Household and community poverty, biomass use, and air pollution in Accra, Ghana

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Many urban households in developing countries use biomass fuels for cooking. The proportion of household biomass use varies among neighborhoods, and is generally higher in low socioeconomic status (SES) communities. Little is known of how household air pollution varies by SES and how it is affected by biomass fuels and traffic sources in developing country cities. In four neighborhoods in Accra, Ghana, we collected and analyzed geo-referenced data on household and community particulate matter (PM) pollution, SES, fuel use for domestic and small-commercial cooking, housing characteristics, and distance to major roads. Cooking area PM was lowest in the high-SES neighborhood, with geometric means of 25 (95% confidence interval, 21–29) and 28 (23–33) μg/m^3 for fine and coarse PM ($PM_{2.5}$ and $PM_{2.5–10}$), respectively; it was highest in two low-SES slums, with geometric means reaching 71 (62–80) and 131 (114–150) μg/m^3 for fine and coarse PM. After adjustment for other factors, living in a community where all households use biomass fuels would be associated with 1.5- to 2.7-times PM levels in models with and without adjustment for ambient PM. Community biomass use had a stronger association with household PM than household's own fuel choice in crude and adjusted estimates. Lack of regular physical access to clean fuels is an obstacle to fuel switching in low-income neighborhoods and should be addressed through equitable energy infrastructure.

sustainable development | urbanization | global health | household energy | Africa

The populations of cities in the developing world are growing, with sub-Saharan Africa having the highest urban population growth rate worldwide (1). Some urban environmental health risks in the developing world are similar to those in high-income countries, such as the role of transportation as a determinant of particulate matter (PM) pollution levels and spatial patterns (2–5). Urban environmental health risks in developing countries also have some unique features, including high exposure to multiple risks in low-income "slum" neighborhoods (6, 7). A feature of urban PM pollution that, with few exceptions, is unique to developing countries is the widespread household use of biomass fuels (8, 9). Therefore, PM pollution in urban homes may be because of household or neighborhood biomass use in addition to sources that are also found in high-income countries, such as transportation and industrial pollution.

The patterns and sources of indoor air pollution in high-income countries have been studied (10–12). There is also increasing attention to residential indoor air quality in developing countries, including the concentrations of various pollutants, their sources, and the role of ventilation (13–15). However, most current studies of biomass fuels and household air pollution in developing countries have focused on the indoor environment in rural areas, where biomass is the most common or even universal household fuel. There are few studies of household PM in developing country cities, especially in relation to household and community biomass fuel use and socioeconomic status (SES) (7, 16–21). This is an important gap in our knowledge about sources of PM pollution in the home environment for the large number of people in urban areas where biomass fuels are common.

We systematically collected and analyzed data on PM in homes in four neighborhoods in Accra, Ghana. We also collected data on household SES, fuel use for domestic and small-commercial cooking, and housing characteristics. All our data were geo-referenced so we could also measure distance to major roads. We obtained small-area community SES and fuel use from the Ghana 2000 Population and Housing Census. Using this unique dataset, we examined household PM pollution in relation to household and neighborhood SES, fuel use, and selected other characteristics.

Our study took place in four neighborhoods in Accra, the capital of Ghana. Accra is located on the Gulf of Guinea and has a total area of more than 250 km^2. The population of the Accra metropolitan area increased from 600,000 in 1970 to 1.7 million in 2000. The four study neighborhoods lie on a line from the coast to the northern boundaries of the Accra metropolitan area: Jamestown/Ushertown (JT), Asylum Down (AD), Nima (NM), and East Legon (EL) (Fig. S1). JT and NM are poor, densely populated communities where biomass is the predominant household fuel and is also used for small-scale commercial purposes, such as cooking street food (Fig. 1). AD is a middle class, mostly residential neighborhood, where fewer people use biomass; street food vendors are less common in AD than in JT and NM. EL is an upper-class, sparsely populated, residential neighborhood, with most families living on large plots of land.

