)	0.465 (0.34)	0.043 (0.19)
Moisture content (%)	0.123 (0.32)	0.308** (0.14)	0.340 (0.29)	0.186 (0.16)	0.044 (0.20)	0.088 (0.13)
Fuel quantity by household size (kgs/ adult equiv)	-0.047 (0.21)	0.008 (0.09)	-0.163 (0.19)	-0.125 (0.10)	0.107 (0.12)	0.084 (0.07)
Fuel_type (1 = high quality fuel wood)	0.114 (0.36)	0.007 (0.16)	0.244 (0.33)	0.249 (0.18)	0.182 (0.23)	0.111 (0.12)
Ventilation (1= well ventilated)	-0.134 (0.37)	-0.021 (0.16)	-0.198 (0.33)	-0.206 (0.19)	-0.059 (0.23)	-0.243* (0.13)
Error Constant	6.201 (0.87)	5.085 (0.39)	1.674 (0.79)	0.400 (0.44)	4.084 (0.55)	2.318 (0.35)
R^2 value	0.0138	0.0689	0.0817	0.0799	0.0714	0.0791

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)

G. Multivariate regression analysis using stove type, fuel type, fuel quantity, household size, ventilation, cooking experience, income quintiles, and moisture content as inputs. The table below shows the coefficient, standard error, and the level of significance for each species' multivariate regression models. The coefficients and significance for the income quintiles are relative to the base 1 quintile.

	Area $PM_{2.5}$ Conc. (µg/m^3)	**Personal $PM_{2.5}$ Conc. (µg/m^3)**	**Area CO Conc. (ppm)**	**Personal CO Conc. (ppm)**	**Area BC Conc. (µg/m^3)**	**Personal BC Conc. (µg/m^3)**
Stove type (1= non-traditional)	0.299 (0.48)	0.258 (0.21)	0.771* (0.43)	0.160 (0.25)	0.522 (0.38)	0.041 (0.21)
Moisture content (%)	0.021 (0.33)	0.300** (0.15)	0.223 (0.30)	0.125 (0.17)	0.097 (0.22)	0.062 (0.14)
Fuel type (1 = high quality fuel wood)	0.015 (0.38)	-0.025 (0.17)	0.124 (0.35)	0.114 (0.20)	0.272 (0.25)	0.084 (0.14)
Fuel quantity (kg)	-0.012 (0.22)	-0.015 (0.10)	-0.087 (0.20)	-0.036 (0.12)	0.107 (0.14)	0.092 (0.09)

Ventilation (1= well ventilated)	-0.205 (0.36)	0.007 (0.16)	-0.298 (0.33)	-0.214 (0.19)	-0.022 (0.25)	-0.235* (0.14)
Household size (# adult equivalents)	0.374 (0.39)	-0.078 (0.17)	0.535 (0.35)	0.399** (0.20)	-0.249 (0.25)	-0.035 (0.141)
Cooking experience (years)	0.023 (0.19)	0.136 (0.09)	-0.103 (0.17)	-0.082 (0.10)	-0.014 (0.15)	-0.047 (0.07)
Income quintiles						
2	-0.681 (0.53)	0.271 (0.24)	-0.511 (0.48)	-0.027 (0.27)	-0.400 (0.37)	-0.004 (0.19)
3	-0.362 (0.567)	-0.243 (0.24)	-0.030 (0.50)	-0.180 (0.28)	-0.051 (0.38)	-0.048 (0.20)
4	-0.842 (0.52)	0.116 (0.24)	-0.219 (0.47)	0.069 (0.27)	-0.459 (0.38)	-0.070 (0.18)
5	-1.430*** (0.54)	-0.049 (0.24)	-1.109** (0.49)	-0.109 (0.28)	-0.249 (0.38)	-0.061 (0.21)
Error Constant	6.694 (1.17)	4.833 (0.53)	2.124 (1.07)	0.334 (0.61)	4.354 (0.88)	2.485 (0.49)
R^2 value	0.1121	0.1586	0.1768	0.1292	0.1424	0.0896

Notation for significance based on p-values of the regression
* = 0.10 (10%) ** = 0.05 (5%) *** = 0.01 (1%)