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A Pilot Study Characterizing Real Time Exposures to Particulate Matter and Carbon Monoxide from Cookstove Related Woodsmoke in Rural Peru

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Abstract

Nearly half of the world's population is exposed to household air pollution (HAP) due to long hours spent in close proximity to unvented cooking fires. We aimed to use $PM_{2.5}$ and CO measurements to characterize exposure to cookstove generated woodsmoke in real time among control (n=10) and intervention (n=9) households in San Marcos, Cajamarca Region, Peru. Real time personal particulate matter with an aerodynamic diameter ≤2.5 µm ($PM_{2.5}$), and personal and kitchen carbon monoxide (CO) samples were taken. Control households used a number of stoves including open fire and chimney stoves while intervention households used study-promoted chimney stoves. Measurements were categorized into lunch (9am – 1pm) and dinner (3pm – 7pm) periods, where applicable, to adjust for a wide range of sampling periods (2.8– 13.1hrs). During the 4-h time periods, mean personal $PM_{2.5}$ exposures were correlated with personal CO exposures during lunch (r=0.67 p=0.024 n=11) and dinner (r=0.72 p=0.0011 n=17) in all study households. Personal $PM_{2.5}$ exposures and kitchen CO concentrations were also correlated during lunch (r=0.76 p=0.018 n=9) and dinner (r=0.60 p=0.018 n=15). CO may be a useful indicator of PM during 4-h time scales measured in real time, particularly during high woodsmoke exposures, particularly during residential biomass cooking.

Keywords

carbon monoxide; cookstove; exposure assessment; household air pollution; particulate matter; Peru

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Introduction

Nearly three billion people worldwide employ biomass as fuel for cooking (Kurmi et al., 2010; Naeher et al., 2007; Smith, 1987). Cooking with solid fuels such as wood over inefficient stoves leads to exposure to products of incomplete combustion in the domestic environment (WHO, 2011). Particularly, women and their young infants experience high household air pollution (HAP) exposures due to long hours spent in close proximity to improperly vented cooking fires (Ezzati and Kammen, 2002; Martin et al., 2011).

HAP from solid fuels ranks 5th in the global burden of disease estimate in 2010 with annual cause-specific deaths exceeding 3.5 million incidents (Lozano et al., 2012). HAP from incomplete biomass combustion contains health-damaging pollutants such as polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO) and particulate matter with an aerodynamic diameter of ≤2.5 μm ($PM_{2.5}$) (Bølling et al., 2009; Jalava et al., 2010). CO and $PM_{2.5}$ are major constituents and are considered chief inhalation hazards of woodsmoke exposure (Naeher et al., 2007).

Recent studies have successfully demonstrated the use of time integrated personal $PM_{2.5}$ and real time CO monitoring instruments to quantify woodsmoke exposure in the indoor environment (Armendáriz-Arnez et al., 2008; Chowdhury et al., 2013; Fitzgerald et al., 2012; Masera et al., 2007; McCracken et al., 2013, Mukhopadhyay et al., 2013; Northcross et al., 2010). There are only a few studies on real time monitoring of personal $PM_{2.5}$ exposures and examination of the correlations between $PM_{2.5}$ and CO are in the scientific literature (Li et al., 2012; Mukhopadhyay et al., 2013), particularly in the developing world where HAP can be relatively high during periods such as meal preparation.

In a developing country such as Peru which has a population of 27 million, almost 30% of the inhabitants still use wood as fuel for cooking on a daily basis (INEI, 2007). In 2009, several organizations aimed to deploy 500,000 certified biomass improved chimney stoves in Peru (Bodereau, 2011); as of December 2011 around 300,000 improved stoves were built. However, the success of these HAP mitigation programs, such as the Peru national stove program, is often measured by the number of installed stoves rather than adoption, continuous utilization, maintenance and improved health over time (Armendáriz-Arnez et al., 2010).

Large-scale interventions need to be carefully informed by conducting pilot studies to address multiple methodological as well as sociocultural concerns (Mukhopadhyay et al., 2013). This study attempts to generate exploratory data and questions for such endeavors in Peru and similar settings in the developing world. Our objective was to use $PM_{2.5}$ and CO measurements in a convenience sample of Peruvian households to characterize exposure to cookstove generated woodsmoke in real time. Additionally, we investigated the association between personal $PM_{2.5}$ and CO exposures and kitchen concentrations in this population during 4-h periods when subjects are involved in meal preparation.