Results

Community and Household SES, Fuel Use, and Housing. NM has the highest population density (441 people per 10,000 m^2), followed by JT (329 per 10,000 m^2), AD (27 per 10,000 m^2), and EL (5 per 10,000 m^2) (Fig. 1*A*). The SES index in census enumeration areas (EAs) in JT and NM are in the lowest quintile of all EAs. In contrast, the SES of AD and EL fall into the wealthiest quintile (Fig. 1*B*). In the census, about 80% of households in JT and NM used biomass fuels, compared with 43% in AD and 53% in EL (Fig. 1*C*). In our study households, biomass use was highest in JT, where 95% [95% confidence interval (CI) 85–100%] and 45% (23–67%) of households used biomass for their own and small-commercial cooking, respectively (Table S1). At the low end, only 22% (3–41%) and 6% (0–17%) of surveyed households in EL used biomass for their own and small-commercial cooking. EL was surrounded by other high-SES and below-median biomass communities. The other three neighborhoods were closer to the city

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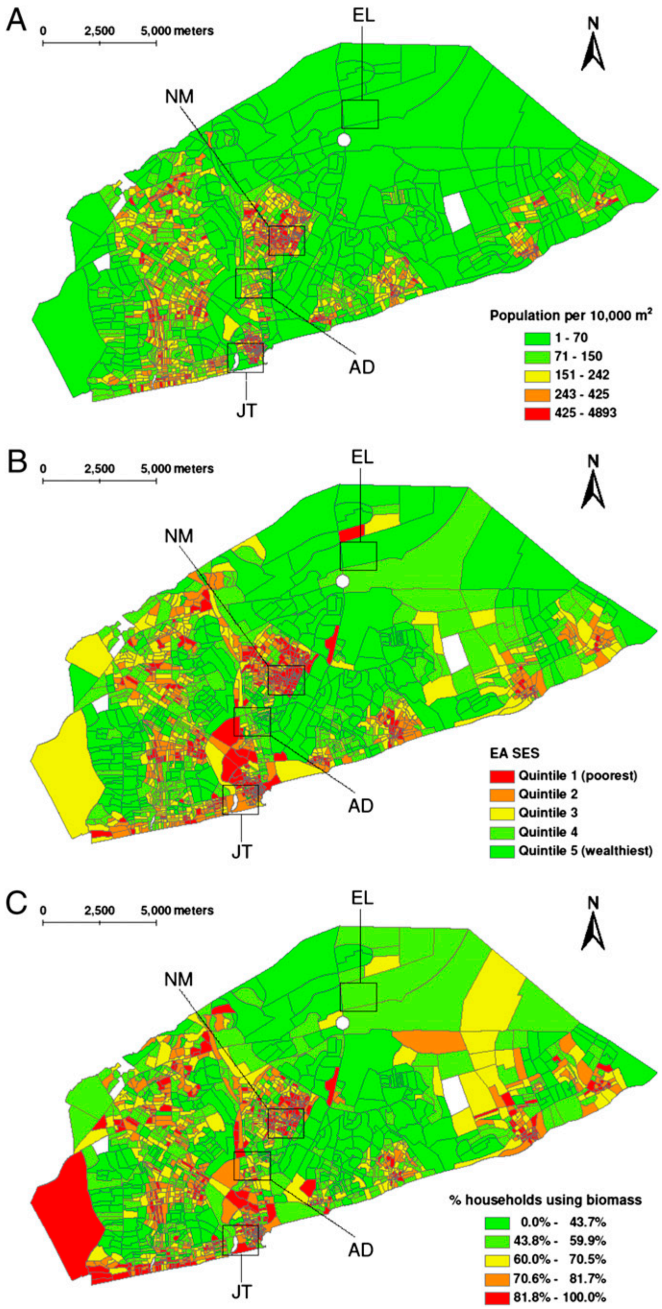

Fig. 1. (*A*) Population density, (*B*) community SES, and (*C*) percentage of households using biomass fuel by EA. Each EA has approximately the same population size, hence the area of an EA is inversely related to population density.

center and were surrounded by communities that may have had lower or higher SES and biomass use prevalence (Fig. 1).

The housing arrangement in most study households in JT (90%) and NM (100%) was a compound room, with multiple households living in different parts of a larger single structure built around a central courtyard. Most households in JT and NM cooked outdoors in the open-air shared compound courtyard, where their neighbors may also cook (Table S1). In EL, 89% of study households lived in separate, free-standing houses, and 83% of the households cooked in separate indoor kitchens (Table S1).

