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Indoor and outdoor $PM_{2.5}$ and CO in high- and low-density Guatemalan villages[1]

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Continuous particles less than 2.5 μm in diameter ($PM_{2.5}$) and carbon monoxide (CO) were monitored during breakfast, lunch, and dinner in three high-density and four low-density villages near Quetzaltenango, Guatemala to help assess the viability of this region for a proposed respiratory health and stove intervention study. Approximately 15 homes were visited during each mealtime in each of the seven villages; in all, 98 homes were visited, with a sampling duration of 2–3 min per home per meal. For each village, a line (transect) was drawn on a village map along existing roads from one end of the village to the other; homes and between-home outside locations along the transect were monitored. Although the predominant stove type was the open fire, several other stoves, in various levels of disrepair, were observed frequently. The highest indoor concentrations of $PM_{2.5}$ were observed in homes using the open fire (avg. = 5.31 mg/m^3; SD = 4.75 mg/m^3) or equivalent, although homes using the *plancha* — indigenous wood-burning stove with chimney — also had measurements > 13.8 mg/m^3, $PM_{2.5}$ limit of detection. The highest indoor concentrations of CO were also observed in homes using the open fire (avg. = 22.9 ppm; SD = 28.1 ppm), with a maximum measurement of > 250 ppm. For both $PM_{2.5}$ and CO, levels measured in homes with *plancha*, *lorena*, or open fire were significantly higher than levels taken in the street or in homes using a gas stove. The Spearman correlation coefficient between $PM_{2.5}$ and CO for all data combined was 0.81, and ranged from 0.30 for the *lorena* to 0.68 for the *plancha* in homes using wood-fueled stoves. Although indoor $PM_{2.5}$ and CO levels were not significantly different between high- and low-density villages, street-level $PM_{2.5}$ ($p = 0.002$) and CO ($p = 0.002$), were significantly higher in the high-density villages. These data provide a useful picture of the pollution levels coming from a range of cooking stoves in various levels of disrepair, as well as a representation of how outdoor particle mass and CO levels vary from high- versus low-density villages. *Journal of Exposure Analysis and Environmental Epidemiology* (2000) **10,** 544–551.

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Introduction

It is estimated that around 50% of the world's population, with as many as 90% in some developing countries, rely on biomass fuels (wood, dung and crop residues), which are typically burnt in simple open stoves, for cooking and sometimes heating (Reddy et al., 1997; WHO, 1997). Such small-scale open combustion of biomass fuels results in indoor pollution levels, including carbon monoxide (CO) and particulate pollution, among the highest ever measured; thus, on a worldwide basis, these populations probably have the greatest mean annual exposures to particulates of all size ranges, although systematic global surveys are not yet available to be certain (Smith, 1993a).

Numerous urban studies in industrialized countries have shown associations between ambient particulate air pollution and acute and chronic respiratory morbidity and mortality in children and adults (Dockery and Pope, 1994). Although exposure characteristics vary tremendously from the developed world to rural areas in the developing world (e.g., particulate composition, exposure circumstances, demographics, and underlying health status), it is hypothesized that high exposure to contaminants from biomass fuel combustion is a risk factor for low birth weight (Astrup, 1972), acute respiratory infections (ARI) and other forms of ill health (Smith, 1987) in the developing world. In its 1993 report, "Investing in Health," the World Bank estimates that indoor air pollution is responsible for almost 50% of the burden of total disease resulting from poor household environments in developing countries (World Bank, 1993).

Further studies from rural areas in developing countries are necessary to clarify the associations, including the exposure–

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Table 1. Approximate total number of houses and housing density in villages monitored in this study.