Methods

Study Design and Study Homes

We report a cross sectional study conducted within the framework of a community-randomized controlled trial (c-RCT) by the Instituto de Investigación Nutricional (IIN) and the Swiss Tropical and Public Health Institute. The c-RCT involved 51 community clusters who used wood as cooking fuel in the Province of San Marcos, Cajamarca region, Peru. For this study, control and intervention households were from participating households in the c-RCT (n=250 and 253 for intervention and controls respectively). Mean altitudes ± SD for

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intervention and control households are 2684 ± 284 and 2727 ± 438 meters above sea level respectively (Hartinger et al., 2013). Measurements presented in this manuscript occurred between June and August of 2009.

Intervention households used OPTIMA-improved stoves (OPTIMA stoves). Several months after air sampling had occurred; OPTIMA stoves were categorized based on their levels of functionality (FL). OPTIMA FL-I refers to OPTIMA stoves in good conditions and OPTIMA FL-II refers to OPTIMA stoves in need of minor repairs (e.g. re-plastering) or major repairs (e.g. chimney valve replacement). Air sampling did not take place to measure HAP levels after the OPTIMA stoves were repaired.

Control households in the c-RCT used various stoves including chimney stoves whose raw materials are provided by nongovernmental organizations (NGO), chimney stoves built by the members of the households (self-improved by household), gas stoves, and non-vented stoves with openings at the top for pots including the common three stone open fire stove (traditional).

In this pilot study, households were conveniently selected from households in the c-RCT enrolled for $PM_{2.5}$ and CO measurements during a 48hr air sampling period (Hartinger et al., 2013). Twenty subjects (11 control and 9 intervention stove users) were measured for cookstove related $PM_{2.5}$ and CO exposures in real time. Exposure monitoring equipment was placed in vests worn in the breathing zone of the subjects.

Study subjects' kitchens were also assessed for HAP. One of the requirements for participation in the c-RCT was for households to have stoves which were located in an in-house kitchen environment (at least three full walls and a roof over the kitchen) (Hartinger et al., 2011). Households in our study had three main kitchen types: completely enclosed (4/9 and 4/10 for intervention and control households respectively); enclosed with windows (4/9 and 5/10 for intervention and control households respectively); and three walls and a roof (1/9 and 1/10 for intervention and control households respectively). Data from one control subject has been excluded from the final data set due to a short sampling duration (17 min).

Exposure Monitoring

Real time $PM_{2.5}$ exposure was monitored with the Sidepak AM510 (TSI Inc, Shoreview, MN). The equipment is a size selective laser photometer designed to read the mass concentration of particulate matter (TSI Inc, 2006). Sidepaks used in this study were fitted with a 2.5 micron impactor, and set to log $PM_{2.5}$ concentrations every 30 seconds. Sidepaks were zero calibrated with a high efficiency particulate air (HEPA) filter before each use. Data was only available for as long as the Sidepaks battery power lasted (range of sampling duration presented in Table 1). Logged data were retrieved from the equipment using *Trakpro v. 4.4.0*5.

Real time exposure to CO was measured using Dräger Pac III single gas monitors (Draeger Safety Inc, Pittsburgh, PA) outfitted with CO sensors. The CO monitors were calibrated before the study at 0 and 50 ppm using pure nitrogen and 50 ppm CO gases respectively (Calgaz, Air Liquide America Corp, Cambridge, MA). CO monitors were also set to log data every seconds. Personal CO monitors were worn in the breathing zones of subjects while kitchen monitors were placed 1.5m from the ground in the subject's kitchen. Logged data were retrieved from the equipment using *Gas Vision v. 4.5*. Unlike the Sidepak measurements, real time CO data was available for a total of 48hrs (Hartinger et al., 2013). Data presented for each household in this study (n=19) reports the sampling durations with corresponding real time $PM_{2.5}$ measurements. Baseline questionnaires were also administered (Hartinger et al., 2013; Commodore et al., 2013).