Average Daily PM. In most households in AD and JT, cooking area $PM_{2.5}$ (particles with aerodynamic diameter ≤ 2.5 μm; fine PM) concentrations were lower than ambient levels (Fig. 2*A*), with geometric mean household-to-ambient ratios of about 0.70. Some cooking area $PM_{2.5}$ concentrations in NM were lower than the ambient levels, whereas others were higher, leading to a geometric mean household-to-ambient ratio of 0.97. Cooking area $PM_{2.5}$ was similar to the ambient levels in most EL households. However, the household-to-ambient ratios had a geometric mean of 1.22 because of higher cooking area concentrations in five households. Two of these five households used charcoal as their primary fuel, another raised poultry on their compound.

Unlike $PM_{2.5}$, cooking area coarse PM ($PM_{2.5–10}$) concentrations exceeded corresponding ambient levels everywhere, except in one AD household (Fig. 2*B*). Mean residual cooking area $PM_{2.5–10}$ (cooking area minus ambient) was 58 μg/m^3 and mean household-to-ambient ratio was 2.32. These results suggest the disproportionate presence of household sources for coarse PM, such as sweeping and resuspension. As a result of such fine and coarse PM patterns, cooking area $PM_{2.5}$-to-PM_{10} ratios were lower than the ambient ratios on the same day (Fig. 2*C*).

Cooking area PM was lowest in EL, with geometric means of 25 (21–29) μg/m^3 for $PM_{2.5}$ and 28 (23–33) μg/m^3 for $PM_{2.5–10}$, and highest in JT with 71 (62–80) μg/m^3 for $PM_{2.5}$ and 118 (101–138) μg/m^3 for $PM_{2.5–10}$, and in NM with 52 (44–63) μg/m^3 for $PM_{2.5}$ and 131 (114–150) μg/m^3 for $PM_{2.5–10}$. Although measurement periods varied, data on seasonal patterns of ambient PM reported elsewhere (2) and the above household-ambient comparisons suggest that PM in JT households would likely be the highest of all neighborhoods, regardless of season, as was ambient PM in this neighborhood.

Association of Average Daily PM with Household and Community Fuel Use. Using biomass fuels and living in a high biomass-use community were both associated with higher cooking area PM (high vs. low biomass-use communities were defined based on whether the proportion of households using biomass fuels in the EA was above vs. below median of all EAs) (Tables 1 and 2). The lowest cooking area $PM_{2.5}$ and $PM_{2.5–10}$ were measured in homes with clean fuels and in low biomass-use communities, 27 (24–31) and 45 (34–59) μg/m^3, respectively, and the highest in homes that used biomass and were in high biomass-use communities, 60 (53–68) and 128 (116–142) μg/m^3, respectively. Of the other two groups, cooking areas in high biomass-use communities with clean fuels had higher PM than those that used biomass fuels but lived in low biomass-use communities. Similarly, commercial cooking with biomass fuels was associated with higher cooking area PM, making such households when located in high biomass-use communities the most polluted, with $PM_{2.5}$ and $PM_{2.5–10}$ geometric means of 77 (64–91) and 143 (120–169) μg/m^3, respectively (Table 2). There was no meaningful difference between homes that did no commercial cooking and those that did so with clean fuels, but the sample size for the latter was four and hence should be considered as suggestive only.

The results in Tables 1 and 2 show crude associations, without controlling for other variables that may vary across households. The multivariate associations confirm that using biomass fuels for own and commercial cooking, and living in EAs with higher biomass-use prevalence, were associated with higher cooking area PM; only the effects of neighborhood fuel use were consistently significant (Table 3). Beyond their statistical significance, living in an EA with 26% higher biomass-use prevalence had about the same effect on cooking area $PM_{2.5}$ as switching from a cleaner fuel to biomass in model 1; the equivalence would be at 69% higher biomass-use prevalence for $PM_{2.5–10}$. A household located in an EA where all households use biomass fuels would have 149% (104–223%) of the $PM_{2.5}$ level and 165% (122–246%) of the $PM_{2.5–10}$ level compared with its counterpart in an EA with no biomass use after adjustment for neighborhood ambient PM; the effects were 272% (182–406%) and 272% (165–448%) in the model that did not adjust for ambient PM. For fine PM, the (proportional) effects of using biomass for commercial cooking seemed larger than using it for household purposes, whereas the

