Indoor Air Quality for Poor Families:
New Evidence from Bangladesh

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Executive Summary

Poor households in Bangladesh depend heavily on wood, dung and other biomass fuels for cooking. This paper provides a detailed analysis of the implications for indoor air pollution, drawing on new monitoring data for respirable airborne particulates (PM_{10}) in a large number of Bangladeshi households. Concentrations of 300 ug/m^3 or greater are common in our sample, implying widespread exposure to a serious health hazard. For comparison, Galassi, Ostro, et al. (2000) find substantial health benefits for PM_{10} reduction in eight Italian cities whose annual concentrations are far lower: 45-55 ug/m^3.

As expected, our econometric results indicate that fuel choice significantly affects indoor pollution levels: Natural gas and kerosene are significantly cleaner than biomass fuels. However, household-specific factors apparently matter more than fuel choice in determining PM_{10} concentrations. In some biomass-burning households, concentrations are scarcely higher than in households that use natural gas. Our results suggest that cross-household variation is strongly affected by structural arrangements: cooking locations, construction materials, and ventilation practices.

To assess the broader implications for poor Bangladeshi households, we extrapolate our regression results to representative household samples from rural, peri-urban and urban areas in six regions: Rangpur in the Northwest, Sylhet in the Northeast, Rajshahi and Jessore in the West, Faridpur in the Center, and Cox's Bazar in the Southeast. Our results indicate great geographic variation, even for households in the same per capita income group. This variation reflects local differences in fuel use and, more significantly, construction practices that affect ventilation. For households with per capita incomes less than $1.00/day, rural PM_{10} concentrations vary from 410 ug/m^3 in Cox's Bazar to 202 ug/m^3 in Faridpur. In urban areas, concentrations for such households differ by almost 100 ug/m^3 between the highest areas, Jessore and Rajshahi, and the lowest, Sylhet. The poorest households in Faridpur face a lower mean indoor concentration (202 ug/m^3) than the highest-income households in Jessore and Rajshahi (215 ug/m^3).

Great variation also characterizes the 24-hour cycle within households. For example, within the "dirtiest" firewood-using household in our sample, readings over the 24-hour cycle vary from 68 to 4,864 ug/m^3. Such variation occurs because houses can recycle air very quickly in Bangladesh. After the midday meal, when ventilation is common, air quality in many houses goes from very dirty to reasonably clean within an hour. Rapid change also occurs within households: Diffusion of pollution from kitchens to living areas is nearly instantaneous in many cases, regardless of internal space configuration, and living-area concentrations are almost always in the same range as kitchen concentrations. By implication, exposure to dangerous indoor pollution levels is not confined to cooking areas.

We find that distinguishing between indoor and outdoor pollution may not be useful in biomass-using areas. In Dhaka, the 24-hour pattern of indoor PM_{10} concentration for the

cleanest fuel, piped natural gas, is nearly identical to the pattern for ambient (outdoor) pollution. Baseline indoor pollution is set by ambient pollution, which varies nearly twelve-fold (from 30 to 350 ug/m^3; mean 113) over the 24-hour cycle. In areas with heavy biofuel use, our results therefore suggest that health benefits may be less than expected for households that switch to clean fuels or improved stoves.

Our survey also suggests that limited information may be a significant impediment to adoption of cleaner, more efficient stoves. Only 15% of our sample households regard improved stoves as a viable option, either because they have not heard of them or because they do not think they are locally available. Even among families that have considered the option, however, improved-stove use appears quite limited because of concerns about convenience or initial investment cost. The intermediate-term prospects for clean-fuel use appear more hopeful in urban and peri-urban areas, if economic growth continues. Our sample evidence suggests very high adoption rates among families whose daily per capita incomes exceed $2.00. However, only 30% of extreme-poverty households (less than $1.00/day per capita) use clean fuels, even in urban areas where their prices are relatively low. In rural areas, our evidence offers little hope for adoption of clean fuels in the near future because their prices relative to biofuels are too high.

However, our analysis also suggests that poor families may not have to wait for clean fuels or clean stoves to enjoy significantly cleaner air. Within our sample household population, some arrangements are already producing relatively clean conditions, even when “dirty” biomass fuels are used. Since these arrangements are already within the means of poor families, the scope for cost-effective improvements may be larger than is commonly believed.

1. Introduction

Indoor air pollution from burning wood, animal dung and other biofuels is a major cause of acute respiratory infections (ARI), which constitute the most important cause of death for young children in developing countries (Murray and Lopez, 1996). Acute lower respiratory infection (ALRI), the most serious type of ARI, is often associated with pneumonia (Kirkwood et al., 1995). ALRI accounts for 20% of the estimated 12 million annual deaths of children under five, and about 10% of perinatal deaths (WHO, 2001; Bruce, 1999). Nearly all of these deaths occur in developing countries, with the heaviest losses in Asia (42% of total deaths) and Africa (28%) (Murray and Lopez, 1996). Through its effect on respiratory infections, indoor air pollution (IAP) is estimated to cause between 1.6 and 2 million deaths per year in developing countries (Smith, 2000). Most of the dead are in poor households and approximately 1 million are children. The size of IAP's estimated impact has prompted the World Bank (2001) and other international development institutions to identify reduction of indoor air pollution as a critical objective for the coming decade.

The current scientific consensus is that most respiratory health damage comes from inhalation of respirable particles whose diameter is less than 10 microns (PM_{10}), and recent attention has focused particularly on fine particles ($PM_{2.5}$). However, the design of cost-effective IAP reduction strategies has been hindered by lack of information about actual PM concentrations in poor households. Data have been scarce because monitoring in village environments has been difficult and costly. Relative small-scale studies of indoor PM_{10} exposure from woodfuel combustion have been conducted in Kenya (Boleij, et al (1989, 36 households), Guatemala (Smith, et al., 1993, 60 households), Mexico (Santos-Burgoa, et al., 1998, 52 households), and Gambia (Campbell, 1997, 12 households. Recently, a larger sample of houses has been studied in rural India (Balakrishnan, et al., 2002; Parikh, et al., 2001). In Section 9, we will compare the India results to those obtained by this study.

Because monitoring studies are costly, IAP exposure analyses frequently use biofuel consumption data to proxy the degree of exposure to fine particulates, and extrapolate to estimates of ARI prevalence and mortality (Smith, 2000). Although fuel-use data are widely available, this approach implicitly assumes a constant relationship between fuel combustion and indoor air pollution across households. However, the previously-mentioned studies indicate that IAP levels in households with identical fuel use are affected by factors such as the location of cooking (inside/outside), ventilation through windows and doors, and air flow through building materials. Additional information could have a large social payoff in this context, since simple alterations in structures, ventilation practices, building materials and cooking locations may be much less costly than switching to cleaner fuels or investing in clean stoves.

This paper provides evidence on PM_{10} and $PM_{2.5}$ concentrations in poor households, using new air monitoring data from Bangladesh. Recent technical advances have significantly increased the power, portability and durability of equipment for monitoring particulate pollution. Our study has used two types of equipment: air samplers that measure 24-hour average PM_{10} concentrations, and real-time monitors that record PM_{10} and $PM_{2.5}$ at 2-minute intervals for 24 hours. Each device has advantages that we will describe in the paper. Together, their readings provide a detailed record of

IAP exposure in poor households, in a stratified sample that captures variations in fuel use, cooking locations, structural materials, ventilation practices, and other factors.

Our research has been designed to answer several questions about particulate exposure in poor households. First, is exposure largely confined to areas where combustion occurs? If so, particulate pollution will mostly affect the women who cook and the children whom they supervise. Second, how different are indoor and outdoor air pollution in high-poverty areas where most households burn biomass fuels? If atmospheric persistence of biomass emissions is high, then the difference between indoor and outdoor pollution may be small because air exchange between indoor and outdoor spaces is relatively rapid. Third, what are the actual differences in PM concentrations in houses that use different fuels? Are these concentrations significantly affected by typical variations in cooking practices, cooking locations, structural characteristics and ventilation practice (opening doors and windows)? If such effects are large, then simple alterations in household arrangements may provide a cost-effective alternative to fuel-switching or investment in clean stoves. Fourth, how much do concentrations vary by geographic region and income group? Finally, what are the prospects for increased use of improved stoves and clean fuels in Bangladesh?

The remainder of the paper is organized as follows. Section 2 introduces the indoor air quality problem in Bangladesh, discusses our stratified sampling strategy, and describes the data that have been collected for this exercise. Section 3 provides comparative results for PM_{10} and $PM_{2.5}$, while Sections 4-7 address the questions that have been posed in this introduction. Section 8 compares our findings to recent results for India. Sections 9 and 10 discuss the prospects for adoption of improved stoves and cleaner fuels, and Section 11 provides a summary and conclusions.

2. Pollution Factors, Sampling Strategy and Data Description

Previous studies have identified several potential determinants of exposure to indoor air pollution: fuel type, time spent in cooking, structural characteristics of houses, and household ventilation practices (opening of windows and doors, etc.) (World Bank, 2002, Brauer and Saxena, 2002, Moschandreas et al, 2002, Freeman and Sanez de Tajeda, 2002). All of these factors may be important in Bangladeshi households, which exhibit significant diversity in cooking fuels, stove types, cooking locations, and quality of ventilation.

In Bangladesh, middle- and upper-income households in urban areas typically use electricity or relatively clean cooking fuels such as natural gas. However, households in peri-urban and rural areas rely primarily on biomass fuels. These include wood, twigs and leaves, animal dung, and agriculture residues such as straw, rice husks, bagasse, and jute sticks. Seasonal and economic factors may dictate the use of different biomass fuels over the annual cycle.

Given the level of emissions from fuel use, the particulate concentration in a space depends on the length of time the emitted particles remain, as well as the ambient (outdoor) concentration. The extent and duration of smoke in the kitchen, and the amount of smoke leaking from the kitchen into the outdoors or other living spaces, may depend on several structural factors: the location of the kitchen, the extent of ventilation, and the porous nature of materials used to construct the roof and walls of the kitchen.

