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Residential Wood Stove Use and Indoor Exposure to $PM_{2.5}$ and its Components in Northern New England

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Abstract

Background: Residential wood stove use has become more prevalent in high-income countries, but only limited data exist on indoor exposure to $PM_{2.5}$ and its components.

Methods: From 2014–2016, we collected 7 day indoor air samples in 137 homes of pregnant women in Northern New England, using a micro-environmental monitor. We examined associations of wood stove use with $PM_{2.5}$ mass and its components [black carbon (BC), organic and elemental carbon and their fractions, and trace elements], adjusted for sampling season,

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community wood stove use, and indoor activities. We examined impact of stove age, EPA certification, and wood moisture on indoor pollutants.

Results: Median (IQR) household $PM_{2.5}$ was 6.65 (5.02) μg/m^3 and BC was 0.23 (0.20) μg/m^3. Thirty percent of homes used a wood stove during monitoring. In homes with versus without a stove, $PM_{2.5}$ was 20.6% higher [although 95% confidence intervals (−10.6, 62.6) included the null] and BC was 61.5% higher (95% CI: 11.6, 133.6). Elemental carbon (total and fractions 3 and 4), potassium, calcium, and chloride were also higher in homes with a stove. Older stoves, non-EPA-certified stoves, and wet or mixed (vs dry) wood were associated with higher pollutant concentrations, especially BC.

Conclusions: Homes with wood stoves, particularly those that were older and non-EPA certified or burning wet wood had higher concentrations of indoor air combustion-related pollutants.

Keywords

indoor air pollution; wood stove use; $PM_{2.5}$; black carbon; organic carbon; trace elements

INTRODUCTION

Use of wood stoves for heating has become more prevalent in households in high-income countries as a result of higher energy prices and preference for renewable fuel. In the US, for example, over 10 million homes currently use wood fuel for heating [1]. Several studies have investigated indoor air pollution in developing countries, where burning wood and other biomass for cooking has been shown to result in high concentrations of pollutants and adversely impact pregnancy [2] and other [3, 4] health outcomes. However, there are less data on and limited awareness of exposure to indoor air pollution as a result of using wood fuel for heating in high-income countries.

Few studies have evaluated the magnitude and types of particles emitted from wood stoves used for household heating, and in particular, there are few studies comparing indoor air pollution in homes with versus without wood stoves in high-income countries. A recent study in Norway (n=36) [5] and two older US studies [n=24 [6] and n=45 [7]] found modestly higher particulate matter in homes with versus without wood stoves. However, existing studies have conducted monitoring in a relatively small number of homes and provide limited data regarding specific components of $PM_{2.5}$. Because components of $PM_{2.5}$ may be differentially linked to unique health outcomes [8, 9], identifying which components are associated with wood stove use is further critical to target populations for preventive interventions.

The objective of our study was to characterize the pollutant mixture in a larger, contemporary sample of homes in Northern rural New England with versus without wood stove use. We examined components of $PM_{2.5}$, with a focus on black carbon (BC) and organic carbon (OC), as well as potassium (K), a known tracer of burning biomass such as wood smoke [10]. In secondary analyses, we examined elemental and organic carbon fractions and trace elements. We also evaluated the extent to which other indoor activities, such as household cleaning or burning candles were associated with air pollutants.

METHODS

Study population and design

From 2014 to 2016, we recruited 152 pregnant women and collected weeklong indoor air samples in their homes during their 3rd trimester of pregnancy. We identified participants during enrollment into the prospective New Hampshire Birth Cohort Study (NHBCS), the details of which we have described previously [11]. Women were eligible for our sub-study if they were non-smokers, lived in a smoke-free home, and were not planning to use a fireplace during the monitoring period. Women were also required to have a street address for monitor delivery, as monitors were shipped from our laboratory to and from participants. Of the 152 women recruited into the sub-study, 15 did not have usable air monitoring data because their air monitors were not plugged in for at least 4 days, for a final sample size of 137 women. All participants provided written informed consent, and Institutional Review Boards of participating institutions approved the study.