Village	Density	Houses per hectare	Approximate total number of houses in village
Buena Vista	Low[a]	0.2	32
Varsovia	Low	0.7	432
Tuipox	Low	1.4	200
Duraznales	Low	2.3	285
San Martin	High[b]	6.1	480
San Juan Ostuncalco	High	11.7	1732
Concepcion Chiquirichapa	High	16.7	310

[a]Villages with less than or equal to five houses per hectare are characterized as low-density villages.
[b]Villages with greater than five houses per hectare are characterized as high-density villages.

response relationships, between particulate pollution from biomass fuel cooking and health. In 1992, a committee organized by the World Health Organization (WHO) began to examine the feasibility of carrying out controlled intervention studies designed to assess the effects on key child and adult respiratory health outcomes of a measured reduction in exposure. Pursuant to a set of epidemiological studies to determine the risk-reduction potentials of various interventions (e.g., including fuel substitution, stove alteration, ventilation provision, and behavioral modification), the WHO sponsored several pilot studies in the western highlands of Guatemala (Bruce et al., 1998; McCracken and Smith, 1998; Neufeld, 1995; Smith et al., 1993b).

Building on the work of Smith et al. (1993b), we contributed to this preliminary work through three exposure assessment-related studies in the western highlands of Guatemala in 1993–1994. The objective of the first, reported herein, was to determine if villages in the proposed region had indoor pollution levels, from indigenous stove emissions, high enough to make it a good area for an intervention study. In this study, we selected several high- and low-density villages in the western highlands of Guatemala, and monitored indoor and outdoor particles less than 2.5 μm in diameter ($PM_{2.5}$) and CO levels during breakfast, lunch and suppertime in approximately 15 homes per village. We investigated the impact of "neighborhood" pollution on indoor levels as well and characterized indoor concentrations for different meals and stoves. The objective of the second study, presented elsewhere (Naeher et al., 2000), was to determine the effectiveness of a range of intervention stoves in reducing indoor exposures to air pollution. The objective of the third study (Naeher et al., 1996) was to investigate efficient and effective $PM_{2.5}$ exposure measurements and to determine how personal measurements relate to area measurements.