Bangladeshi rural and peri-urban households have a number of cooking arrangements. In many cases, kitchens are not enclosed by four walls and a ceiling. Some poor homes do not have separate kitchens; cooking takes place inside the single dwelling room during the rainy season and outside during the dry season. In others, kitchens have three walls (i.e., the entrance is entirely open), with or without a roof. Others have four walls and a gap of a few inches between the walls and the roof. Figure 1 provides descriptions of six typical kitchen arrangements that may have a significant effect on the duration of particles from combustion.

Particle duration may also depend on other characteristics of a house that affect ventilation, such as the number of rooms, the number, size and placement of doors and windows, and materials used in the construction of walls and roofs. In Bangladesh, houses incorporate many combinations of these characteristics.

We have used stratified sampling in urban and peri-urban areas of Dhaka to incorporate representative variations in fuel use, cooking arrangements and structural characteristics that affect ventilation.[1] We separated the households into groups defined by cooking fuel, kitchen type and location, and construction material. Then we selected samples independently from each group. Tables 1a and 1b present the characteristics of the samples for our two air monitoring devices. The 24-hour real-time monitors are much more costly, so their deployment was more limited and the sample consequently smaller. In almost all cases, we generated comparable results by deploying our air samplers alongside the real-time monitors.

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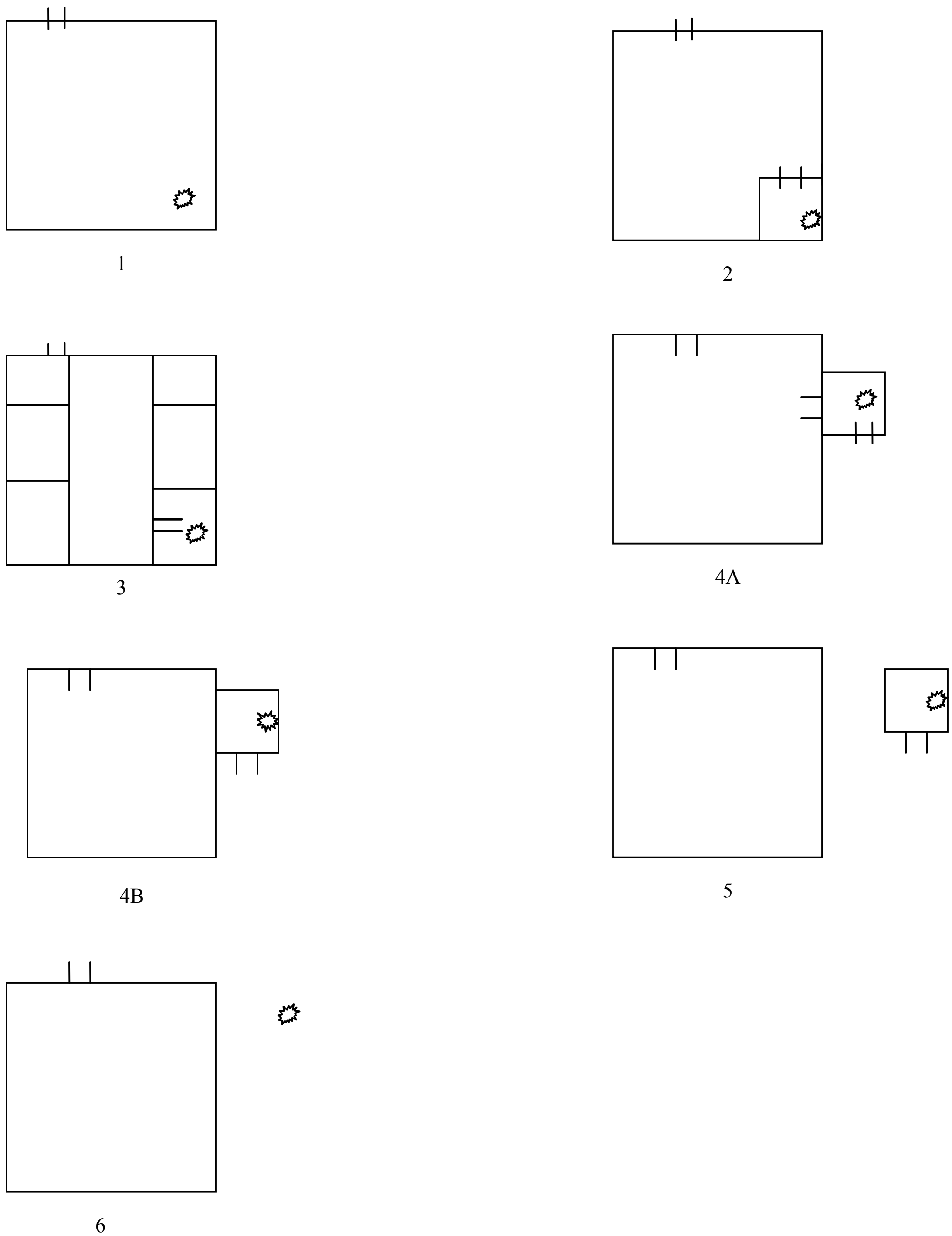
[1] Although we use the term "peri-urban" to describe areas proximate to Dhaka, our sample includes many rural farm-households.

Figure 1: Cooking Locations in Bangladeshi Households
(Stove denoted by)



In each household, we monitored PM_{10} concentrations in the kitchen and living room during the period December, 2003 – February, 2004. For a subsample of households, we also monitored $PM_{2.5}$ concentrations. We monitored most houses for one day, and a few for two days. Our real-time monitoring instrument is the Thermo Electric Personal DataRAM (pDR-1000) (Thermo Electron, 2004). The pDR-1000 uses a light scattering photometer (nephelometer) to measure airborne particle concentrations.[2] At each of 67 locations, the instrument operated continuously, without intervention, for a 24-hour period to record PM_{10} concentrations at 2-minute intervals.

Our other instrument is the Airmetrics MiniVol Portable Air Sampler (Airmetrics, 2004), a more conventional device that samples ambient air for 24 hours. While the MiniVol is not a reference method sampler, it gives results that closely approximate data from U.S. Federal Reference Method samplers. Our MiniVols were programmed to draw

Table 1a: Sample Composition (Kitchens): Thermo Electric Personal DataRAM

Fuel Type		Kitchen Type		Construction Material	
Gas, Electricity, Kerosene	6	Single room dwelling, no separate kitchen	9	Wall: Thatch	24
Firewood, Twigs, Leaves	31	Kitchen with a partition (4 walls and a roof)	11	Wall: Tin	22
Cow Dung	15	Separate, attached kitchen (4 walls and a roof)	14	Wall: Mud	14
Rice Husks, Straw, Jute Sticks, Bagasse, Sawdust	15	Separate, detached kitchen (4 walls and a roof)	31	Wall: Brick/ Mud, Roof: Other than Concrete	4
		Outside/ open kitchen (0 walls, no roof)	2	Wall: Brick/ Mud, Roof: Concrete	1
Total Number of Households	67	Total Number of Households	67	Total Number of Households	65

[2] The operative principle is real-time measurement of light scattered by aerosols, integrated over as wide a range of angles as possible.

Table 1b: Sample Composition (Kitchens): Airmetrics MiniVol Air Sampler

Fuel Type		Kitchen Type		Construction Material	
Gas, Electricity, Kerosene	35	Single room dwelling, no separate kitchen	36	Wall: Thatch	100
Firewood, Twigs, Leaves	89	Kitchen with a partition (4 walls and a roof)	37	Wall: Tin	37
Cow Dung	42	Separate, attached kitchen (4 walls and a roof)	43	Wall: Mud	39
Rice Husks, Straw	16	Separate, detached kitchen (4 walls and a roof)	89	Wall: Brick/ Mud, Roof: Other than Concrete	9
Jute Sticks, Bagasse, Sawdust	54	Outside/ open kitchen (0 walls, no roof)	31	Wall: Brick/ Mud, Roof: Concrete	20
Total number of households	236	Total number of households	236	Total number of households	205

air at 5 liters/minute through PM_{10} and $PM_{2.5}$ particle size separators (impactors) and then through filters. The particles were caught on the filters, and the filters were weighed pre- and post exposure with a microbalance. We operated the air samplers at 236 locations.

3. Sample Evidence: PM_{10} vs. $PM_{2.5}$

We focus on PM_{10} in this paper because our monitoring sample is much larger. However, we have also monitored $PM_{2.5}$ at over 80 sampling points, to assess the stability of the relationship between the two measures. Overall, we find an extremely stable relationship: The mean ratio ($PM_{2.5}/PM_{10}$) is .51, with a standard error of .02. This implies a 95% confidence interval of .47 - .55. As Table 2 shows, the ratio does not vary significantly across biomass fuels for which we have information. Our results suggest that the PM_{10} results in this paper can reasonably be recast as $PM_{2.5}$ results, simply by dividing them by 2.

Table 2: $PM_{2.5}/PM_{10}$ Ratios for Biomass Fuels

Fuel	Ratio	Houses
Dung	0.52	22
Firewood	0.51	18
Straw	0.56	4
Branches, Twigs	0.56	16
Total	0.51	85

4. Is Exposure Largely Confined to Cooking Areas?

Analyses of indoor air pollution in poor households often stress the health risks for women who cook and children under their supervision in cooking areas (Rosemarin, 2002; Smith, 2000). Higher health risks are attributed to two factors: higher pollutant concentrations in cooking spaces, and longer times spent indoors. This section examines the first factor, using our 24-hour real time (PDRam) monitoring results for PM_{10} in kitchens and living rooms. Section 6 reports equivalent results from the MiniVol samplers for a large sample of households. In a forthcoming paper, we will compare times spent indoors by different age / sex groups.