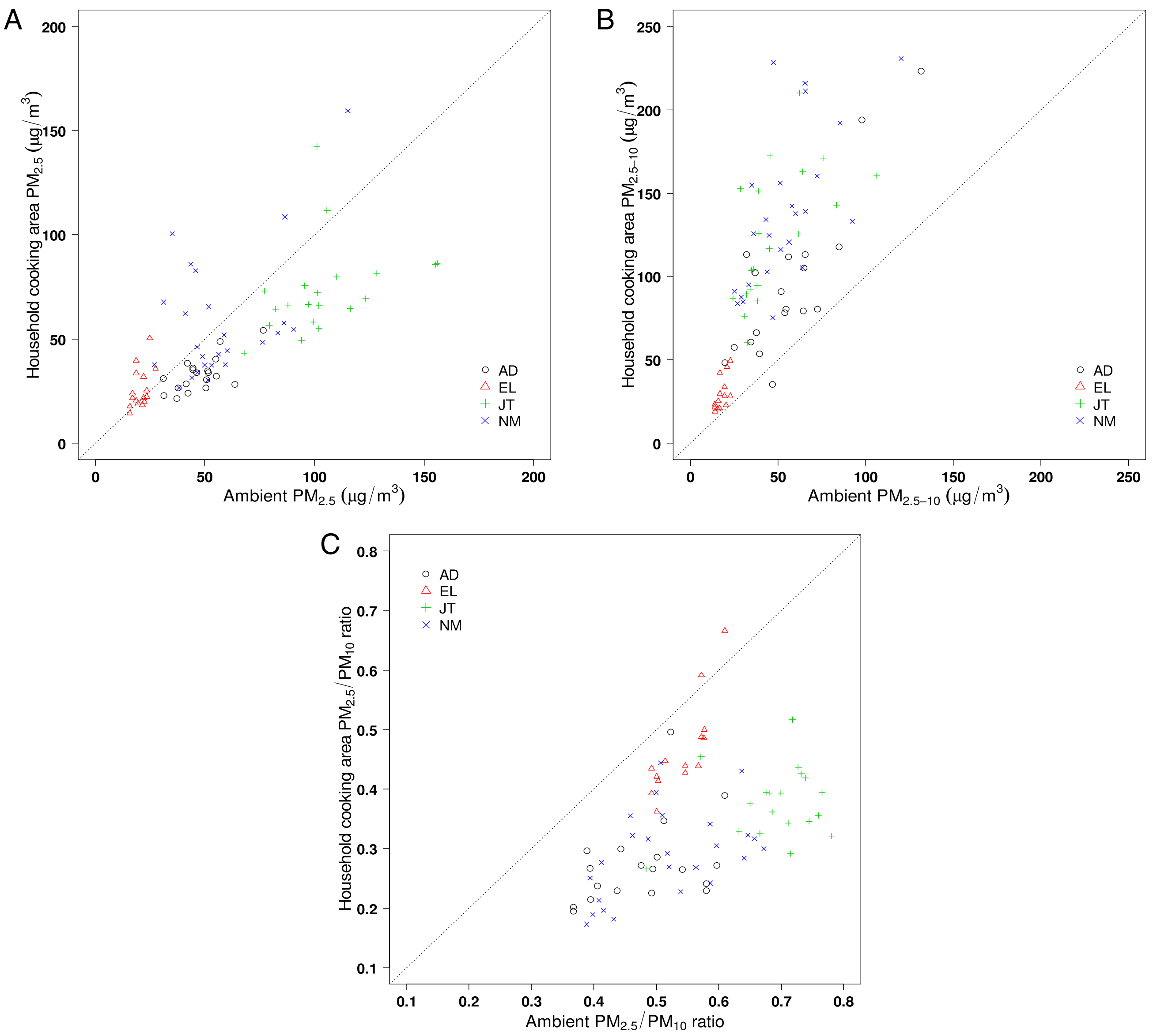

Fig. 2. The relationship between cooking area and ambient PM using data from simultaneous measurement periods for (*A*) fine PM ($PM_{2.5}$), (*B*) coarse PM ($PM_{2.5–10}$), and (*C*) $PM_{2.5}$-to- PM_{10} ratio.

opposite was seen for coarse PM, although the differences were not statistically significant. The associations with household size, average distance to main roads, cooking location, and the presence of smokers in the house were generally nonsignificant. Adjusting for neighborhood PM weakened the association with EA biomass use for both size fractions, and that of household biomass use for $PM_{2.5}$, but the effect of household biomass use on $PM_{2.5–10}$ became larger and significant after this adjustment.