Air pollution measurement

We instructed each participant to position an in-home micro-environmental air monitor with a pump set to a flow rate of 1.8 L/min (VP0140, Medo USA, Roselle, IL) in the room where she spent the most time, excluding the kitchen. Within that room, we instructed participants to place the air monitor at least 6 inches from the wall and as far from the wood stove as possible. We used a size-selective impactor to collect $PM_{2.5}$ on 137 Teflon filters, and we measured $PM_{2.5}$ mass by weighing filters with an electronic microbalance (MT-5 Mettler Toledo, Columbus, OH, USA) before and after sample collection. We measured blackness of the filters with a SootScan Model OT21 Transmissometer (Magee Scientific Corp., Berkeley, CA, USA) to obtain the mass of BC, and we used X-ray fluorescence (XRF) spectroscopy (model Epsilon 5, PANalytical, The Netherlands) to determine the mass of several trace elements on 136 filters. One filter had a hole that precluded measurement of BC and trace elements. We calculated concentrations of air pollutants by dividing the mass (μg or ng) of the pollutant by the total volume of air sampled on that filter (m^3).

We also collected particles on a pre-fired quartz-fiber filter and used thermal-optical analysis to determine the mass of elemental carbon (EC), OC, and their fractions with a Lab OC-EC Aerosol Analyzer (Sunset Laboratory Inc., Tigard, OR) in a subset of homes (n=100), as we did not have quartz-fiber filters available when we started data collection. We determined thermally-resolved carbon fractions based on the temperatures at which they evolved during gradual heating in an oxygen-free, helium environment and in an environment with 2% oxygen and 98% helium [12].

We used the mean + 2 times the standard deviation of pollutant concentrations on 7 blank filters to calculate a limit of detection (LOD) for $PM_{2.5}$ (1.39 μg/m^3) and BC (0.08 μg/m^3). For EC, OC, and trace elements, we calculated a unique uncertainty value (*measured concentration* × *relative counting statistical error* + *standard deviation of laboratory blanks*) and LOD (3 × *uncertainty*) for each pollutant on each filter.

Participant, household, and neighborhood characteristics

We used a questionnaire at enrollment to collect data on participant demographics, parity, and pre-pregnancy BMI. Participants completed a self-administered questionnaire during the air monitoring period detailing household characteristics, hours that participants engaged in particle-generating or particle-mitigating activities during the monitoring period, and wood stove and fuel characteristics.

We geocoded home addresses at the time of enrollment. We used data from the 2011–2015 five-year American Community Survey [13] to obtain the following characteristics of the block group surrounding each geocoded address: median household income, proportion of homes that used wood as primary household fuel, and population density. We used the U.S. Census Bureau's 2015 TIGER/Line database [14] to obtain residential proximity to the nearest MTFCC Class S1100 roadway (i.e., primary road, typically a divided, limited-access highway [15], and used the NASA Shuttle Radar Topography Mission's 3-arcsecond digital elevation model [16, 17] to determine the elevation above sea level for each residence.

Statistical analysis

We examined the extent to which each participant, household, or neighborhood characteristic was associated with key pollutants ($PM_{2.5}$, BC, OC, and K) in unadjusted linear regression analyses. In multivariable models, we examined the association between wood stove use and each key pollutant adjusted for season of monitoring (heating versus non-heating), proportion of wood fuel-heated homes in the census block, and other indoor activities (e.g., household cleaning or burning candles) associated with the pollutant in univariate analyses ($p<0.10$). We examined the associations of factors that might mitigate wood stove pollution (e.g., no wood stove vs. EPA-certified stove vs. non-EPA-certified stove) with each key pollutant. In multivariable models, we included covariates as continuous variables if their associations with the pollutant were linear in the univariate analyses; otherwise, we categorized covariates. We excluded four participants who reported having used a wood stove but their monitoring was during the non-heating season, as we anticipated inherent differences in frequency of wood stove use during the non-heating season. For samples with pollutant concentrations below the LOD (n=3 for $PM_{2.5}$, n=9 for BC, n=0 for OC, and n=3 for K), we substituted LOD/$\sqrt{2}$ [18]. We natural-log transformed air pollutant concentrations to meet model assumptions, and for ease of interpretation, we exponentiated regression coefficients and reported results as percent changes [$\% \ change = (exp(\beta) - 1) \times 100$].

In secondary analyses, we compared concentrations of carbon fractions and trace elements in homes that used a wood stove versus those that did not. Because air pollutant concentrations were not normally distributed, we used a non-parametric Wilcoxon rank-sum test.

RESULTS

Population characteristics

NHBCS mothers included in our study versus those recruited during the same time period but not included (n=1,621) were more educated and more likely to be multiparous and live in a census block with a higher proportion of wood fuel heated homes, lower population density, and higher elevation (see Table S1).