Figure 2a displays the time paths of PM_{10} concentrations in four representative households. We express concentrations in log form to prevent visual scaling problems in the graphs. Although the 24-hour patterns in the four graphs are quite different, all four exhibit very close tracking of PM_{10} concentrations in the kitchen and living room. The 2-minute observations for the kitchens exhibit many short-interval "spikes", and the living room observations closely resemble smoothed versions of the kitchen series.

Remarkably, Figure 2b shows that the close relationship can hold even when cooking is done outdoors. Table 3 provides log-log regression results for various 2-minute lag structures. The implied adjustment lag is very short, and the overall fit is obviously very strong. Summary evidence for all households indicates that the observations in Figure 2 are very common in our sample. The correlation coefficient for the PDRam households is .93 for median PM_{10} concentrations in kitchens and living rooms; Figure 3 illustrates the strength of the relationship. To summarize, the PDRam evidence strongly indicates that air pollution from cooking diffuses into living spaces very rapidly, and at similar intensity.

Figure 2a: Comparative PM_{10} Concentrations in Four Bangladeshi Houses: Kitchens and Living Rooms

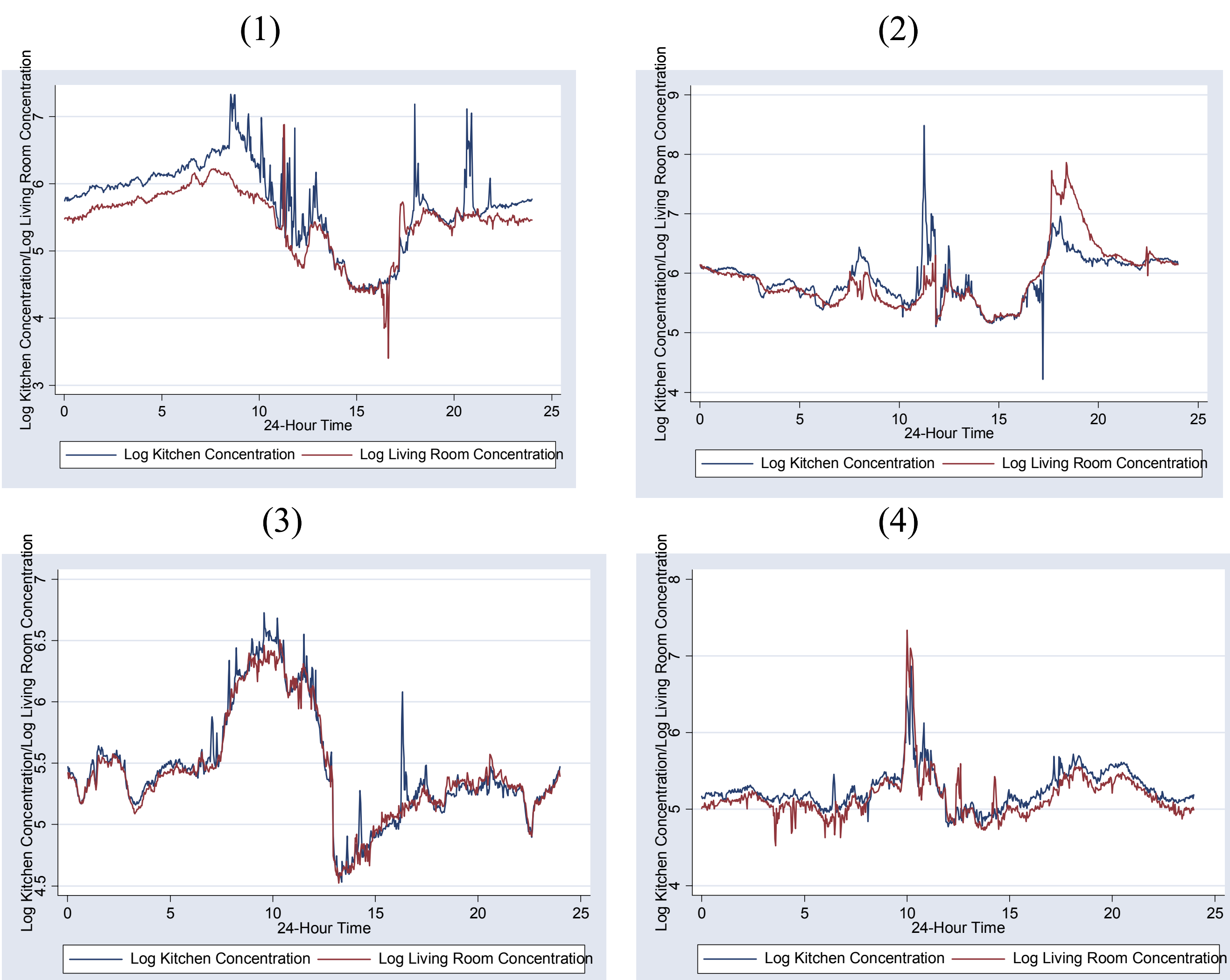
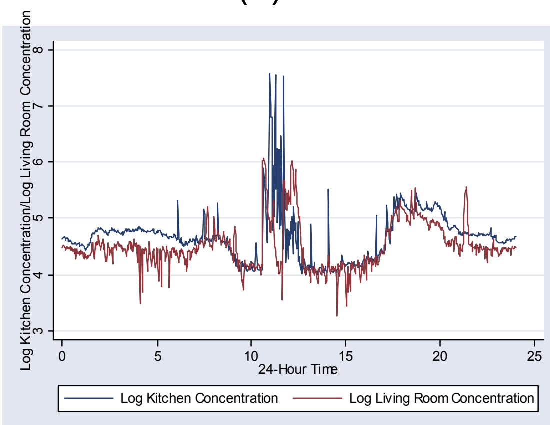
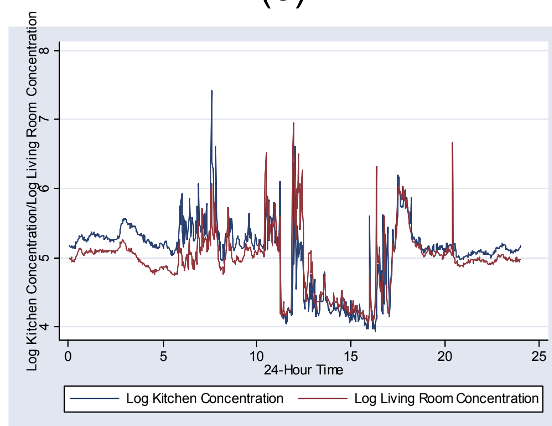


Figure 2b: PM_{10} Concentrations: Outdoor Kitchens vs. Living Rooms

(5)



(6)



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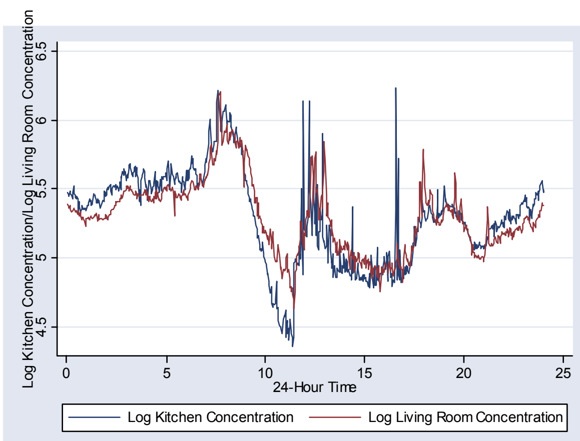

Figure 3: Household PM_{10} Concentrations: Kitchens vs. Living Rooms

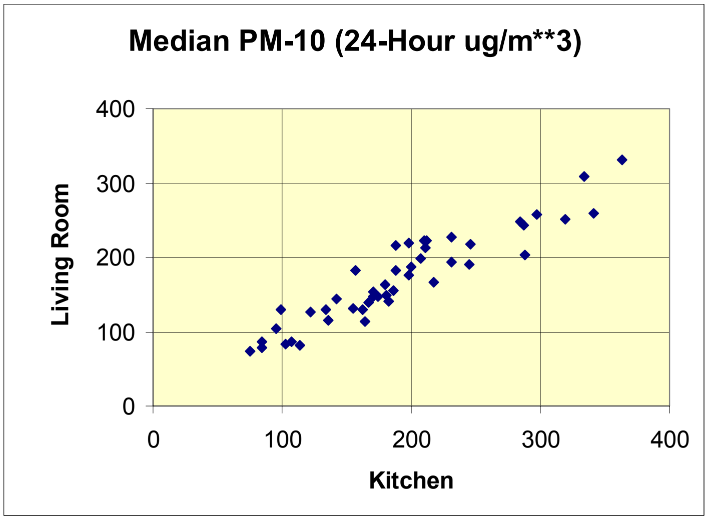

Table 3: Living Room vs. Kitchen PM_{10} Concentrations: Lag Relationship

Dependent Variable: Log Living Room PM_{10}

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log Kitchen PM_{10}	0.770 (253.14)**	0.383 (37.79)**	0.366 (36.59)**	0.345 (34.44)**	0.336 (33.68)**	0.328 (32.87)**	0.326 (32.67)**
L1		0.405 (39.93)**	0.121 (8.97)**	0.129 (9.64)**	0.120 (8.99)**	0.121 (9.07)**	0.116 (8.72)**
L2			0.314 (31.34)**	0.123 (9.16)**	0.129 (9.63)**	0.122 (9.10)**	0.122 (9.16)**
L3				0.212 (21.22)**	0.070 (5.23)**	0.075 (5.61)**	0.069 (5.17)**
L4					0.159 (15.93)**	0.051 (3.84)**	0.056 (4.16)**
L5						0.121 (12.11)**	0.030 (2.22)*
L6							0.103 (10.28)**
Const	1.094 (67.98)**	1.001 (62.97)**	0.933 (58.94)**	0.892 (56.23)**	0.862 (54.19)**	0.842 (52.65)**	0.825 (51.33)**
Obs	33,096	33,061	33,015	32,969	32,923	32,877	32,831
R^2	0.66	0.68	0.68	0.69	0.69	0.69	0.69
Adj. R^2	0.66	0.68	0.68	0.69	0.69	0.69	0.69

Absolute value of t statistics in parentheses
* significant at 5%; ** significant at 1%

5. Outdoor vs. Indoor Air Pollution

Policy researchers often view indoor and outdoor air pollution as separate problems in developing countries. Although a rationale is seldom provided, this distinction reflects two beliefs: that indoor pollution is a more serious problem for poor households, particularly in rural areas, and that outdoor pollution is distinct because it comes from multiple sources that may be distant from the household. Our 24-hour monitoring data for a Dhaka household with an extremely clean fuel – piped natural gas – provide us with some insight in this context, because we have also monitored the ambient concentration at five locations in urban Dhaka.