PM Patterns During the Day. In all neighborhoods, both the ambient and cooking area $PM_{2.5}$ rose in the early morning hours. This morning rise started as early as 0300 hours in JT and NM vs. around 0600 hours in EL (Fig. 3). Although in any single neighborhood this pattern may either be because of morning residential and small commercial cooking, other commercial activities that use biomass (e.g., fish smoking and bakeries), and traffic, or because of overnight surface temperature inversions, the differences in start time and rise across neighborhoods make the differential patterns of sources a more likely explanation. Specifically, in both JT and NM, cooking street food and other activities that use biomass fuels begin at very early hours. In JT and NM, we also observed a midday peak around 1100 hours, which may correspond to midday cooking and traffic. As described elsewhere (2), ambient PM also showed a rise in $PM_{2.5}$ in the evening (1800–2100 hours) except in EL, possibly because of evening rush hour and biomass use; this evening rise was less noticeable in cooking areas. In JT and AD, ambient $PM_{2.5}$ was higher than cooking-area levels, whereas the two environments had similar $PM_{2.5}$ in EL and NM.

On average, $PM_{2.5}$ concentrations in the cooking and living areas tracked relatively well, suggesting diffusion between household environments or from the ambient air to household environments (Fig. 3). However, the pairwise correlations between continuous $PM_{2.5}$ in different indoor and ambient environments varied substantially, with living area concentration in households using nonbiomass fuels having higher correlation with ambient levels than those that used biomass (Fig. S2).

Discussion and Conclusions

To our knowledge, this study is unique in presenting a detailed analysis of the association between household air pollu-

Table 1. Cooking area concentrations of $PM_{2.5}$ and $PM_{2.5–10}$ ($\mu g/m^3$) stratified by household and neighborhood fuel use

		Biomass fuels	Nonbiomass fuels
$PM_{2.5}$			
Low biomass use community*	Number of households	14	21
	Geometric mean (95% CI)	31 (25, 38)	27 (24, 31)
High biomass use community†	Number of households	42	2
	Geometric mean (95% CI)	60 (53, 68)	53 (3, 983)
$PM_{2.5–10}$			
Low biomass use community	Number of households	13	20
	Geometric mean (95% CI)	71 (45, 110)	45 (34, 59)
High biomass use community	Number of households	42	2
	Geometric mean (95% CI)	128 (116, 142)	80 (37, 175)

*The proportion of households using biomass fuels in the EA is below median of all EAs.
†The proportion of households using biomass fuels in the EA is above median of all EAs.

tion and its household and community determinants in a large city in the developing world, especially in sub-Saharan Africa, where urban population is growing faster than any other region (1). In summary, we found that household and community biomass fuel use were important predictors of household PM pollution in Accra neighborhoods. Notably, community biomass use had a stronger effect on cooking area PM than a household's own fuel in crude and adjusted estimates. At the household level, fuel use for both own and small-commercial cooking seemed to be associated with PM pollution. We also considered associations by PM size fraction and found that cooking area $PM_{2.5–10}$ concentrations consistently exceeded corresponding ambient levels, suggesting the presence of household sources for coarse particles, such as sweeping and resuspension; the pattern for ambient and household $PM_{2.5}$ was more mixed.