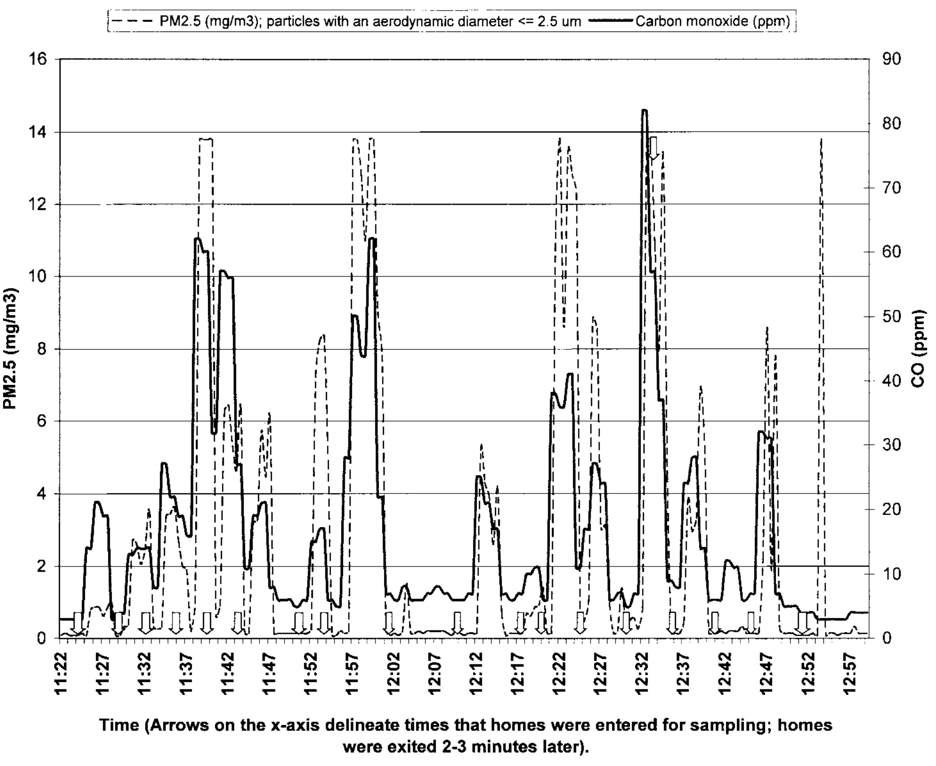

Figure 1. Carbon monoxide and $PM_{2.5}$ real-time measurements during lunch in Duraznales, Guatemala, a low-density village; 22 different homes were visited during the sampling period, 16 of which were operating their stove.

Methods

A cross-sectional plot of ambient and indoor CO and $PM_{2.5}$ levels during cooking of breakfast, lunch, and dinner was measured in seven villages in the Quetzaltenango (Xela) region of the western highlands of Guatemala (altitude range 2500–2800 m). In this region, most families burn wood on open fires, with around 10–20% using wood-burning stoves with chimneys like the *plancha* and the *lorena*, and a few using standard four-burner gas stoves fueled by a mixture of propane and butane. The open fires used for cooking in this region are typically wood-burning fires positioned at ground-level within a traditional three-rock configuration. The *planchas* are roughly 3 ft high, 4 ft

Table 2. Particles less than 2.5 μm in diameter ($PM_{2.5}$) and CO measurements for all kitchen and street locations, in all villages, for all meal times combined.

		Gas stove	Lorena	Open fire	Plancha	Street
Descriptive analysis						
Carbon monoxide (ppm)	*N*	14	13	146	81	59
	Average	3.5	15.4	22.9	10.3	2.9
	Standard deviation	2.4	9.2	28.1	13.3	2.3
	Maximum	11	32	250	88	12
	Minimum	1	3	0	0	0
$PM_{2.5}$ (mg/m^3)[a]	*N*	13	15	167	81	57
	Average	0.13	6.03	5.31	1.91	0.23
	Standard deviation	0.06	4.99	4.75	3.33	0.28
	Maximum	0.20	13.80	13.80	13.80	1.70
	Minimum	0.02	0.32	0.26	0.08	0.02
Carbon monoxide/PM$_{2.5}$ ratio						
	N	11	13	139	70	52
	Average	35.5	8.1	6.6	15.8	23.3
	Standard deviation	38.9	8.6	7.5	28.4	25.8

	All data	Gas stove	Lorena	Open fire	Plancha	Street
Correlation between CO and PM$_{2.5}$						
Number of observations	290	11	13	140	72	54
Pearson correlation (*R*)	0.52	0.50	0.31	0.43	0.59	0.67
p-Value	***	ns	ns	***	***	***
Spearman correlation (*R*)	0.81	0.51	0.30	0.66	0.68	0.31
p-Value	***	ns	ns	***	***	**

		Gas stove	Lorena	Open fire	Plancha
t-Test results for source comparisons					
Carbon monoxide (ppm)	Lorena	***			
	Open fire	**	ns		
	Plancha	*	ns	***	
	Street	ns	***	***	***
$PM_{2.5}$ (mg/m^3)[a]	Lorena	***			
	Open fire	***	ns		
	Plancha	*	***	***	
	Street	ns	***	***	***

Source-specific correlation coefficients and *t*-test comparisons for $PM_{2.5}$ and CO.
[a]For the monitoring method used in this study, 13.8 mg/m^3 is the $PM_{2.5}$ limit of detection.
*$p<0.10$.
**$p<0.05$.
***$p<0.01$.