Over half (51%) of participants in our study were 30.0–34.9 years old at cohort enrollment in mid-pregnancy, 80% were married, and 77% were college educated. Ninety-five percent lived in a freestanding home (rather than apartment or trailer), and 78% of homes were built after 1960 (Table 1). Eighty-six (63%) participants had air monitoring during the heating season, and of those, 41 (48%) used a wood stove and loaded the wood stove a median (IQR) of 14.0 (19.4) times per week. Among participants who had air monitoring during the heating season, a higher percentage of those who used a wood stove (versus those who did not) had a college education and were nulliparous, lived in homes that were smaller and older, and lived in census blocks with higher proportion wood fuel heated homes but lower population density and annual median household income. Activities (e.g., cooking or cleaning) that may have influenced indoor pollution during the monitoring period were similar in homes with versus without a wood stove (Table 1).

Pollutant concentrations and their distribution

During indoor air monitoring for a median (IQR) of 7.0 (0.3) days, median (IQR) concentration of $PM_{2.5}$ was 6.65 (5.02) μg/m^3, BC was 0.23 (0.20) μg/m^3, EC was 0.12 (0.14) μg/m^3, OC was 2.80 (1.60) μg/m^3, and K was 41.29 (41.73) ng/m^3. For reference, the World Health Organization (WHO) 24-hour average indoor $PM_{2.5}$ threshold is 25 μg/m^3. In the present study, Spearman correlations between $PM_{2.5}$ and each of its components ranged r=0.50 (EC and $PM_{2.5}$) to r=0.75 (OC and $PM_{2.5}$) (Table 2).

Personal and household characteristics associated with pollutants

In univariate analyses, several personal characteristics were associated with indoor air pollution concentrations. Homes of older and more educated women located in census blocks with higher median household incomes had the lowest concentrations of $PM_{2.5,}$ BC, OC, and K, although confidence intervals crossed the null for some of these associations (Table 3). For example, BC was 42.1% lower (95% CI: −60.8, −14.6) in homes of women ≥ 35 years of age versus <30 years of age, 43.1% lower (95% CI: −60.7, −17.7) in homes of women with any post-graduate education versus less than a college education, and 25.3% lower (95% CI: −48.5, 8.4) in homes located in census blocks with median household income > $75,000 versus < $60,000.

In unadjusted models, wood stove use was associated with higher concentrations of all pollutants, although confidence intervals crossed the null for $PM_{2.5}$ and OC [e.g., BC was 71.0% higher (95% CI: 27.6, 129.3) in homes with versus without a wood stove, and $PM_{2.5}$ was 21.6% higher (95% CI: −5.4, 56.4)]. Overall, pollutant concentrations were higher during the heating versus non-heating season, with the most pronounced seasonal differences observed for BC and K [e.g., BC was 53.6% higher (95% CI: 16.0, 103.4) during the heating versus non-heating season whereas $PM_{2.5}$ was only 12.8% higher (95% CI: −10.9, 42.8)]. All pollutants, particularly $PM_{2.5}$ and K, were higher in homes in census blocks with a higher proportion of wood fuel heated homes [e.g., $PM_{2.5}$ was 45.2% higher (95% CI: 6.2, 98.5) in homes in census blocks with > 30% (versus < 15%) of homes using wood as a primary heat source] (Table 3).

Several activities during the monitoring period were also associated with some or all of the pollutants. In unadjusted models, using a humidifier was associated with higher concentrations of all pollutants [e.g., $PM_{2.5}$ was 58.9% higher (95% CI: 1.8, 148.0) in homes where a humidifier was used for > 60 hours per week versus not at all]. Household cleaning and burning candles or incense were strongly associated with BC [e.g., 130.6% higher (95% CI: 38.7, 283.3) in homes with ≥ 4 hours per week dusting, sweeping, or vacuuming], whereas opened windows were associated with lower BC [33.2% lower (95% CI: −53.1, −4.8) in homes with windows open for > 60 hours per week versus not at all]. All pollutants, particularly OC, were higher in homes undergoing renovation and lower in homes using an air purifier [e.g., OC was 41.4% lower (95% CI: −63.6, −4.8) in homes that used an air purifier versus those that did not] (Table 3).

In covariate-adjusted models, wood stove use was associated with BC and K independent of heating season, proportion of wood fuel heated homes in census block, and other indoor activities. Wood stove use was also associated with $PM_{2.5}$ and OC, although confidence intervals crossed the null. The strength of the association between wood stove use and each pollutant was attenuated slightly in adjusted as compared to unadjusted models, but remained elevated. For example, in homes with versus without a wood stove BC was 61.5% higher (95% CI: 11.6, 133.6) in adjusted versus 71.0% higher (95% CI: 27.6, 129.3) in unadjusted models (Table 4).