Although in rural areas better ventilation may be able to reduce exposure to indoor air pollution from solid fuels, our results on the role of both household and community biomass use indicate that population-based reduction in solid fuel use is necessary for reducing air pollution exposure and its health effects in developing country cities, also supported by the recent evaluation of the Dublin coal sale ban (22). As seen in our data and in previous studies (8, 9, 23), in Accra and in other developing country cities, biomass use is indeed more common in low-income households and communities. Fuel price and the initial cost of stove price are likely to be one of the reasons for this pattern, which should be addressed through policies that facilitate financial access to cleaner fuel for the poor. However, community-level lack of regular physical access may be a larger obstacle to fuel switching than actual fuel cost and household level affordability (24). For example, in our household questionnaire, fuel price ranked lower than "availability when needed," "availability near home," or "ease of use when cooking" as a reason for fuel choice. This finding is consistent with the fact that both JT and NM also have a large number of biomass fuel vendors (Fig. S1).

In contrast, liquefied petroleum gas purchase would involve taking an empty cylinder to a fuel depot, itself requiring a private car or taxi, with a nontrivial risk that the depot will not have replacement fuel when they arrive there. With such issues, households do not make the initial investment in liquefied petroleum gas equipment (a stove, hose, regulator, and cylinder) or revert back to biomass fuels after some period. Ghana has planned to use the West Africa Gas Pipeline (http://www.wagpco.com/) to increase its supply of natural gas, primarily for power generation and large industrial use. This project, which has been affected by multiple delays, does not have a residential energy component. Ghana has also recently found crude oil off the shores of its Western Atlantic Coast; it is expected that natural gas would be produced together with oil. Given the public financing of both projects, a relevant policy debate should focus on whether a portion of the proceeds and supply from these projects should be used to develop energy infrastructure in low- and middle-income Accra neighborhoods. Such a community-based approach may ultimately be the only effective way to reduce air pollution in Accra communities and homes, contributing toward Millennium Development Goal 7 (ensure environmental sustainability) as well as the associated Millennium Development Goal 4 (reduce child mortality), which is directly affected by biomass air pollution.

Materials and Methods

This research was approved by the Harvard School of Public Health and by the Noguchi Memorial Institute for Medical Research at the University of Ghana Institutional Review Boards.

Table 2. Cooking area concentrations of $PM_{2.5}$ and $PM_{2.5–10}$ ($\mu g/m^3$) stratified by small-commercial cooking and neighborhood fuel use

		Commercial cooking (biomass fuels)	Commercial cooking (nonbiomass fuels)	No commercial cooking
$PM_{2.5}$				
Low biomass use community*	Number of households	5	4	26
	Geometric mean (95% CI)	27 (18, 39)	23 (11, 47)	30 (26, 33)
High biomass use community†	Number of households	16	0	28
	Geometric mean (95% CI)	77 (64, 91)	—	52 (45, 60)
$PM_{2.5–10}$				
Low biomass use community	Number of households	4	4	25
	Geometric mean (95% CI)	63 (24, 167)	47 (11, 194)	53 (40, 71)
High biomass use community	Number of households	16	0	28
	Geometric mean (95% CI)	143 (120, 169)	—	117 (103, 132)

*The proportion of households using biomass fuels in the EA is below median of all EAs.
†The proportion of households using biomass fuels in the EA is above median of all EAs.

Table 3. Regression coefficients for multivariate analysis of the association of cooking area PM with sources, cooking area location, and meteorological covariates