Figure 4 displays the 24-hour concentrations separately and overlaid. The kitchen readings for the natural-gas household closely resemble the ambient readings. The ambient readings, in turn, appear related to the daily cooking cycle for the great majority of households that use biomass fuels.[3] Because outdoor air rapidly replaces indoor air, the indoor concentration in a clean-fuel household closely reflects the ambient concentration. In urban Dhaka, our MiniVol readings at five outdoor locations yield a mean 24-hour concentration of 89 ug/m^3.[4] The mean daily concentration for the natural gas household monitored with a PDRam unit is 101 ug/m^3. For a broader group of 10 urban households monitored by our MiniVol sampler, the mean daily outdoor 24-hour concentration is also 101 ug/m^3. By implication, burning piped natural gas adds negligible PM_{10} pollution to cooking and living spaces.

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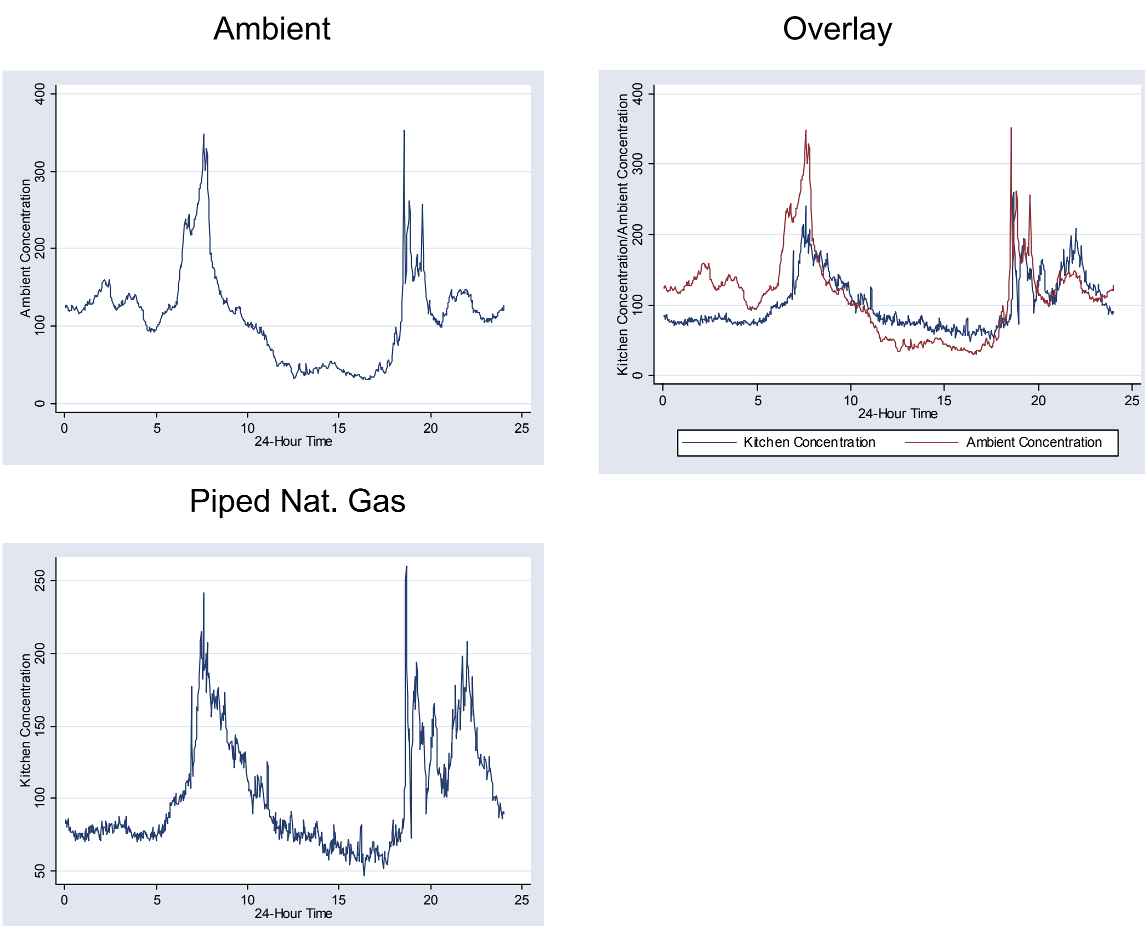
[3] The 24-hour cycle of ambient PM_{10} concentrations is very similar to the pattern of average hourly residuals from a panel regression that controls for differences in average PM_{10} concentrations for households that use biomass fuels.

[4] For comparison, we cite PM_{10} concentration measured by the Bangladesh Air Quality Management Program monitor situation at the Parliament building in Dhaka. From March, 2002 to February, 2003, the mean daily concentration was 137 ug/m^3. Our thanks to our colleague Paul Martin for this contribution.

Our comparative ambient monitoring in peri-urban Dhaka has been undertaken in areas with rural characteristics, well-removed from major transport arteries and industrial sites. MiniVol monitoring at three locations yields a mean 24-hour concentration of 48 ug/m^3, which compares favorably with the Indian safe standard of 100 for rural areas (World Bank, 2002). Nevertheless, our results suggest that ambient pollution from biomass burning is substantial in rural villages.

Figure 4: PM_{10} Concentrations: Outdoor vs. Indoor for Piped Natural Gas



6. Sources of Variation in Household PM_{10} Concentration

In this section, we provide comparative evidence from both monitoring devices. The two instruments use completely different monitoring techniques (weighted filters for the MiniVol, laser optics for the PDRam), so we use regression analysis to compare their readings for a common sample of kitchen and living spaces. For each PDRam reading, we use the 24-hour mean of 2-minute observations as the closest approximation to the corresponding MiniVol reading.

Table 4: Comparative PM_{10} Concentrations: MiniVols vs. PDRams

Dependent Variable: MiniVol PM_{10} Concentration	Coefficient	t-Statistic
PDRam 24-Hour Mean PM_{10} Concentration	0.84	9.27
Constant	73.88	2.95
Observations	85	
Adjusted R^2	0.50	

Our results (Table 4) suggest a reasonably close correspondence between readings from the two devices. Across the common sample of 85 kitchens and living rooms, mean PM_{10} concentrations are 261 for the PDRams and 272 for the MiniVols. The regression of MiniVol readings on PDRam readings yields highly-significant parameter estimates and an adjusted R^2 of .50. The regression constant is 73.88 and the marginal coefficient is 0.84 (i.e., the predicted MiniVol reading increases .84 ug/m^3 for each increase of 1 ug/m^3 in the PDRam reading). Although the overall means for the two devices are almost identical, the regression result suggests that MiniVol readings tend to be higher than PDRam readings in houses with below-average readings, and lower in houses with above-average readings. Since the MiniVol results reflect the current scientific convention for measuring indoor air pollution, we rely on them for our cross-sectional analysis.

However, the PDRam readings in Figure 2 provide a very useful perspective on the timing of pollution. They show that the largest source of variation in PM_{10} concentrations is the 24-hour cycle in individual households. Peaks occur during morning and evening cooking periods, and houses with three cooking periods have an additional peak. Typically, concentration levels plunge in the afternoon in houses where kitchens are aired out, and they fall in the evening as well (although often not as far, since windows and doors may be closed at night). Most houses have relatively low concentrations for significant parts of the day.

Inter-household differences in pollution exposure are largely attributable to two factors: the level of peak concentrations during cooking, and the rate at which concentrations decline after cooking. As Figure 2 suggests, these factors differ substantially from house to house. Their significance emerges strikingly when we control for fuel use. Table 5 presents MiniVol PM_{10} statistics for sample households in the three most common fuel-use categories: firewood, dung and jute. None of these households reports using an improved stove or a chimney. Across households, PM_{10} concentrations vary from 84 to 1165 ug/m^3 for firewood, 60 to 755 for dung, and 72 to 727 for jute. As Figure 2 indicates, many houses are relatively "clean" during parts of the night and afternoon, when indoor readings resemble ambient readings. However, differences in cooking practices, structural arrangements and ventilation behavior generate very large differences in overall concentrations. As a result, some households

Table 5: Household PM_{10} Concentrations (ug/m^3) by Fuel

Fuel	Sample Households	Mean	Minimum	1st Quartile	Median	3rd Quartile	Maximum
Dung	95	291	60	172	231	380	755
Firewood	159	263	84	161	201	323	1165
Jute	68	190	72	136	165	219	727

using "dirty fuels" such as firewood, dung and jute have PM_{10} exposures resembling those for natural gas, while others face concentrations at extremely high levels.