Statistical Analysis

SAS version 9.2 (SAS Institute, NC, USA) was used for all data analysis. Raw personal $PM_{2.5}$ exposures ranged from 0 to 20, 000 μg/m^3 (upper and lower limit of the Sidepak), and after a calibration factor of 0.77 was applied (Jiang et al., 2011), the upper limit was 15, 400 μg/m^3. Real time exposures were averaged over the corresponding sampling duration in each household (hence a time weighted average which is hereafter termed mean). Measurements were also categorized into lunch (9am – 1pm) and dinner (3pm – 7pm) periods, where applicable, to adjust for a wide range of sampling periods (2.8–13.1 hours). We use descriptive measures to characterize personal $PM_{2.5}$ and CO exposures and kitchen concentrations.

To determine how well PM and CO measurements are correlated in time, PROC RANK was used to create 4-h mean and median measurement rankings. Then, PROC CORR was used to calculate correlation coefficients. Spearman's rank correlation coefficients (r) between 4-h mean and median personal $PM_{2.5}$, CO exposures and CO concentrations are calculated separately for lunch and dinner sampling periods. Correlation coefficients are only presented for all stove types rather than by intervention arm or specific stove types due to sample size constraints.

Results

Household characteristics

Characterization of the entire study population is found elsewhere (Hartinger et al., 2011, Hartinger et al., 2013). Firewood from eucalyptus trees was used by 47% (8/17) subjects for cooking and over half of the subjects had completed at least elementary school (10/17). Mean sampling was 9.9 hours (SD: 2.3 hours, range: 2.8 – 13.1 hours). Summary statistics of personal $PM_{2.5}$, personal CO and kitchen CO measurements are presented (Table 1).

Overall mean (95% CI) personal $PM_{2.5}$ exposures were 557.9 (0, 1404.7) μg/m^3 and 396.8 (0, 840.1) μg/m^3 in intervention and control households respectively. Likewise personal COexposures were 4.9 (0, 12.5) ppm and 2.8 (1.0, 5.0) ppm; and kitchen CO concentrations were 12.3 (0, 30.0) ppm and 10.8 (2.0, 15.2) ppm in intervention and control households respectively. Prior analysis of this study population revealed no statistically significant differences between control and intervention stove users (Hartinger et al., 2013; Commodore et al., 2013) and the rest of this communication focuses on all households sampled without differentiating between stove types.

$PM_{2.5}$ and CO measurements

Given the short sampling duration, we are unable to compare our results with 24-h air quality limits set by the WHO and USEPA. A comparison with the 8-h air quality limits set by these organizations, as well as OSHA may be more appropriate, given the suggestion that women in the developing world represent the single highest occupational group exposed to biomass smoke. None of the mean $PM_{2.5}$ and CO measurements in our study exceeded the OSHA limit for respirable fraction for particulate matter (5000 μg/m^3) and for CO (50 ppm) (OSHA, 1992). However, over 50% (11/19) of the households experienced $PM_{2.5}$ levels greater than 5000 μg/m^3. For personal CO, 2/19 measurements were above 8-h ambient US EPA CO limit of 9 ppm and the WHO's 8-h guideline of 8.7 ppm (Table 1), while 4/19 were over these limits for kitchen CO.

Correlations between $PM_{2.5}$ and CO

Temporal profiles for personal $PM_{2.5}$ vs. personal CO and personal $PM_{2.5}$ vs. kitchen CO are presented for a traditional (Figure 1A and B) and an OPTIMA FL-II stove user (Figure 1

C and D). The plots reveal the close similarity in the temporal pattern of exposure between the two air pollutants particularly during high exposure periods. In all study households, mean personal $PM_{2.5}$ exposures were marginally correlated with personal CO exposures (r=0.41 p=0.08 n=19) and significantly correlated with kitchen CO levels (r=0.56 p=0.03 n=16).

In all study households, 4-h mean personal $PM_{2.5}$ exposures were correlated with personal CO exposures during lunch (r=0.67 p=0.024 n=11) and dinner (r=0.72 p=0.0011 n=17). Personal $PM_{2.5}$ exposures and kitchen CO concentrations were also correlated during lunch (r=0.76 p=0.018 n=9) and dinner (r=0.60 p=0.018 n=15).

Discussion

We present personal $PM_{2.5}$ exposure, personal CO and kitchen CO measurements in real time from 9 chimney stove intervention and 10 control households in San Marcos, Cajarmarca Region, Peru. Although limited by small sample size, our results add to the growing evidence that the use of biomass fuels results in elevated HAP levels, which have been reported to be associated with adverse health effects (Kim et al., 2011; Smith et al., 2011; Smith and Peel, 2010).