long, 2.5 ft wide, with a brick and mortar base, and a top with three steel burners surrounded by tile. The *lorenas* are taller and more massive than the *planchas*, and typically have three burners in a circle atop a mud-based unit with no brick, steel or tile components like the *plancha*. Most of the *lorenas* were constructed over a decade ago, are in poor condition (e.g., cracked stove body and top), and function more or less as an open fire stove as opposed to a functional wood stove with chimney like the newer *planchas*. The houses are generally made of adobe and wood, sometimes with only one room but with a separate sleeping area in many. Sampling occurred in November 1993, a month characterized by cool temperatures and large amounts of rainfall in the study region. Four of these villages were low-density (Varsovia, Buena Vista, Duraznales, and Tuipox) and three high-density (San Juan Ostuncalco, Concepcion Chiquirichapa, and San Martin) (see Table 1). Low- and high-density villages are defined as those with $\leq$5 houses/hectare and those with >5 houses/hectare, respectively. In the primarily Mayan population of this region, the women typically carry children under 2 years of age on their backs during much of the day, which results in high exposure for these children when the mother is cooking.

A battery-operated SKC pump running at 3.5 l/min attached to an MIE cyclone (respirable cyclone precollector [DR-RCP10], Dorr-Oliver 10-mm nylon cyclone and

Table 3. Particles less than 2.5 μm in diameter ($PM_{2.5}$) and CO measurements for all kitchen and street locations, in all villages, for all meal times listed separately.

		Gas stove	Lorena	Open fire	Plancha	Street
Breakfast						
Carbon monoxide (ppm)	*N*	3	4	46	27	19
	Average	2.7	6.8	15.6	8.1	3.0
	Standard deviation	0.6	3.3	18.8	10.2	2.6
	Maximum	3	10	93	45	12
	Minimum	2	3	2	0	0
$PM_{2.5}$ (mg/m^3)[a]	*N*	3	5	60	31	20
	Average	0.10	4.86	5.04	0.85	0.29
	Standard deviation	0.04	5.87	4.55	0.97	0.29
	Maximum	0.14	13.80	13.80	3.38	0.98
	Minimum	0.08	0.32	0.32	0.08	0.02
Lunch						
Carbon monoxide (ppm)	*N*	6	4	42	26	14
	Average	3.5	25.5	30.0	11.5	2.7
	Standard deviation	1.4	5.5	24.6	12.4	0.8
	Maximum	6	32	117	47	4
	Minimum	2	21	2	2	2
$PM_{2.5}$ (mg/m^3)[a]	*N*	7	5	54	31	15
	Average	0.13	6.64	6.56	1.33	0.13
	Standard deviation	0.07	4.80	5.31	2.10	0.08
	Maximum	0.20	13.80	13.80	10.10	0.32
	Minimum	0.02	0.86	0.26	0.14	0.02
Dinner						
Carbon monoxide (ppm)	*N*	5	5	58	28	26
	Average	4.0	14.2	23.5	11.4	2.9
	Standard deviation	4.0	6.8	34.9	16.7	2.5
	Maximum	11	20	250	88	11
	Minimum	1	3	0	0	0
$PM_{2.5}$ (mg/m^3)[a]	*N*	3	5	53	19	22
	Average	0.14	6.58	4.36	4.58	0.24
	Standard deviation	0.06	5.20	1.14	5.50	0.35
	Maximum	0.20	13.80	13.80	13.80	1.70
	Minimum	0.08	0.50	0.26	0.20	0.08

[a]For the momitoring method used in this study, 13.8 mg/m^3 is the $PM_{2.5}$ limit detection.