Of course, part of the variation across households is also determined by fuel use. Table 6 summarizes the MiniVol data for cooking areas across all households, by fuel type. While these descriptive statistics provide some insight, they can be misleading because fuel choices may be correlated with other variables in the sample: cooking practices, structural characteristics and ventilation practices. In Table 6, the cleanest fuels are natural gas (101 ug/m^3) and kerosene (134). As we have previously noted, these concentrations are not far above urban ambient pollution levels. Among biomass fuels, dung seems to be the dirtiest fuel (291 ug/m^3), followed by firewood (263), sawdust (237), straw (197), jute (190), and twigs and branches (173). In our sample, the relatively few households using LPG/LNG have an average PM_{10} count (206) above the level for several biomass fuels. We attribute the elevated PM_{10} concentrations in these households to several factors: Ambient pollution from biomass cooking in the same locality, ambient pollution from other sources (e.g., motor vehicles, industrial sources), underreporting of complementary biomass fuel use (particularly for LPG/LNG), and particulate pollution from the fuels themselves. Recent monitoring research has suggested that kerosene is a significant PM_{10} source when burned indoors (Leaderer, et al., 1999), and even natural gas produces some PM_{10} (Beer, 2000).

Table 6: Mean PM_{10} Concentration by Fuel Used (MiniVols)

Fuel	Mean (ug/m^3)	Households
Dung	291	95
Firewood	263	159
Sawdust	237	7
LPG/LNG	206	8
Straw	197	29
Jute	190	68
Twigs, Branches	173	46
Kerosene	134	18
Piped Nat Gas	101	20

In order to assess the role of other factors (which may be correlated with fuel use), we have used regression analysis to explore the relationships between PM_{10} concentrations and a large set of variables that describe household cooking and ventilation practices, structure characteristics and building materials. The variables tested are described in the Appendix. Besides fuels employed during the monitored day, these include cooking time, duration of fire after cooking, numbers of people cooked for, stove location (see Figure 1), the use of iron, mud, thatch and concrete for construction, the placement and size of windows, doors and ventilation spaces between walls and roofs, ventilation practices such as opening doors and windows after cooking, smoking practices, and the use of lanterns and mosquito coils.

Among these variables, we find a small set that significantly affect household PM_{10} concentrations through their impact on ventilation: Stove locations, building materials, and opening doors and windows after cooking. Regression results are summarized in Table 7. The first column provides joint estimates for kitchens and living areas; the others provide estimates for the two spaces separately. Columns 3 and 4 drop the control for the relatively weak effect of opening doors and windows after midday cooking.

Table 7: Regression Results: Determinants of PM_{10} Concentrations In Kitchens and Living Areas[a]

	Kitchen & Living	Kitchen	Kitchen	Living
Living Room Dummy	-40.057			
	(3.52)**			
Mud Walls	252.921	261.472	253.896	229.729
	(9.84)**	(6.67)**	(6.53)**	(6.39)**
Mud Walls,	-158.160	-121.130	-124.058	-163.725
Detached Kitchen	(3.99)**	(1.72)	(1.76)	(3.83)**
Thatch Roof	-100.357			-70.898
(Living Room)	(5.17)**			(6.01)**
Kitchen Windows, Doors	-32.016	-39.906		
Open After Midday Meal	(2.25)*	(1.79)		
Detached Kitchen	-46.711	-40.672	-37.599	-57.381
	(4.25)**	(2.48)*	(2.44)*	(4.86)**
Open-Air Kitchen	-64.134	-88.337	-79.887	-80.504
	(4.31)**	(4.11)**	(3.77)**	(5.90)**
Jute	-41.136	-40.645	-45.233	-41.225
	(3.45)**	(1.97)	(2.20)*	(3.27)**
Kerosene	-89.758	-103.172	-106.729	-76.197
	(8.15)**	(6.59)**	(7.46)**	(6.68)**
Lpg/Lng	-102.597	-113.334	-112.523	-89.441
	(4.16)**	(3.16)**	(3.40)**	(3.04)**
Piped Natural Gas	-136.411	-144.226	-155.285	-135.870
	(12.09)**	(9.27)**	(10.22)**	(10.07)**
Constant	289.830	287.410	258.563	235.342
	(16.43)**	(11.47)**	(17.47)**	(19.94)**
Observations	424	207	234	246
R-squared	0.46	0.41	0.40	0.54

[a] Huber-White robust t statistics in parentheses

Robust t statistics in parentheses
significant at 5%; ** significant at 1%

The results provide several insights into the sources of variation in indoor air pollution in Bangladeshi households. First, PM_{10} concentrations in living areas are lower to a relatively small but significant degree. The living-area adjustment in regression 1 is -40.1, or about 16% of mean PM_{10} for kitchens. Comparison of the kitchen and living-area regressions suggests similar responses to fuel and ventilation factors. In the following discussion, we focus on the combined-area results (regression 1).

Controlling for factors correlated with fuel use provides a significantly different view of fuel-based pollution factors. Our combined-area results suggest that among biomass fuels, jute is a negative outlier, and all others (dung, firewood, twigs and branches, rice husks, straw) cannot be distinguished from one another. With other biomass fuels as the baseline, use of jute subtracts about 41 ug/m^3 from the indoor PM_{10} concentration. Relative to the biomass baseline, kerosene subtracts about 90 ug/m^3, lpg/lng 103, and piped natural gas 136. These results contrast significantly with the unadjusted means in Table 6, which are misleading because they do not account for correlation with ventilation factors. There are particularly divergent results for dung and lpg/lng, whose estimated relative contributions to PM_{10} are higher in Table 6 than in Table 7.

Our results highlight the importance of ventilation factors in the determination of PM_{10} concentrations. We find that two construction factors – mud walls and thatch roofs – have highly significant effects on ventilation. Mud walls are particularly important in this context. In most localities in Bangladesh, the soil has low sand content and mud walls and floors are frequently re-coated with fresh mud to prevent cracking. This creates an effective seal that permits almost no ventilation by comparison with thatch and corrugated iron, the other two common building materials.

The effect of mud-wall construction depends on the location of cooking. If it is inside the house, the sealing effect of mud walls increases the PM_{10} concentration by 253 ug/m^3 in the baseline case. If cooking occurs in a detached or open-air location, mud walls in the kitchen have the same sealing effect. However mud walls in the living room have an insulating effect when the kitchen is outside, and the overall PM_{10} concentration is reduced by 158 ug/m^3. For other construction materials, the PM_{10} concentration is reduced 47 ug/m^3 by having a detached kitchen (stove location 5 in Figure 1), and 64 ug/m^3 by having an open-air kitchen. It is further reduced 32 ug/m^3 by opening kitchen doors and windows after the midday meal. We also find a significant ventilation role for thatched roofs in living spaces, which lower the PM_{10} concentration by 100 ug/m^3.

In Table 8, we tabulate the interactive effect of critical pollution factors by computing mean PM_{10} concentrations for groups that distinguish between "clean" (kerosene, natural gas) and biomass fuels, inside and outside (detached or open-air) cooking, and mud-wall and other construction. Table 8(a) tabulates results for all fuels in the sample households, while 8(b) provides the same information for houses using firewood only. We present the information in 8(b) to show how other critical factors affect variations in indoor pollution associated with a single biomass fuel.

Table 8: Pollution Factors and PM_{10} Concentrations

(a) All Fuels

Fuel	Cooking Location	Building Material	Space	Abbrev.	Mean PM_{10}	Median PM_{10}	Houses	Difference in Mean (From BIOL)	t-statistic
Biomass	Inside	Mud	Kitchen	BIMK	515	528	23	292	11.15
Biomass	Inside	Mud	Living	BIML	467	453	20	244	8.86
Biomass	Outside	Mud	Kitchen	BOMK	351	258	22	128	4.81
Biomass	Inside	Other	Kitchen	BIOK	250	220	74	27	1.46
Biomass	Outside	Mud	Living	BOML	244	218	29	21	0.87
Biomass	**Inside**	**Other**	**Living**	**BIOL**	**223**	**213**	**62**		
Biomass	Outside	Other	Kitchen	BOOK	203	191	101	-20	-1.16
Biomass	Outside	Other	Living	BOOL	166	162	116	-57	-3.41
Clean				CLN	133	117	46	-90	-4.34
Overall					231	187	493		

(b) Firewood Only

Cooking Location	Building Material	Space	Abbrev.	Mean PM_{10}	Median PM_{10}	Houses	Difference in Mean (From BIOL)	t-statistic
Inside	Mud	Kitchen	BIMK	498	520	10	248	5.24
Inside	Mud	Living	BIML	475	443	9	226	4.59
Outside	Mud	Kitchen	BOMK	638	567	5	389	6.33
Inside	Other	Kitchen	BIOK	267	220	31	17	0.49
Outside	Mud	Living	BOML	293	301	4	44	0.65
Inside	**Other**	**Living**	**BIOL**	**250**	**210**	**21**		
Outside	Other	Kitchen	BOOK	210	193	35	-39	-1.15
Outside	Other	Living	BOOL	165	163	44	-84	-2.58
Overall				263	201	159		

The tables reveal a nearly-identical pattern of results for all fuels and firewood only, so we focus on the results for all fuels. For statistical comparison of means, our benchmark is the mean living-space PM_{10} concentration for households with biomass fuels, inside cooking and non-mudwall construction (acronym BIOL in the tables). The mean concentrations for these households are 223 ug/m^3 for all fuels, and 250 ug/m^3 for firewood. By comparison, cooking and living spaces have far greater pollution for inside cooking and mud-wall construction (BIMK, BIML). In these cases, mean PM_{10} concentrations for kitchens and living areas are 515 and 467 ug/m^3, and the differences from the benchmark (BIOL) mean are highly significant. Outside kitchens with mud-wall construction also have much higher pollution (351 ug/m^3 – a highly-significant difference from BIOL). However, the mean concentration for mud-wall living rooms with outside cooking (BOML) is no higher than the BIOL benchmark. This reflects the symmetric effect of mud walls, which act as a sealant against airflow in or out of the living area. For other building materials, outside cooking generates a kitchen concentration (BOOK) that is not significantly different from the benchmark concentration. However, the living room concentration in the same case (BOOK) is significantly lower than the benchmark case. As expected, clean-fuel households have the lowest mean concentration (133), which is significantly (90 ug/m^3) lower than the benchmark case. Our clean fuel results are quite similar to those obtained by earlier studies in Chile (Pino, et al., 1998; Caceres, et al., 2001) and India (Balakrishnan, et al., 2002; Parikh, et al., 2001).