$PM_{2.5}$ has been identified as the best single indicator of the health effects of combustion of biomass such as wood (Naeher et al., 2007; Perez-Padilla et al., 2010). Over 50% (11/19) of the households in our study experienced $PM_{2.5}$ levels greater than the 5000 μg/m^3 limit set by OSHA for an 8 hour period. Although the results from this study are not within the same time frame as $PM_{2.5}$ air quality limits set by OSHA, the potential for cumulative exposures and decrease in recovery time on a daily basis exist in our study population. It then becomes evident establishing such limits for 8-h or even 24-h periods can protect against the HAP peaks capable of causing substantial excess morbidity and mortality among women and children in the developing world (Fullerton et al., 2008; WHO, 2008; Smith and Peel, 2010).

The time weighted averages for personal $PM_{2.5}$ and personal CO measurements were correlated in all study households, particularly during 4-h cooking periods where HAP exposures were high. This agrees with literature that over time, CO can be used as an indicator of PM depending on the HAP source or cooking activity (McCracken and Smith, 1998; Naeher et al., 2001; Northcross et al., 2010; Li et al., 2012, McCracken et al., 2013, Chowdhury et al., 2013). The correlations between $PM_{2.5}$ and CO, particularly personal PM and kitchen CO do not appear to be very strong; this may be the result of time periods during which subjects prepared portions of the meal without fire, which produced a microenvironment where the PM and CO association is different from cooking scenarios (McCracken et al., 2013). It may also be that subjects modified their behavior to avoid high HAP exposures in the kitchen (McCracken et al., 2013). Thirdly, the four hour time periods we used were quite short thereby missing important cooking activities of the subjects. Longer sampling duration and repeated household sampling in the future may improve the characterization of HAP exposures in real time among our study population.

With the use of real time instruments, the temporal patterns of $PM_{2.5}$ and CO can be observed and subjects can be educated on when exactly during the cooking process these peaks occur in order to adopt strategies to avoid exposure to the high levels of HAP generated during cooking. Clearly, it is desirable for a stove to not only have low value of the typical exposure on any given day, but also a low extreme exposure. As expected from both 4-h periods, most of the highest exposures accounted for about 5% of the total exposures. Hence knowing when to mitigate these peak values can greatly reduce HAP exposures.

Table 1 gives an indication not only of the typical exposure but also of the extreme levels of exposure resulting from each stove. These extremes are highly variable both within and across stove types and do not yield a clear superiority of one stove type over another. Earlier results from our study showed no statistically significant differences between intervention and control stove measurements (Hartinger et al., 2013) Lack of stove maintenance, improper use, as well as lack of continuous and exclusive stove usage can introduce HAP into the kitchen environment and must be addressed if a stove intervention program is to be successful (Commodore et al., 2013).

This study adds to the growing body of literature on real time HAP exposure even as the Global Alliance for Clean Cookstoves (GACC) aims to reduce HAP and its associated adverse health effects. The GACC, led by the United Nations Foundation, has the goal of 100 million households adopting clean and efficient cookstoves by the year 2020 (GACC, 2011). In the advent of national cookstove programs in Peru and in other countries, appropriate stove selection and field evaluation of new stove models is an important step to understanding the impact of cookstove related woodsmoke exposure (Smith et al., 2011; Martin et al., 2011; Fitzgerald et al., 2012).

Conclusion

Given the cross sectional nature of this study and our small sample size, this brief analysis is an attempt to answer questions regarding periods during which household cooks may experience relatively high woodsmoke exposure. It could also contribute to discussions regarding health effects (both acute and chronic) experienced during these high exposure periods. We characterized personal $PM_{2.5}$ and personal CO exposures, and kitchen CO concentrations in real time among intervention and control households in San Marcos Peru. Personal $PM_{2.5}$ exposures were correlated with personal CO exposures and kitchen CO levels during the short sampling ranging from 2.8-13.1 hours. Results suggest that CO may be a useful indicator of PM in real time even during 4-h time scales, and particularly during high PM exposures.

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Highlights

- Potential for lack of recovery time on a daily basis exist in study population.
- Mean personal $PM_{2.5}$ and CO measurements were well correlated in all study households.
- This was so particularly during 4hr cooking periods where HAP exposures were high.
- CO may be a useful indicator of PM during periods of high residential biomass smoke.
- Temporal $PM_{2.5}$ and CO patterns can be used to mitigate high exposure during cooking.