fittings with a 3.5-μm particle cut point) and an infrared-scattering MIE Miniram (Monitoring Instruments for the Environment, Inc.) with Langan DataBear datalogger (Langan Products, Inc.) was used to collect continuous PM$_{2.5}$. The Miniram is a light-scattering aerosol monitor of the nephelometric type that can be used to measure the concentration of all forms of aerosol: dusts, fumes, smokes, fogs, etc. The scattering sensing parameters for the Miniram have been designed for preferential response to the particle size range of 0.1 to 10 μm, with an upper limit of detection (LOD) of 100 mg/m^3, making it suitable for this study (GCA Corporation, 1984). However, the upper limit and resolution of the PM$_{2.5}$ sampling apparatus were dictated by the Langan DataBear datalogger with an upper LOD of 13.8 mg/m^3 and a resolution of 0.06 mg/m^3. Manufacturer-suggested routine maintenance was performed on the Miniram as part of the study quality assurance/quality control, including daily calibration using a Miniram "zero check module," controlling for particle contamination on the inner surfaces of the sensing chamber (i.e., saturation/absorbtion) and zero drift. A battery-operated Draeger CO electrochemical sensor with datalogger was used to collect continuous CO. Pumps were calibrated daily using a bubble tube. Draeger CO monitors were calibrated daily at the field base using 100 and 250 ppm CO calibration gas (CalGas, Inc.), typically with little to no drift.

Local helpers visited each village the day before sampling to find homes that would permit 2-min air sampling during meal preparations of the following day; the refusal rate was $<10\%$, and there were no indications that the homes of those who refused were different from the other homes in any observable manner. We visited all participating homes along the transect. Stove types observed in participating homes included the gas stove, *plancha*, *lorena*, and or open fire. The sampling strategy was straightforward. The technician carried a bag that the SKC pump and the Miniram were attached to; the datalogger was placed inside the bag. The air sampling inlet for the PM$_{2.5}$ sample (attached to the Miniram via tygon tubing) and the Draeger CO monitor were attached to the technician's clothing on his chest, within 8–10 in. of his mouth (breathing zone). The instruments were turned on just outside the village, and the sampling was done by walking on as much of a direct transect as possible through the village with frequent stops both on the street to determine outdoor street-level CO and PM$_{2.5}$ measurements from one end of the village to the other (i.e., a cross-sectional look at outdoor air pollution in the village), and in homes to determine indoor and stove-specific levels of CO and PM$_{2.5}$. The in-home sampling was taken by having the technician stand or sit in the kitchen in the approximate position that the home occupant would assume if they were cooking (i.e., near the stove in a position one would typically cook from). Although cigarette smoke is a potential source of PM$_{2.5}$ and CO in these homes, since the primary interest in this study was to determine indoor and stove-specific levels of CO and PM$_{2.5}$, smoking was not allowed in the homes during the air monitoring.

The average PM$_{2.5}$ and CO concentrations used in this analysis were derived from the peak measurement observed during the 2- to 3-min sampling duration for each location during which PM$_{2.5}$ and CO averages were calculated and collected on the dataloggers in 10- and 60-s intervals, respectively. Street-level air measurements of CO and PM$_{2.5}$ were taken between participating homes. Although measure-

Table 4. Comparison of street-level carbon monoxide (CO) and particles less than 2.5 μm in diameter (PM$_{2.5}$) measurements in high- versus low-density villages.

Location/stove type	CO (ppm) Village density		PM$_{2.5}$ (mg/m^3) Village density	
	High	Low	High	Low
Gas stove				
Average	3.2	3.8	0.13	0.13
Standard deviation	1.5	3.1	0.07	0.05
N	6	8	8	5
t-Test	− 0.428		− 0.083	
p-Value	0.338		0.468	
Lorena				
Average	11.0	16.7	6.24	5.98
Standard deviation	9.2	9.3	2.43	5.53
N	3	10	3	12
t-Test	− 0.935		0.079	
p-Value	0.185		0.469	
Open fire				
Average	21.1	24.0	4.92	5.52
Standard deviation	20.4	32.0	4.75	4.75
N	56	90	57	110
t-Test	− 0.596		− 0.772	
p-Value	0.276		0.221	
Plancha				
Average	9.6	11.2	1.77	2.05
Standard deviation	10.2	16.1	3.28	3.41
N	42	39	40	41
t-Test	− 0.532		− 0.370	
p-Value	0.298		0.356	
Street				
Average	3.6	2.0	0.32	0.11
Standard deviation	2.7	1.2	0.36	0.05
N	31	28	31	26
t-Test	2.983		2.890	
p-Value	0.002		0.003	

ments were taken in homes whether the stoves were in use or not, only measurements taken while the stoves were in use are included in this analysis. Notes were kept of stove characteristics and unusual wood-smoke-related building characteristics (i.e., makeshift ventilation portals, soot-filled ceilings, etc.) of each household visited. A village map showing the transect and visited households was prepared for each village. The building characteristics data were collected and the village maps prepared for data troubleshooting and descriptive purposes, and are not included specifically in the quantitative results reported herein.