	Model 1		Model 2	
Variable	Coefficient (95% CI)	*P* value	Coefficient (95% CI)	*P* value
Dependent variable: ln ($PM_{2.5}$)	*n* = 79; adjusted R^2 = 0.68		*n* = 79; adjusted R^2 = 0.50	
Constant	1.246 (0.610, 1.881)	<0.001	3.038 (2.704, 3.372)	<0.001
ln (neighborhood average)	0.517 (0.351, 0.683)	<0.001		
Households using biomass in the EA (%)	0.004 (0.000, 0.008)	0.03	0.010(0.006, 0.014)	<0.001
Household size	0.014 (−0.015, 0.043)	0.35	0.000 (−0.035, 0.036)	0.99
Average distance to main roads (km)	0.527 (−0.200, 1,254)	0.15	−0.143(−1.008, 0.722)	0.74
Household cooking fuel				
Nonbiomass	0.0	NA	0.0	NA
Biomass	0.104 (−0.153, 0.362)	0.42	0.174 (−0.146, 0.493)	0.28
Small commercial cooking fuel				
No commercial cooking	0.0	NA	0.0	NA
Nonbiomass	−0.093(−0.428, 0.242)	0.58	−0.116 (−0.533, 0.301)	0.58
Biomass	0.211 (0.025, 0.396)	0.03	0.255 (0.025, 0.486)	0.03
Cooking area				
Inside the house	0.0	NA	0.0	NA
Open air	−0.040(−0.342, 0.217)	0.78	−0.112 (−0.456, 0.231)	0.52
Separate cookhouse	−0.221(−0.536, 0.094)	0.17	−0.227 (−0.620, 0.165)	0.25
Secondhand smoke				
No smoker in the house	0.0	NA	0.0	NA
Smoker in the house	−0.053(-0.345, 0.239)	0.72	0.160 (−0.193, 0.514)	0.37
Meteorological factor				
Raining duration (hours)	−0.000(−0.033, 0.032)	0.98	−0.024 (−0.063, 0.015)	0.22
Dependent variable: ln ($PM_{2.5–10}$)	*n* = 77; adjusted R^2 = 0.86		*n* = 77; adjusted R^2 = 0.60	
Constant	1.049 (0.487, 1.611)	<0.001	3.903 (3.516, 4.289)	<0.001
ln (neighborhood average)	0.750 (0.615, 0.885)	<0.001		
Households using biomass in the EA (%)	0.005 (0.002, 0.009)	0.001	0.010 (0.005, 0.015)	<0.001
Household size	0.017 (−0.009, 0.042)	0.19	−0.022 (−0.064, 0.019)	0.29
Average distance to main roads (km)	−0.480 (−1.100, 0.139)	0.13	−1.522(−2.519, −0.525)	0.003
Household cooking fuel				
Nonbiomass	0.0	NA	0.0	NA
Biomass	0.343 (0.126, 0.561)	0.002	0.225 (−0.140, 0.591)	0.22
Small commercial cooking fuel				
No commercial cooking	0.0	NA	0.0	NA
Nonbiomass	0.050 (−0.233, 0.334)	0.72	−0.012 (−0.490, 0.467)	0.96
Biomass	0.103 (−0.054, 0.261)	0.20	0.155 (−0.111, 0.421)	0.25
Cooking location				
Inside the house	0.0	NA	0.0	NA
Open air	−0.033(−0.266, 0.201)	0.78	0.094(−0.299, 0.488)	0.63
Separate cook house	−0.144 (−0.411, 0.123)	0.29	0.021 (−0.427, 0.468)	0.93
Secondhand smoke				
No smokers in the house	0.0	NA	0.0	NA
Smokers in the house	−0.098 (−0.338, 0.142)	0.42	−0.041 (−0.446, 0.364)	0.84
Meteorological factor				
Raining duration (hours)	−0.007 (−0.035, 0.021)	0.62	−0.063 (−0.108, -0.018)	0.006

NA, not applicable. Model 1 is adjusted for neighborhood average PM concentrations at nontraffic rooftop sites and model 2 is not. See *SI Text* for details.

We measured $PM_{2.5}$ and PM_{10} (aerodynamic diameter ≤ 10 μm) in 80 households in the four study neighborhoods (Fig. S1). The households were selected from those in the Women's Health Study of Accra (25), whose participants were a random sample of all adult women in Accra, through stratified SES and age-group sampling using the 2000 Population and Housing Census of Ghana as the sampling frame. We selected households in the study neighborhoods that had more than two members. Furthermore, we selected households at varying distances from main roads.

In each household, we measured 48-h integrated $PM_{2.5}$ and PM_{10} concentrations in the cooking area. Over the same 48-h period, we measured $PM_{2.5}$ continuously in both the cooking and living areas. We also measured integrated and continuous ambient $PM_{2.5}$ and PM_{10} concentrations at rooftop sites in the same neighborhood, as described elsewhere (2). Further information on study design, pollution measurement methods, number of measurements, and meteorological variables is provided in *SI Text* and Table S2.

We also used a structured questionnaire to collect data on the number of household members, housing and cooking-area characteristics, ownership of assets, fuels and stoves used for domestic and small-commercial cooking, and the presence of other combustion sources and smokers in the house. Following previous analyses of household data in developing countries (23, 26), we measured household and community SES using an index based on housing characteristics, water and waste systems, and ownership of durable assets, using the questionnaire data and data from the Ghana 2000 Population and Housing Census. Details of data and SES analyses are provided in *SI Text*.