Mitigating factors

Next, we used the covariate-adjusted models to examine the role of factors we anticipated might mitigate the higher pollutant concentrations in homes with wood stoves. Homes with newer wood stoves, EPA-certified stoves, or stoves that burned only dry wood had lower concentrations of $PM_{2.5,}$ BC, OC, and K [e.g., BC was 25% higher (95% CI: −17.4, 89.1) in stoves ≤ 10 years old and 134.9% higher (95% CI: 40.9, 291.6) in homes of stoves > 10 years old versus homes without a wood stove] (Figure 1). Air purifiers also appeared to be associated with lower concentrations of all pollutants in homes with wood stoves, although only three participants used a wood stove and air purifier. For example, as compared to homes without a wood stove, BC was similar [−6.2% (95% CI: −63.0, 137.4)] in homes using both a wood stove and air purifier and higher [69.4% (95% CI: 16.4, 146.7)] in homes using a wood stove and without an air purifier (data for other pollutants not shown). Although only four participants reported using a pellet stove, as compared to homes without a wood stove, $PM_{2.5}$ and K were higher in homes with a pellet stove [e.g., $PM_{2.5}$ was 58.2% higher (95% CI: −20.8, 215.7)] and less elevated in homes with a log-burning stove [e.g., $PM_{2.5}$ was 17.5% higher (−13.4, 59.4)] (data not shown for other pollutants).

Secondary analyses of wood stove use, carbon fractions, and trace elements

In secondary analyses, we investigated household carbon fractions overall and in relation to wood stove use. Of the EC fractions, we found EC3 and EC4, which have moderate levels of polarity and volatility, to be the most prevalent and most strongly associated with wood stove use (Tables S2 and S3). For example, median (IQR) of EC4 was 0.13 (0.30) $\mu g/m^3$ in homes that used a wood stove versus 0.08 (0.09) $\mu g/m^3$ in homes that did not (p=0.01). Of the OC fractions, we found OC1, which is less polar and more volatile than the other OC fractions, to be the most prevalent (Table S2), and while all OC fractions were higher in homes that used a wood stove versus those that did not, the difference did not reach statistical significance for any fraction (Table S3).

We also examined concentrations of trace elements in the full cohort and in relation to wood stove use. In addition to K which we examined in primary analyses (Tables 2-4), we detected aluminum, calcium (Ca), sulfur, silicon, chloride (Cl), and iron most widely (i.e., >85% of samples above the LOD). Titanium, zinc, copper, and sodium had 38–75% of samples above the LOD, and several elements had less than 20% of samples above the LOD (Table S4). Of the elements with > 20% of samples above the LOD, Ca and Cl were higher in homes with versus without a wood stove (Table S4).

DISCUSSION

In homes of pregnant women in Northern New England, we found higher overall levels of indoor air pollution than reported in nearby urban Boston, MA where median (IQR) BC measured over one week in homes was 0.18 (0.21) $\mu g/m^3$ [19]. We found that wood stove use was associated with higher concentrations of BC and K in covariate-adjusted models. Total EC, EC3, EC4, Ca, and Cl were also higher in homes with versus without a wood stove. Newer stoves, EPA-certified stoves, and stoves burning exclusively dry wood were associated with lower pollutant concentrations in homes of wood stove users.

In our cohort, $PM_{2.5}$ concentrations were modestly (21%) higher in homes with versus without wood stove use, with limited statistical precision. Our finding is consistent with older studies that showed small, often not statistically significant differences in PM concentrations in US homes with versus without wood stoves. These prior studies found PM concentrations to be 4% higher [n=24 homes in Vermont in 1984 [6]], 5% higher [n= 35 homes in Suffolk county, NY [7]], and 36% higher [n=45 homes in Onondaga county, NY [7]] in homes with (vs without) wood stove use. Directly in line with our results, a more recent study in Norway showed $PM_{2.5}$ concentrations to be 24% higher in homes with versus without wood stove use, independent of other combustion sources [5]. Thus, our results are consistent with prior studies that found only modestly higher $PM_{2.5}$ levels in homes with versus without wood stoves, suggesting that $PM_{2.5}$ is not the best indicator of wood stove exposure, as it is not a specific marker of combustion source particulate matter.