Results

A typical village transect of real-time $PM_{2.5}$ and CO measured during lunchtime in and out of homes in a low-density village (Duraznales) is presented in Figure 1. The highest indoor concentrations of $PM_{2.5}$ were observed in homes using the open fire (n=167, avg.=5.31±4.75 mg/m^3), although concentrations in homes using the *lorena* (n=15, avg.=6.03±4.99 mg/m^3) and the *plancha* (n=81, avg.=1.91±3.33 mg/m^3) were also elevated with respect to outdoor (street) concentrations (Table 2). Average concentrations of $PM_{2.5}$ for each stove type were calculated using a value of 13.8 mg/m^3 for measurements exceeding the $PM_{2.5}$ upper LOD (13.8 mg/m^3); 24 open fire, 2 *lorena*, and 2 *plancha* measurements exceeded the $PM_{2.5}$ upper LOD. Thus, reported $PM_{2.5}$ estimates (Tables 2–4) for the open fire, *plancha*, and *lorena* are underestimates. The highest indoor concentrations of CO were observed in homes using the open fire (avg.=22.9±28.1 ppm), although concentrations in homes using the *lorena* (avg.=15.4±9.2 ppm) and the *plancha* (avg.=10.3±13.3 ppm) were also elevated with respect to outdoor (street) concentrations. Average concentrations of CO for each open fire measurements were calculated using a value of 250 ppm for the one measurement that exceeded the CO upper limit of detection (250 ppm). Thus, the reported CO estimates (Tables 2–4) for dinnertime open-fire measurements are slight underestimates.

For both $PM_{2.5}$ and CO, levels measured in homes with the *plancha*, *lorena*, or open fire were significantly higher than levels taken in the street ($PM_{2.5}$ avg.=0.23±0.28 mg/m^3; CO avg.=2.9±2.3 ppm) or in homes using a gas stove ($PM_{2.5}$ avg.=0.13±0.06 mg/m^3; CO avg.=3.5±2.4 ppm) (see Table 2 and Figures 2 and 3). The Pearson correlation coefficient between the two measured pollutants for all data combined was 0.52, and ranged from 0.31 for the *lorena* to 0.59 for *plancha* in homes using wood-fueled stoves (see Table 2). The corresponding Spearman correlation coefficient (possibly a more appropriate measure of correlation due to the skewness of the data) between $PM_{2.5}$ and CO for all data combined was slightly higher at 0.81, and ranged from 0.30 for the *lorena* to 0.68 for the *plancha* in homes using wood-fueled stoves. The CO/ $PM_{2.5}$ ratios for street measurements and all stove conditions are also presented in Table 2.

Overall, lunchtime indoor levels of $PM_{2.5}$ and CO were slightly higher than levels during breakfast and dinner, which were largely similar (see Table 3). Indoor $PM_{2.5}$ and CO levels were not significantly different between high- and low-density villages (see Table 4). Street levels, however, were significantly higher in the high-density versus low-density villages for $PM_{2.5}$ (0.32±0.36 mg/m^3 and 0.12±0.05 mg/m^3, respectively) and CO (3.7±2.7 ppm and 2.0±1.2 ppm, respectively) (see Table 4).