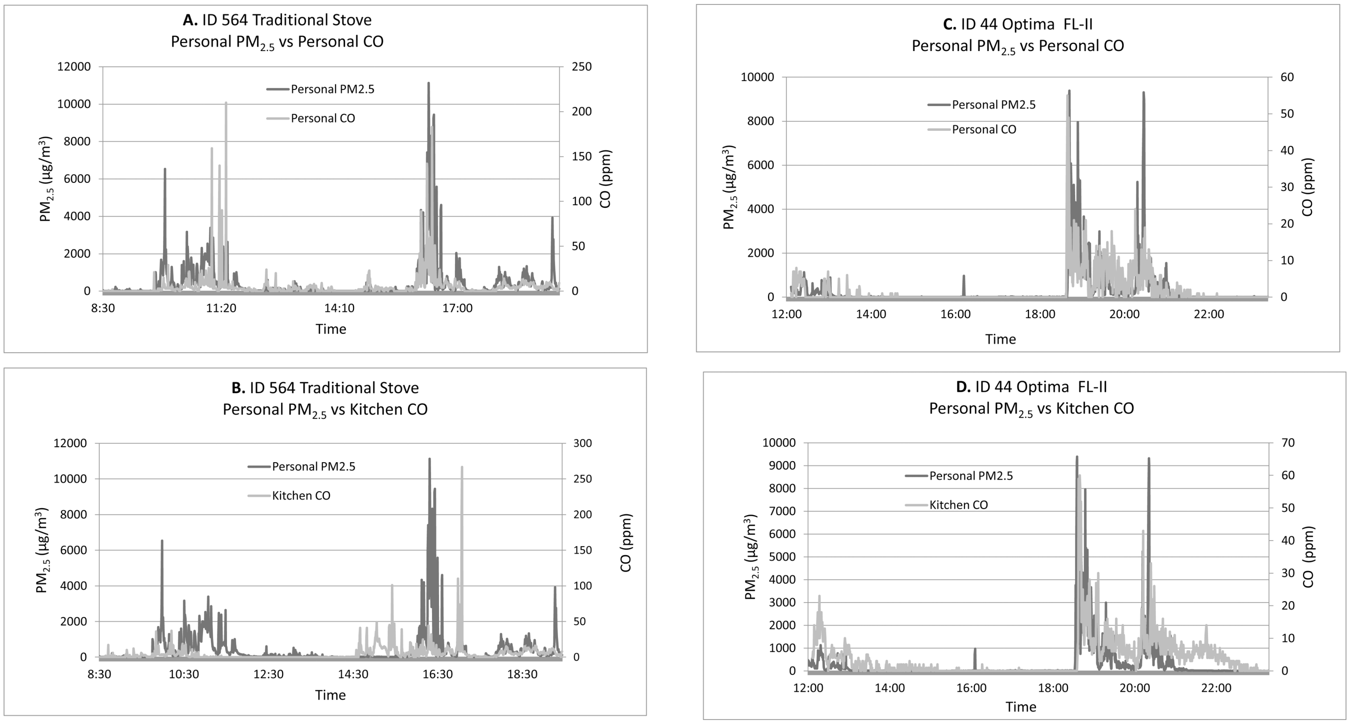

Figure 1.

Temporal profiles for personal $PM_{2.5}$ vs. personal CO and personal $PM_{2.5}$ vs. kitchen CO for a traditional stove user (A and B) and an OPTIMA FL-II stove user (C and D).

Table 1

Time weighted average (TWA) real time $PM_{2.5}$ and CO measurements from intervention and control households