Replication of this pattern in the firewood-only case highlights an important implication of the results: Two ventilation factors – kitchen location and mud-wall construction – account for very large differences in PM_{10} concentrations across households. This is as true for a single biomass fuel (firewood) as it is for all fuels combined.

7. PM_{10} Concentrations by Geographic Area and Income Group

We have analyzed the determinants of indoor air pollution using a stratified sample of urban and peri-urban households in the Dhaka region. Our stratification has been designed for cell values large enough to test fuel and ventilation effects, and is not intended to represent all Bangladeshi households. However, extrapolation of our results requires more representative household samples. Accordingly, we have surveyed households in six areas of Bangladesh whose major cities are identified in Figure 5: Rangpur (Northwest), Rajshahi (West Central), Jessore (Southwest), Sylhet (Northeast), Faridpur (Central) and Cox's Bazar (Southeast). In each region, we have attempted to randomly survey 50 rural households, 25 peri-urban households, and 25 urban households. Implementation difficulties intruded in Rangpur, but otherwise, the data in Table 9 reflect our original intent.

Table 9: Household Sample Sizes by Area

Area	Rural	Peri-Urban	Urban	Total
Cox's Bazar	51	24	25	100
Faridpur	50	25	25	100
Jessore	50	25	25	100
Rajshahi	54	21	24	99
Rangpur	25	25	50	100
Sylhet	49	25	25	99
Total	279	145	174	598

We have sampled by locality to assess the impact of local differences in ventilation characteristics and fuel use. To indicate the potential significance of these differences, Table 10 presents the rural incidence of four important determinants of indoor air pollution: mud walls, thatch roofs, detached kitchens and open-air kitchens.

Figure 5: Household Survey Regions in Bangladesh

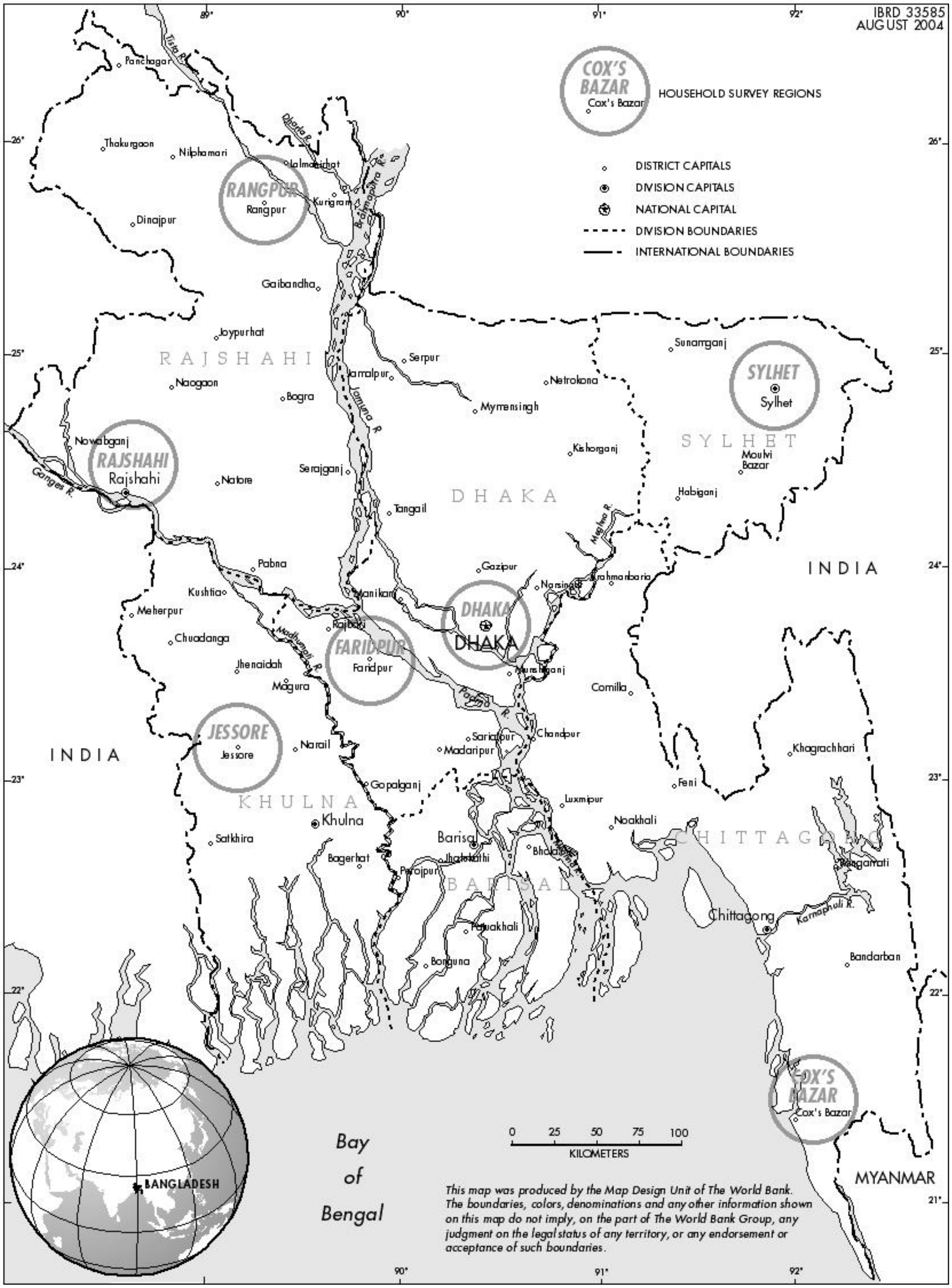


Table 10: Determinants of Indoor Air Pollution
Six Rural Areas of Bangladesh

	Sample Incidence of Pollution Factors			
Rural Area of:	Mud Walls %	Thatch Roof %	Detached Kitchen %	Open-Air Kitchen %
Cox's Bazar	71	51	14	0
Faridpur	0	8	60	36
Jessore	64	16	66	12
Rajshahi	89	0	70	7
Rangpur	0	20	72	20
Sylhet	20	18	12	35

Our survey results indicate the potential importance of regional customs and differential availability of building materials and fuels. Mud walls, the most important ventilation characteristic, are extremely common in Cox's Bazar, Jessore and Rajshahi, but extremely scarce in Faridpur and Rangpur. Significant variation is also apparent for thatch roofs. Detached or open-air kitchens are present in 14% of households in Cox's Bazar, 47% in Syhlet, and 96% in Faridpur.

To capture the simultaneous effect of ventilation factors and fuel use in each surveyed household, we use the PM_{10} model in Table 7 to estimate PM_{10} concentrations in kitchens and living areas. We drop ventilation after midday meals because this was not recorded in the country-wide survey, and use of jute fuel because its incidence in our sample is negligible (3 users in 599 households). We tabulate the results by geographic area in Table 11, which highlights the effect of local variations. For kitchens in rural areas, mean estimated PM_{10} concentrations range from 410 in Cox's Bazar to 202 in Faridpur. Similar variation characterizes living spaces, although the range is somewhat more limited. For Cox's Bazar and Sylhet, there is a clear pattern of declining PM_{10} concentration in the transition from rural to urban areas. As Table 12 shows, a significant part of this pattern is attributable to increased use of clean fuels.

Table 11: Mean PM_{10} Concentrations (ug/m^3)

Kitchens

Region	Rural	Peri-Urban	Urban	Total
Cox's Bazar	410	249	181	314
Faridpur	202	203	185	198
Jessore	295	207	199	249
Rajshahi	248	252	204	238
Rangpur	208	205	178	192
Sylhet	246	214	108	203
Total	274	221	176	233

Living Areas

Region	Rural	Peri-Urban	Urban	Total
Cox's Bazar	333	215	164	262
Faridpur	162	165	172	165
Jessore	219	175	168	196
Rajshahi	276	197	181	236
Rangpur	159	163	151	156
Sylhet	212	185	100	177
Total	234	183	155	199

Table 12: % Clean Fuel Use, by Geographic Area

Region	Rural	Peri-Urban	Urban	Total
Cox's Bazar	0	8	64	18
Faridpur	0	12	44	14
Jessore	0	20	28	12
Rajshahi	0	0	42	10
Rangpur	4	8	28	17
Sylhet	0	44	92	34
Total	1	16	47	18

We have also tabulated incomes by source for the surveyed households. Table 13 shows that our sample reflects the generally-high level of poverty in Bangladesh. Overall, 78% of sample households have per capita incomes less than $1.00/day. Across regions, the percentage of households below this extreme-poverty threshold varies from 67% in Sylhet to 94% in Rajshahi.

Table 13: Household Distribution by Income Per Capita (%)

Region	0-$.50	$.51-$1.00	$1.01-$2.00	$2.01-$5.00	$5.01+
Cox's Bazar	41	36	18	3	2
Faridpur	46	28	20	5	1
Jessore	40	36	19	4	1
Rajshahi	62	32	5	1	0
Rangpur	47	33	17	3	0
Sylhet	41	26	20	9	3
Total	46	32	17	4	1

Table 14 displays the distribution of estimated mean PM_{10} concentrations by income group for our sample households. In general, higher-income groups have lower concentrations. For the whole sample, the average concentration is 253 ug/m^3 for the poorest households (0-$.50/day) and declines steadily to 141 for households with $5.00/day or more. An important part of this trend can be attributed to a greater incidence of clean fuel use by higher-income households. However, the importance of regional building and fuel-use patterns again emerges here. For example, average PM_{10} for the highest income group in Cox's Bazar (195 ug/m^3) is almost identical to the concentration for the lowest-income group in Rangpur (198).