Discussion

Kitchen measurements of CO and $PM_{2.5}$ observed in this study are comparable to a number of other similar studies, although it is difficult to fully compare the current study to the others because each deals with different cooking fuels, different sample durations and techniques, and/or a different size cut of the particulate pollution. Most recently, a study in 12 rural Bolivian households (169 samples) that cooked with biomass fuel found measured morning 6-h average kitchen PM_{10} concentrations of 3.69±5.38 mg/m^3 (Albalak et al., 1999). Similarly, a study in seven rural Mexican households (one sample per household) that cooked with biomass fuel measured early morning 9-h average kitchen $PM_{2.5}$ concentrations of 0.55±0.49 mg/m^3, and PM_{10} measurements of 0.77±0.54 mg/m^3 (Brauer et al., 1996). $PM_{2.5}$ peaks in the Mexico study were on the same order as in the current study. Another study of 114 households (one sample per household) in Maputo, Mozambique found wood users monitored for 1.5 h during cooking time were exposed to 1.2±0.13 mg/m^3 $PM_{7.1}$ (particles less than 7.1 μm in diameter) (Ellegard, 1996). The findings of these studies, the current study, and earlier work (Smith et al., 1993b) all clearly demonstrate that biomass fuel combustion causes extremely elevated exposures to particulate matter and CO. While earlier studies in Beijing, China and Pune, India clearly demonstrate an apparent contribution of neighborhood particulate and CO air pollution to indoor levels in semi-urban villages (Smith et al., 1994), the neighborhood effect in this case was not strong enough to be detected by our method, although it may still exist and be detectable with a study that included other influencing factors including, but not limited to, stove type, number of individuals per home, and altitude.

Relevant to future intervention studies, preliminary results suggest two issues of importance. First, findings of the current study demonstrate that there is a significant difference in indoor concentrations between stove types

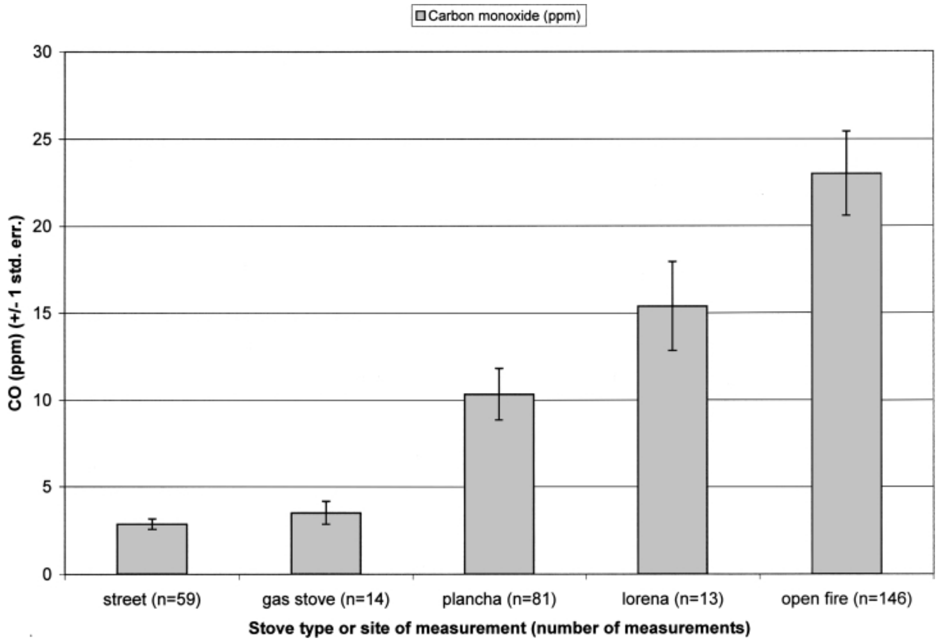

Figure 3. Carbon monoxide measurements for all kitchen — with gas stove, *plancha*, *lorena*, or open fire — and street locations in all villages for all meal times combined.