Our study builds on the prior literature by examining components of $PM_{2.5}$ in relation to wood stove use. For example, we found BC to be 62% higher in homes of pregnant women with (vs. without) wood stoves, whereas OC was only 24% higher and the difference did not reach statistical significance. Consistent with this, biomass burning in developing countries is also associated with higher concentrations of BC than OC [20]. In addition to being a known marker of combustion source particulate matter, BC is thought to be a major contributor to the toxicity of $PM_{2.5}$ [21]. Greater BC exposure has been linked to premature mortality, cardiovascular health, and birth weight, independent of particle mass [reviewed in [22]], suggesting that additional data are needed on health effects of wood stove use in pregnant women and other potentially vulnerable populations. In addition, interventions to lower wood stove pollution in high-income countries may benefit from targeting populations such as pregnant women.

In homes with wood stoves versus without wood stoves, we found higher K, Ca, and Cl, generally consistent with two prior, smaller studies that investigated airborne trace elements in relation to wood stove use. The study of Suffolk and Onondaga counties in New York state found homes with wood stoves to have higher median concentrations of K and Ca, and Cl was higher in homes with wood stoves in Onondaga county only [7]. In a more recent study in Sweden (n=24), homes with wood stoves had higher median concentrations of K, Ca, and zinc [23]. These findings are important in the setting of emerging evidence suggesting that trace element components of $PM_{2.5}$ may have unique associations with health outcomes, including birth weight [9, 24].

Our study is among the first studies to evaluate elemental and organic carbon fractions in relation to household wood stove use. Carbon fractions group particulate matter originating from disparate sources based on common physical and/or chemical properties, with lower numbered fractions being less polar and more volatile [12]. Among all homes in our cohort, we found EC3 and EC4 to be the most prevalent EC fractions, in contrast to data from a sample of 37 homes in New York City in which highest concentrations were of EC1 [25]. The discrepancy may be explained by wood stove use in our cohort, as we found EC fractions 3 and 4 to be significantly higher in homes with wood stove use. We found OC1 to be the most prevalent OC fraction in homes, consistent with the New York City sample, and we did not find OC fractions to be significantly associated with wood stove use. Our results contrast with a study in Atlanta that found wood smoke to be a source of higher numbered OC fractions and not a source of EC fractions [26]. However, the Atlanta study included wood smoke from forest fires and prescribed burnings, and the emission profile may be different. Replication of our finding and additional data on associations of EC and OC fractions with health outcomes will help to guide specific pollutant targets of future efforts to mitigate household wood stove pollution.

We found using a newer wood stove, using an EPA-certified stove, or burning exclusively dry wood to be associated with lower household concentrations of $PM_{2.5}$, BC, OC, and K. Our finding is in contrast to results from a recent randomized controlled trial in Libby, Montana that showed no change in household $PM_{2.5}$ following replacement of older stoves with newer, EPA-certified stoves. Possible explanations for this discrepancy may be that we found the most pronounced difference in BC (whereas only $PM_{2.5}$ was measured in the Libby study) and household pollution concentrations were overall higher in Libby [27]. Differences in ambient air pollutant concentrations may also lead to community differences in the extent to which more fuel-efficient stoves lower household air pollution. Consistent with the findings in Libby, we found that homes with wood stoves had lower pollutant concentrations if an air purifier was also in use. Contrary to the limited existing literature [28], we found pellet stoves to be associated with higher household concentrations of $PM_{2.5}$ and K than log-burning stoves. However, we sampled very few homes with air purifiers or pellet stoves, so additional data in a larger sample is needed.

We observed that other activities in the home influenced household air pollution as much as or more than wood stove use. Consistent with the existing literature [5, 25], we found that homes with frequent household cleaning or burning candles/incense (versus those without these activities) had elevated BC, and the magnitude of BC elevation was similar to that of homes with versus without wood stove use. These indoor activities were more strongly associated with household air pollution than ambient characteristics (i.e., season of monitoring or proportion of wood fuel heated homes in census block). Identifying specific types of household cleaning and candle use that most strongly contribute to indoor air pollution would help to frame public health messages.

Limitations of our study include the fact that we did not measure carbon monoxide or other non-particulate pollutants, such as polycyclic aromatic hydrocarbons or benzene, previously associated with wood burning [29-31], although carbon monoxide has been highly correlated with $PM_{2.5}$ emissions from wood burning [32]. Also, our data on household activities and characteristics, including wood stove and fuel characteristics such as EPA-certification and fuel moisture level, were self-reported by questionnaire and thus subject to misclassification which could have biased results toward the null. In addition, our sample size was relatively small, although our study is larger than previous studies comparing pollutants in homes with versus without wood stoves. Finally, we did not directly measure ambient (outdoor) air pollution or residential air exchange rates [33], but we did adjust for heating season and proportion wood fuel heated homes in census block as proxies of ambient air pollution. Strengths of our study include the fact that we measured components of $PM_{2.5}$, accounted for other indoor activities, and investigated factors that may mitigate wood stove pollution. In addition, our individual-level data allowed us to evaluate differences in participant characteristics among wood stove users versus non-users.