We used regression analysis to examine the association of cooking area PM with its potential household and neighborhood determinants that may be

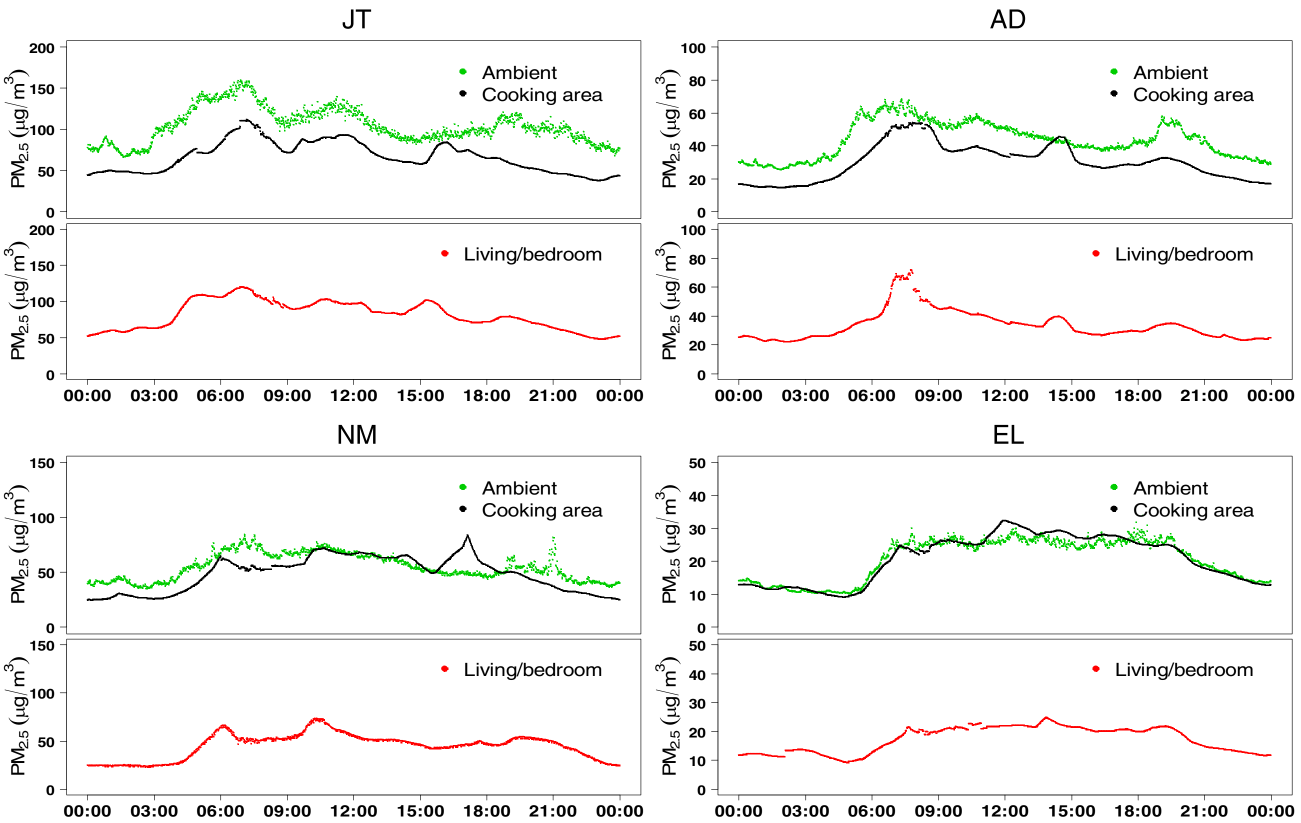

Fig. 3. Continuous $PM_{2.5}$ concentrations in the household cooking and living areas and at ambient rooftop sites. The measurements were standardized for variation in relative humidity throughout the day, corrected against gravimetric measurements and smoothed as described in *SI Text*. In each panel, measurements from all days over the measurement period are averaged.

proxies for PM sources and for ventilation. Details of the statistical model are provided in *SI Text*.

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