during cooking times; thus, from an exposure-based assessment perspective, the Xela region of Guatemala is a viable area in which to conduct an epidemiological intervention study aimed at investigating the association between biomass fuel combustion and ARI and other health effects in women and children. Second, the variation of indoor levels of PM$_{2.5}$ and CO in homes with *plancha*s, also observed by Naeher et al. (2000), demonstrates that some *plancha*s produce indoor levels intermediate between gas stoves and open fires. Thus, in future related epidemiology studies, it seems that more intensive monitoring of exposures in *plancha* households must be contemplated to keep track of whether each individual household maintains low levels, similar to those in gas-stove homes, or rises to the higher levels that have been measured with many *plancha*s over time (but are still lower than those found in most open fire kitchens).

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References

Albalak R., Keeler G.J., Frisancho A.R., and Haber M. Assessment of PM10 concentrations from domestic biomass fuel combustion in two rural Bolivian highland villages. *Environ Sci Technol* 1999: 33: 2505–2509.

Astrup P. Some physiological effects of moderate carbon monoxide exposure. *Br Med J* 1972: 4: 447–452.

Brauer B., Bartlett K., Regaldo-Pineda J., and Perez-Padilla R. Assessment of particulate concentrations from domestic biomass combustion in rural Mexico. *Environ Sci Technol* 1996: 30: 104–109.

Bruce N., Neufeld L., Boy E., and West C. Indoor biofuel air pollution and respiratory health: the role of confounding factors among women in highland Guatemala. *Int J Epidemiol* 1998: 27: 454–458.

Dockery D.W., and Pope C.A. III. Acute respiratory effects of air particulate pollution. *Annu Rev Public Health* 1994: 15: 107–132.

Ellegard A. Cooking fuel smoke and respiratory symptoms among women in low-income areas in Maputo. *Environ Health Perspect* 1996: 104: 980–985.

GCA Corporation. Miniram Personal Monitor, Model PDM-3, Operations Manual. GCA Corporation, Technology Division, 213 Burlington Road, Bedford, MA 011730, February 1984.

McCracken J.P., and Smith K.R. Emissions and efficiency of improved woodburning cookstoves in highland Guatemala. *Environ Int* 1998: 24 (7): 739–747.

Naeher L.P., Leaderer B.P., Smith K.R., et al. CO as a tracer for assessing exposure to particulates in wood and gas cooking households of highland Guatemala. Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan 1996: 2: 417–422.

Naeher L.P., Smith K.R., Leaderer B.P., et al. Particulate matter and carbon monoxide in highland Guatemala: indoor and outdoor levels from traditional and improved wood stoves and gas stoves. *Int J Indoor Air Qual Clim* 2000 (in press).

Neufeld L. The influence of smoke from indoor cooking fires on haemoglobin concentration in women from rural highland Guatemala. Masters thesis, Cornell University, Ithaca, NY. 1995.

Reddy A.K.N., Williams R.H., and Johansson T.B. Energy after Rio: Prospects and Challenges. United Nations Development Programme, New York, 1997.

Smith K.R. Biofuels, Air Pollution and Health: A Global Review. Plenum Press, New York, 1987, pp. 79–83.

Smith K.R. Fuel combustion, air pollution exposure, and health: the situation in developing countries. *Annu Rev Energy Environ* 1993a: 18: 529–566.

Smith K.R., Apte M.G., Yuqing M. Wongsekiarttirat W., and Kulkarni A. Air pollution and the energy ladder in Asian cities. *Energy* 1994: 19: 587–600.

Smith K.R., Liu Y., Rivera J., Boy E., Leaderer B.P., Johnston C.S., Yanagisawa Y., and Lee K. In: Jaakkola, J.K.K., et al. (ed), Indoor Air '93 Proceedings, University of Technology, Helsinki, Finland. 1993b: 1: 441–446.

WHO. Health and Environment in Sustainable Development. World Health Organization, Geneva, 1997.

World Bank. World Development Report: Investing in Health. Oxford University Press for the World Bank, New York, 1993.