In conclusion, wood stove use in a population of pregnant women in Northern New England was associated with higher household BC and EC, particularly carbon fractions EC3 and EC4, as well as higher concentrations of airborne trace elements K, Ca, and Cl. Newer wood stoves, EPA-certified stoves, and those burning exclusively dry wood were associated with lower household concentrations of air pollutants in this region. Populations such as pregnant women who are most vulnerable to health effects related to BC/EC may benefit most from these or other interventions to mitigate wood stove pollution.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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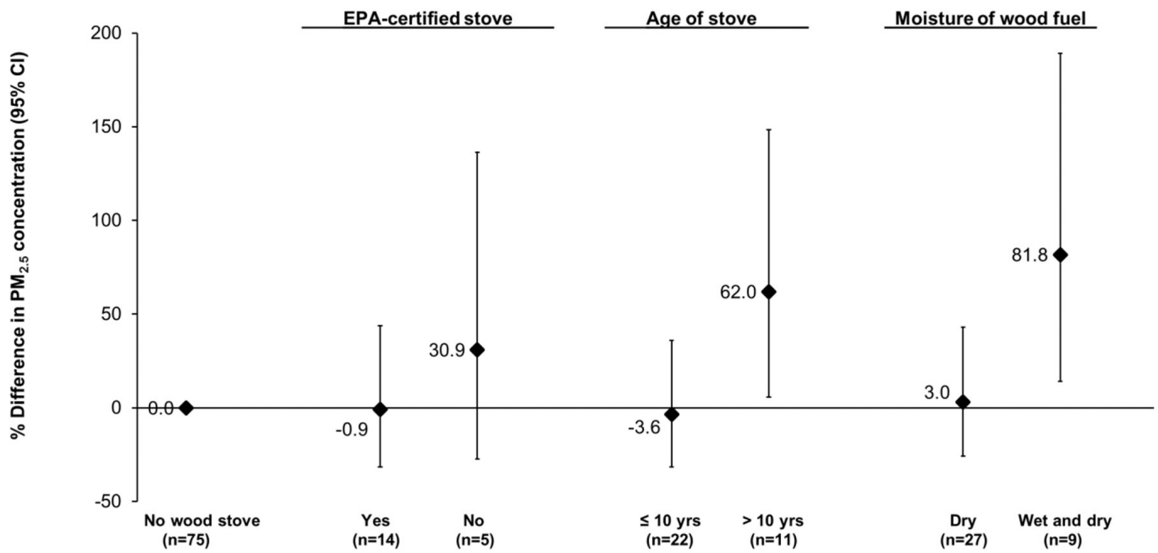
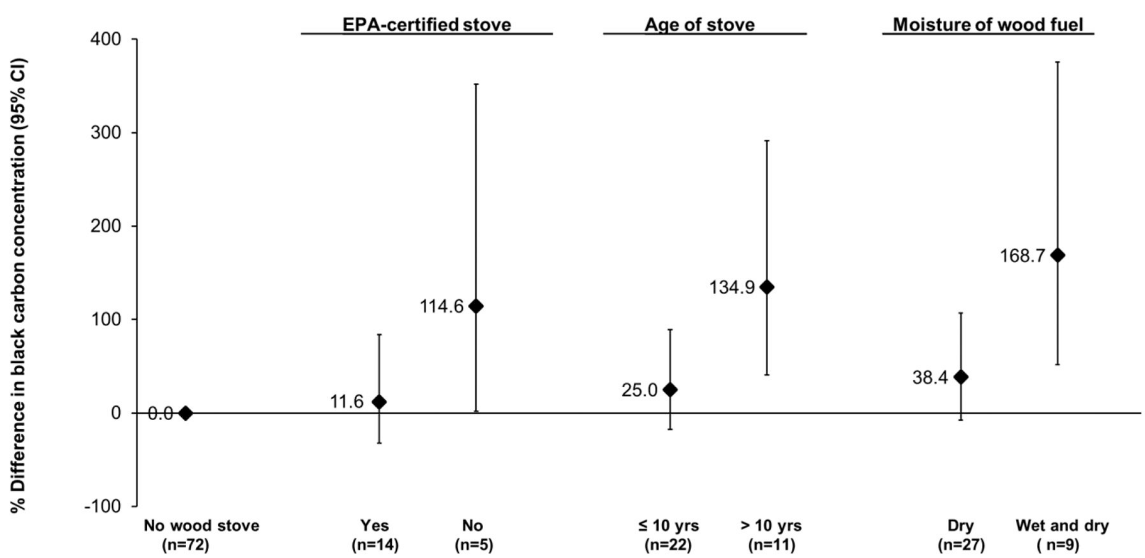
(*A*)