Type of Household	Stove Type	Sampling Duration (hrs)	Adjusted[c] Personal $PM_{2.5}$ ($\mu g/m^3$)			Personal CO (ppm)			Kitchen CO (ppm)		
			Mean (95% CI)	Median	Range	Mean (95% CI)	Median	Range	Mean (95% CI)	Median	Range
	Optima FL-I[a]	6.7	315.3 (250.8, 379.8)	10.8	0 – 14840	2.5 (2.2, 2.8)	0.5	0 – 56.0	10.1 (9.1, 11.1)	5.0	0 – 179.0
	Optima FL-I	13.1	63.1 (52.3, 115.4)	5.4	0 – 4198.8	0.8 (0.7, 1.6)	0	0 – 15.0	1.9 (1.7, 3.6)	0	0 – 50.0
	Optima FL-I	11.0	175.8 (147.6, 323.4)	12.3	1.5 – 7188.7	1.2 (1.0, 2.2)	0	0 – 19.0	4.5 (4.1, 8.6)	1.0	0 – 126.0
	Optima FL-I	10.3	7.6 (7.2, 8.0)	6.2	3.1 – 132.4	0.0	0	0	0	0	0 – 2.0
Intervention	Optima FL-I	11.1	19.7 (16.6, 22.8)	5.4	0 – 1096.5	0.3 (0.2, 0.3)	0	0 – 10.0	0.6 (0.5, 0.7)	0	0 – 12.0
	Optima FL-I	2.8	1911.4 (1624.3, 2198.5)	653.7	3.1 – 6545.0	0.8 (0.5, 1.1)	0	0 – 16	-	-	-
	Optima FL-II	8.1	15.5 (11.4, 19.7)	1.5	0 – 793.1	0.8 (0.7, 0.9)	0	0 – 22.0	2.9 (2.6, 3.2)	2.0	0 – 63.0
	Optima FL-II	11.3	303.2 (254.5, 557.7)	9.2	3.1 – 9389.4	1.7 (1.5, 3.2)	0	0 – 55.0	3.7 (3.4, 7.2)	1.0	0 – 60.0
	Optima FL-II	9.0	3562.7 (3263.1, 3862.2)	1.6	0 – 15400	31.9 (29.2, 34.6)	13.0	0 – 257.0	74.9 (69.2, 80.7)	40.0	0 – 812.0
	Built by NGO[b]	10.3	75.3 (62.5, 88.2)	9.2	0 – 2067.5	0.4 (0.3, 0.4)	0	0 – 6.0	-	-	-
	Built by NGO	12.4	526.1 (458.9, 593.2)	27.0	0 – 11665.5	5.0 (4.7, 5.4)	3.0	0 – 55.0	20.9 (19.0, 22.8)	10.0	0 – 383.0
	Built by NGO	9.4	83.7 (62.9, 104.5)	0.8	0 – 4118.0	2.0 (1.7, 2.2)	0	0 – 35.0	4.1 (3.8, 4.2)	3.0	0 – 60.0
	Built by NGO	9.5	9.7 (8.4, 11.0)	2.7	0 – 360.4	2.9 (2.5, 3.3)	0	0 – 61.0	5.3 (4.7, 5.9)	0	0 – 104.0
Control	Improved by household	11.2	92.2 (74.5, 109.8)	13.1	1.5 – 8130.0	0.6 (0.5, 0.6)	0	0 – 10.0	0.5 (0.4, 0.5)	0	0 – 16.0
	Traditional	9.1	324.9 (252.6, 397.2)	30.0	5.4 – 12657.3	1.2 (1.0, 1.4)	0	0 – 27.0	-	-	-
	Traditional	11.1	2365.9 (2165.6, 2566.2)	252.2	0 – 15400	11.3 (10.6, 12.1)	5.0	0 – 67.0	29.8 (28.5, 31.1)	24.0	0 – 148.0
	Traditional	9.2	15.4 (14.3, 16.6)	14.6	0 – 515.9	0.0	0	0 – 3.0	0	0	0
	Traditional	10.9	415.3 (363.5, 467.1)	98.2	2.3 – 11133.4	4.9 (4.2, 5.6)	2.0	0 – 210.0	4.9 (4.2, 5.6)	1.0	0 – 267.0
	Traditional	10.5	60.0 (41.8, 78.1)	7.7	0 – 5664.9	0.2 (0.2, 0.3)	0	0 – 15.0	2.9 (2.6, 3.1)	2.0	0 – 40.0

[a]Functionality level (FL) I refers to a stove in good conditions, level II refers to a stove in need of minor repairs (re-plastering) or major repairs (e.g. chimney valve

[b]NGO: three main NGOs had improved stoves; JUNTOS-National cash transfer program. Part of the requirements is that families must build an improved stove with a chimney; SEMBRANDO & ADIAR are NGOs that work in nearby communities.

[c]Sidepak $PM_{2.5}$ measurements adjusted with a correction factor of 0.77 according to measurements by Jiang et al (2011)

- denotes unavailable data

Mean here denotes the time weighted average (TWA) of the real time measurements for the respective sampling durations