Table 14: Kitchen PM_{10} Concentration by Income Group

Region	0-$.50	$.51-$1.00	$1.01-$2.00	$2.01-$5.00	$5.01+
Cox's Bazar	355	330	212	266	195
Faridpur	204	205	181	171	144
Jessore	291	230	218	169	144
Rajshahi	245	237	185	144	.
Rangpur	198	201	170	132	.
Sylhet	244	191	172	156	103
Total	253	236	190	171	141

Table 15: Kitchen PM_{10} Concentrations (ug/m^3): Households With Less Than $1.00/Day Per Capita

Region	Rural	Peri-Urban	Urban	Total
Cox's Bazar	410	267	196	343
Faridpur	202	209	208	205
Jessore	297	209	215	262
Rajshahi	248	252	215	242
Rangpur	208	206	188	199
Sylhet	248	223	122	223
Total	275	226	193	246

Table 15 focuses on the geographic pattern of indoor air quality for households below the extreme poverty threshold (less than $1.00/day). Even among the poorest households, we see large variations that are attributable to within-region differences in construction practices and fuel use. In Cox's Bazar, the rural poor face far higher concentrations than the urban poor, but there is no difference in Faridpur. Overall, households living in extreme poverty face mean concentrations of 275 ug/m^3 in rural areas, 226 in peri-urban areas, and 193 in urban areas.

8. **Comparison with Monitoring Results for India**

A recent monitoring study for Indian households (World Bank, 2002; Balakrishnan, et al., 2002; Parikh, et al., 2001) has provided useful comparative information about indoor pollution levels and their determinants. Table 16 displays average pollutant concentrations by room, stove location and fuel type for the two countries. The Indian data are reported for respirable suspended particulate matter (RSPM), defined as the fraction of inhaled aerosols capable of penetrating the alveolar (gas-exchange) regions of the adult lung. The authors report that ratios of RSPM to PM_{10} varied from 0.57 to 0.73 in their samples, with a mean of .61.

Comparison of Tables 16a (India) and 16b (Bangladesh) indicates both similarities and differences. The India results for gas fuels are almost identical to the Bangladesh results when the latter are multiplied by .61 (the RSPM/PM_{10} ratio). The Indian ambient reading is also within the same range as the Bangladesh urban reading. However, the results for solid (biomass) fuels are quite different. For kitchen areas, the India concentrations are all much higher than their RSPM-adjusted counterparts for Bangladesh. The India concentrations for living areas are also much higher than the Bangladesh concentrations, although the differences are not as extreme.

Both studies have used regression analysis to explore the determinants of indoor air pollution, and both have come to generally-similar conclusions: Fuel choice, cooking location and other ventilation factors all play significant roles. However, the India study finds that fuel choice is the dominant factor, while our results for Bangladesh suggest that ventilation factors are collectively more significant. In the India study, pollution intensity is highest for dung, followed by woodfuels, kerosene and gas. Our estimated means in

Table 6 follow the same pattern, but our multivariate regressions find no statistically-significant difference between dung and woodfuels. Our results suggest that kerosene is somewhat more pollution-intensive than gas, but the difference is much less than the difference in the India study.

Table 16: Comparative Air Pollutant Concentrations (ug/m^3)

16a: India (RSPM ≈ .61 PM_{10})

Area	Fuel	Inside Kitchen With Partition	Inside Without Partition	Detached Kitchen	Open Air Kitchen
Kitchen	Solid	666	652	575	297
	Gas	70	70	86	
Living	Solid	357	559	280	215
	Gas	70	76	96	
Ambient					
91					

Source: World Bank (2002), p. 32

16b: Bangladesh (PM_{10})

Area	Fuel	Inside Kitchen	Detached Kitchen	Open Air Kitchen
Kitchen	Solid	313	248	182
	Gas	134		
Living	Solid	286	189	155
	Gas	129		
Ambient				
Urban			Peri-Urban	
89			48	

9. Use of Improved Stoves

New biofuel stove designs offer the prospect of reduced indoor air pollution, along with more efficient combustion. Air-monitoring research in Guatemala has indicated that improved stoves can lower indoor PM_{10} concentrations by 50% or more (Smith, et al., 1993; McCracken, et al., 1999; Naeher, et al., 2001). In Bangladesh and elsewhere, programs to promote improved stoves have stressed their long-run financial advantages for poor households, as well as their environmental benefits. To date, however, our survey suggests that progress has been quite limited. Of 686 biofuel-using households in our 7-region survey (including Dhaka), only 9 (1.3%) report using an improved stove: 4 in Jessore and 5 in Sylhet. Another 2 households have tried improved stoves, but have stopped using them. Of the 9 current users, 8 are in rural areas.

Our results suggest that limited information may be the greatest deterrent to consideration of improved stoves. Of the 659 biofuel-using households that don't use improved stoves and offer an explanation, 45% claim to be unaware of them. Another 40% state that improved stoves are not available locally. After accounting for these, our sample includes only 105 biofuel-using households that have considered improved stoves. Of these, 9 (8.5%) decided to use one, 49% didn't adopt because of the large initial investment, 39% viewed improved stoves as inconvenient, and the remaining 4% had other reasons for non-adoption.

Jessore and Sylhet may have witnessed greater promotional efforts than other areas. Of the 21 Sylhet households (in our sample of 99) that consider improved stoves a feasible option, 5 (24%) actually use one. In Jessore, 4 of 37 households (11%) with a viable option use improved stoves. In all other regions, we have found no adoption among biofuel-using households. Since 85% of all sample households regard improved stoves as unknown or unavailable, our results suggest that an information strategy may offer the best near-term prospect for promoting clean stove use in Bangladesh.

10. Use of Clean Energy Sources

Among 598 households in our six-region random sample, 108 report using one of five clean energy sources for cooking: Piped natural gas (32), lpg/lng (67), kerosene (5), electricity (3) and biogas (1). Although we have small sample sizes for higher-income groups (Table 17b), our results are consistent with a strong preference for clean energy, even at low incomes (Table 17a). They also suggest wide geographic variation in response to local supply conditions and prices.

In Table 17a, urban and peri-urban use of clean energy rises rapidly with income, reaching 80% among households reporting daily incomes of more than $2.00 per capita. Even among families living in extreme poverty ($1.00 per capita per day or less), clean energy use is used by 29% of the households in urban areas and 10% in peri-urban areas. A striking contrast is provided by rural areas, where clean-energy prices are increased by distance from urban distribution sources. In our sample, there is effectively no use of clean energy in rural areas, regardless of income.

Table 17: Household Use of Clean Energy Sources

(a) Percent of Households Using Clean Energy

	Locality			
Income Per Capita ($US Per Day	Rural %	Peri-Urban %	Urban %	Total %
Less Than $1.00	0.4	9.9	28.9	8.6
$1.00 - $2.00	0.0	37.9	63.6	46.5
More Than $2.00	0.0	80.0	81.8	68.8
Total	0.4	17.9	46.6	18.1

(b) Total Households (Clean & Dirty Energy Sources)

Income Per Capita	Rural	Peri-Urban	Urban	Total
Less Than $1.00	259	111	97	467
$1.00 - $2.00	15	29	55	99
More Than $2.00	5	5	22	32
Total	279	145	174	598

11. Summary and Conclusions

In this paper we have investigated the determinants of indoor air pollution in Bangladesh, using monitoring data for a stratified sample of 236 households in the region of Dhaka. Extrapolating from our results, we have estimated indoor air pollution levels for a random sample of 600 rural, peri-urban and urban households in six regions: Rangpur, Sylhet, Rajshahi, Faridpur, Jessore and Cox's Bazar.

We have used the results of our analysis to address several basic questions about air quality for poor households in Bangladesh:

(1) Does air pollution from cooking primarily affect the women who cook and children who are with them in the kitchen? An appropriate answer to this question must consider both potential exposure (from pollution levels in kitchens and living areas) and actual exposure (from age/sex differences in time spent indoors, in kitchens and living areas. In a future paper, we will analyze the sources and consequences of age/sex differences in exposure time. In this paper, we can only summarize the implications of our results for potential exposure.

Overall, our results suggest that potential exposure is similar in kitchens and living areas. Pollution from cooking diffuses into living spaces rapidly and fairly completely in many cases, so that exposure is similar for all household members who are indoors during the same periods. Table 18 indicates that living-area PM_{10} is about 17% lower than kitchen PM_{10} on average, although regional differences in ventilation factors cause this percent difference to vary considerably. In absolute magnitude, all kitchen PM_{10} concentrations and most living-area levels are above 200 ug/m^3 in all rural areas. As we have noted in the paper, the sealing effect of mud-wall construction can pose a major exception to this general pattern. In a firewood-using, mud-wall household with detached kitchen, for example, cooking women face PM_{10} concentrations over 600 ug/m^3, in contrast to concentrations near 300 in living areas. Neither concentration is healthy, but the latter is obviously more desirable.

Second, differences in ventilation factors produce great variations in potential exposure for all household members, even for poor families that use biomass fuels for cooking. For example, Table 8 shows that ventilation factors can vary typical PM_{10} concentrations in firewood-using households from 210 to 638 ug/m^3.

Table 18: Percent Difference: Kitchen vs. Living Area PM_{10}

Region	Rural	Peri-Urban	Urban	Total
Cox's Bazar	23	16	11	20
Faridpur	25	23	8	20
Jessore	34	18	18	27
Rajshahi	-10	28	13	1
Rangpur	31	26	18	23
Sylhet	16	16	8	15
Total	17	21	13	17

(2) How are indoor and outdoor pollution related? Our analysis suggests that ambient pollution contributes significantly to indoor pollution, with pronounced effects for households that use clean fuels. During our sample period, ambient pollution created a daily indoor pollution "baseline" near 100 ug/m^3 in urban Dhaka, and a baseline near 50 ug/m^3 in peri-urban areas. Since many of the latter are actually rural (no proximate motor roads or industries), our results suggest that diffusion of smoke from biomass cooking is sufficient to produce ambient pollution of 50 ug/m^3.