EPA-certified stove
Age of stove
Moisture of wood fuel
% Difference in PM2.5 concentration (95% CI)
200
150
100
50
0
-50
0.0
-0.9
30.9
-3.6
62.0
3.0
81.8
No wood stove (n=75)
Yes (n=14)
No (n=5)
≤ 10 yrs (n=22)
> 10 yrs (n=11)
Dry (n=27)
Wet and dry (n=9)

(*B*)


EPA-certified stove
Age of stove
Moisture of wood fuel
% Difference in black carbon concentration (95% CI)
400
300
200
100
0
-100
0.0
11.6
114.6
25.0
134.9
38.4
168.7
No wood stove (n=72)
Yes (n=14)
No (n=5)
≤ 10 yrs (n=22)
> 10 yrs (n=11)
Dry (n=27)
Wet and dry (n=9)

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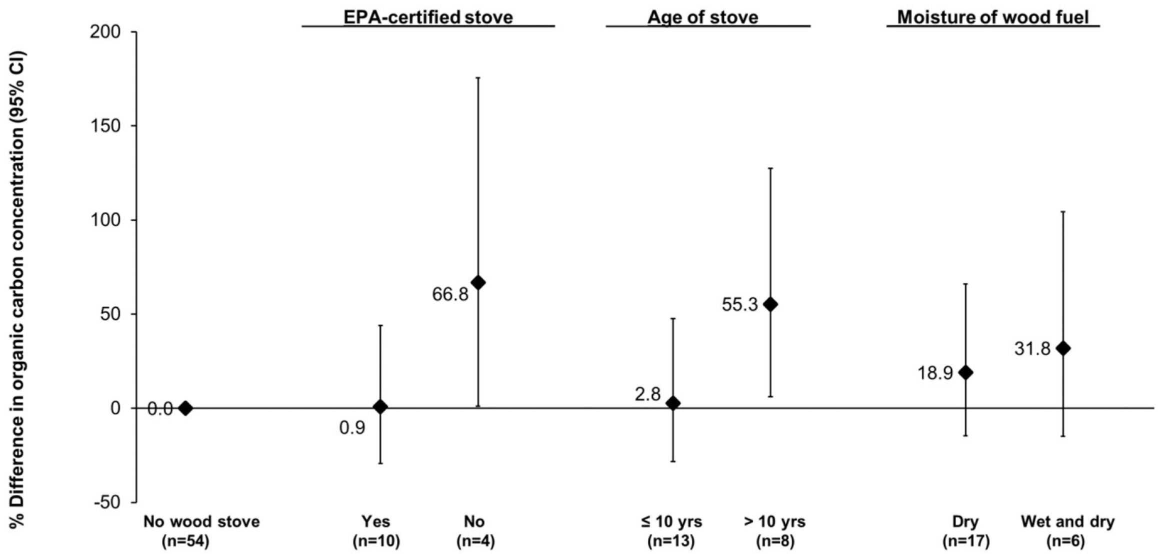
Author Manuscript

(*C*)



(*D*)