(3) How much difference does fuel choice make for indoor air pollution? After allowing for the effect of household ventilation characteristics, we find very significant

differences between biomass and "clean" fuels. As Table 8 shows, mean PM_{10} in clean-fuel households is 133 ug/m^3 – little higher than ambient pollution in the urban area where most clean fuels are used. For biomass-using households, on the other hand, the average concentration is 242 ug/m^3. Among biomass fuels, we fine a statistically significant difference only for jute (about 40 ug/m^3 lower). However, as we noted in Section 7, very few households in our sample use jute as cooking fuel.

For biomass fuels, a cautionary note is introduced by large differences in median and mean exposures recorded by our 24-hour monitors. Very large pollution "spikes" for short periods (e.g., 10,000 ug/m^3 or higher) under some conditions can have large effects on estimated mean concentrations. Median concentrations are often much lower. This difference highlights the importance of better information about the time-structure of the relationship between pollution and respiratory disease. To illustrate the problem, for two houses with identical mean concentrations, is it better to experience two daily PM_{10} spikes of 5,000 ug/m^3, with very low levels for the rest of the day, or constant exposure at 150ug/m^3 over the 24-hour cycle? Limited evidence from time series studies has not yet provided a robust answer.[5] Given the intensity of indoor pollution spikes under some conditions, further research on this issue seems warranted.

(4) How important is fuel choice for pollution when we account for other household characteristics? Although fuel choice certainly affects indoor air pollution, our results suggest that its role is secondary to the role of ventilation factors for Bangladeshi

[5] The available evidence is for outdoor particulates in industrial economies, and may have limited relevance for indoor air pollution from biomass fuels. Studies of short exposures to outdoor particulate concentrations suggest some impact on heart rate variability and the rate of heart attacks. However, a recent study in Palm Springs, California suggests that the short-period effect disappears when 24-hour average exposure is controlled for. Similarly, average exposures seem to dominate day-to-day variations in daily time series studies. Our thanks to Dr. Bart Ostro, Chief, California Office of Environmental Health Hazard Assessment, for his insights.

households. Moving from indoors to an open kitchen lowers the PM_{10} concentration in cooking and living areas by almost the same magnitude as switching from firewood to kerosene. Switching from mud walls to other materials lowers PM_{10} far more than any other factor, and use of thatch roofs also has a large effect.

(5) In a representative sample of households, how serious is the indoor air quality problem for poor families in Bangladesh? For our assessment, we adopt the Indian rural PM_{10} exposure standard: a 24-hour average of 100 ug/m^3. Our results for six Bangladeshi regions suggest that indoor PM_{10} concentrations are quite high for many poor families. For all rural families with per capita incomes below $1.00/day, we estimate a mean PM_{10} concentration of 275 ug/m^3 for kitchen spaces -- nearly three times the Indian standard. This falls somewhat in peri-urban and urban areas (to 226 and 193 ug/m^3, respectively), but remains much higher than the standard.

(6) Are there significant geographic variations in indoor air quality? Our results suggest great geographic variation, even for households in the same per capita income group. This variation reflects local differences in fuel use and, more significantly, construction practices that affect ventilation. For the poorest households, rural PM_{10} concentrations vary from 410 ug/m^3 in Cox's Bazar to 202 ug/m^3 in Faridpur. Even in urban areas, concentrations differ by almost 100 ug/m^3 between the highest areas, Jessore and Rajshahi, and the lowest, Sylhet. The poorest households in Rangpur face the same mean indoor concentration (198 ug/m^3) as the highest-income households in Cox's Bazar.

(7) What are the prospects for clean stoves and clean fuels?

Our survey suggests that limited information may be a significant impediment to adoption of improved stoves. Only 15% of our sample households regard improved stoves as a viable option, either because they have not heard of them or because they do not think they are locally available. Even among families that have considered the option, however, improved-stove use appears quite limited because of concerns about convenience or initial investment cost.

The intermediate-term prospects for clean-fuel use appear more hopeful in urban and peri-urban areas, if economic growth continues. Although our sample evidence is limited, it suggests very high adoption rates among families whose daily per capita incomes exceed \$2.00. Only 30% of extreme-poverty families use clean fuels, even in urban areas where their prices are relatively low. In rural areas, our evidence offers little hope for adoption of clean fuels in the near future.

However, our analysis also suggests that poor families may not have to wait for clean fuels or clean stoves to enjoy significantly cleaner air. Within our sample household population, some arrangements are producing relatively clean conditions, even when “dirty” biomass fuels are used. Since these arrangements are already within the means of poor families, the potential for cost-effective improvements may be larger than is commonly believed.

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Appendix

Cooking and Ventilation Behavior, Structural Characteristics and Building Materials:
Data Recorded for the Day of PM_{10} Monitoring
and Tested for PM_{10} Impact via Regression Analysis

1. Characteristics of house

No of stories in house
No of rooms in the house
(excluding toilet, kitchen and lawn)
Is there a chimney?
For cooking events during the monitored day:

Cooking Period	Number Cooked For	Cooking Time	Time Fire Continued After Cooking
1			
2			
3			
…			

2. Characteristics of Living Area

Roofing material
1.□ Tile 2.□ Thatched 3.□ Concrete
4.□ Corrugated Iron

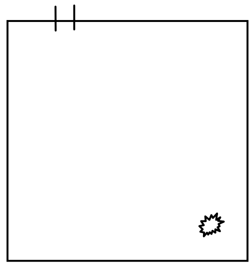
Wall construction material
1.□ Brick wall 2.□ Thatched 3.□ Concrete
4.□ Corrugated Iron 5.□ Wood 6.□ Mud

3. Characteristics of kitchen

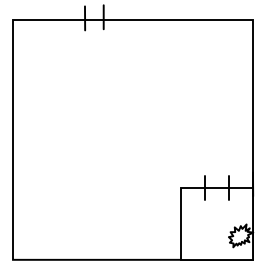
Roofing material
1.□ Tile 2.□ Thatched 3.□ Concrete
4.□ Corrugate Iron

Wall construction material
1.□ Brick wall 2.□ Thatched 3.□ Concrete
4.□ Corrugated Iron 5.□ Wood 6.□ Mud

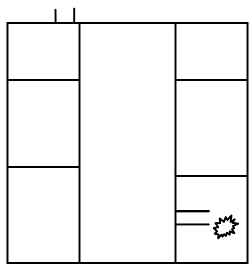
4. Location of kitchen



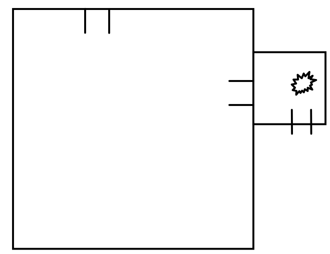
Stove-1



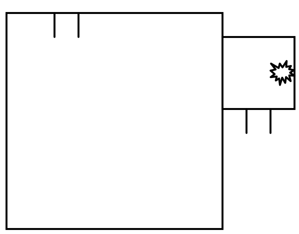
Stove-2



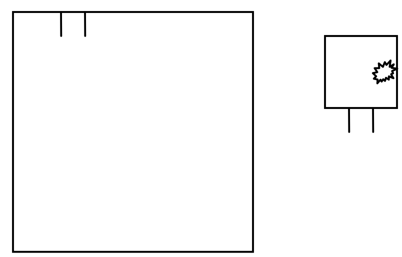
Stove-3



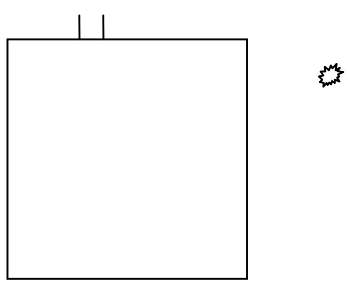
Stove-4A



Stove-4B



Stove-5



Stove-6

5. House ventilation related factors:

For kitchen:

No of walls
No of windows
No of doors
Location of windows/doors allows cross-ventilation?
Any screen doors/windows?
Doors, windows open after midday meal?
Doors, windows open after evening meal?

Vertical surface area of kitchen Length [ ] Width [ ] Height [ ]

Vertical surface area of openings (doors/windows/other) out of kitchen

ID	Doors		Windows		Others please specify__________	
	Height	Width	Height	Width	Height	Width
1						
2						
3						

Ventilation area between walls and roof in kitchen?
Number of walls with opening to the outside of the house:
Number of walls with opening to the inside of the house:
If there are two or more openings in the walls, are openings on opposite walls?

For living area:

No of walls
No of windows
No of doors
Location of windows/doors allows cross-ventilation?
Any screen doors/windows?
Doors, windows open after midday meal?
Doors, windows open after evening meal?

Vertical surface area of living area: Length [ ] Width [ ] Height [ ]
(Non-kitchen monitor site)

Vertical surface area of openings (doors/windows/other) out of living area

ID	Doors		Windows		Others please specify__________	
	Height	Width	Height	Width	Height	Width
1						
2						
3						

Ventilation area between walls and roof in living area?
Number of walls with opening to the outside of the house:
Number of walls with opening to the inside of the house:
If there are two or more openings in the walls, are openings on opposite walls?

6. Fuel Used on Monitoring Day

1.□ Firewood	2.□ Sawdust	3.□ Tree residue
4.□ Straw	5.□ Rice husk	6.□ Jute Sticks
7.□ Bagasse	8.□ Other crop residue	9.□ Briquette
10.□ Animal residue	11.□ Charcoal	12.□ Kerosene
13.□ Piped natural gas	14.□ LPG/LNG	15.□ Bio gas

7. Other Sources of Smoke on Monitoring Day

Kitchen

Cigarettes smoked
Lanterns lit (time, fuel)
Mosquito coils lit (time)

Living Area

Cigarettes smoked
Lanterns lit (times, fuels)
Mosquito coils lit (times)