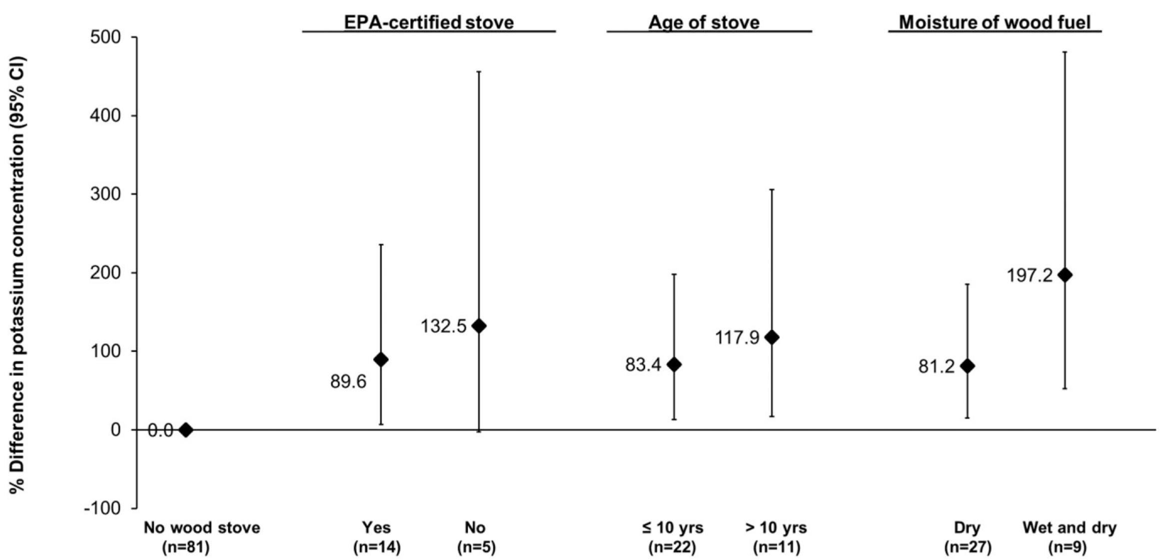


Figure 1.

Adjusted[I] associations of EPA-certification of stove, age of stove, moisture of wood fuel, and open windows in home on household $PM_{2.5}$ (*A*), black carbon (*B*), organic carbon (*C*), and potassium (*D*), among participants who used a wood stove, as compared to those who did not use a wood stove during monitoring[II, III]

[I] Adjusted for covariates as in Table 4

[II] Excluded four participants who used a wood stove during monitoring in the non-heating season

[III] Missing data: *n*=1 for EPA-certification; *n*=2 for age of stove; *n*=3 for moisture of wood fuel

Participants who responded "don't know" for EPA-certification: *n*=19 for $PM_{2.5}$, BC, and potassium and *n*=11 for OC

Participants who responded "don't know" for age of stove: *n*=1 for $PM_{2.5}$, BC, and K and *n*=2 for OC

Table 1.

Characteristics of participants, overall and by categories of season and wood stove use during air monitoring

	Overall	Heating season (Oct 1-Apr 30) Used wood stove	Heating season (Oct 1-Apr 30) Did not use wood stove	Non-heating season [1]
	n=137	n=41	n=45	n=47
	Percent			
Personal characteristics				
Age at enrollment (years)				
< 30	26	32	29	17
30-34.9	51	46	44	64
≥ 35	23	22	27	19
Pre-pregnancy BMI (kg/m^2)				
< 25	58	59	62	57
25-29.9	28	34	20	25
≥ 30	14	7	18	18
Educational attainment				
Less than college	23	19	25	22
College graduate	32	43	25	32
Any post-graduate education	45	38	50	46
Married	80	83	78	81
Multiparous	57	46	69	53
Activities during monitoring				
Dusted, swept, or vacuumed (hours/week)				
< 1	25	20	21	31
1-3	65	65	72	60
≥ 4	10	15	7	9
Burnt candles or incense (hours/week)				
< 1	66	65	59	71
1-3	15	18	17	13
≥ 4	18	18	24	16
Fried, cooked, or baked (hours/week)				
< 5	37	33	40	38
5-9	46	45	49	47
≥ 10	17	23	12	16
Used fan above cook stove (hours/week)				
<1	57	55	67	49
1-3	26	30	21	29
≥ 4	17	15	12	22
Used fan in other location (hours/week)				
0	62	63	83	42
1-40	20	20	15	27
> 40	18	18	2	31

	Overall	Heating season (Oct 1-Apr 30)		Non-heating season [1]
		Used wood stove	Did not use wood stove	
	n=137	n=41	n=45	n=47
Opened windows (hours/week)				
0	49	75	74	7
1-60	27	20	21	36
> 60	24	5	5	57
Used humidifier (hours/week)				
0	85	68	83	100
1-60	8	18	10	0
> 60	7	15	7	0
Used air purifier	6	8	10	2
Indoor renovation	8	10	5	9
Household/neighborhood characteristics				
Number of rooms in home				
< 6	16	20	9	15
6-8	43	40	48	43
> 8	41	40	43	41
Year of construction				
< 1960	22	25	18	26
1960-1989	37	35	34	37
≥ 1990	41	40	48	37
Freestanding home	95	100	93	93
Pets in home	76	68	68	93
Census block characteristics				
Median household income (USD)				
< 60,000	37	41	31	38
60,000-75,000	32	31	28	40
> 75,000	31	28	41	21
Percent of wood-fuel heated homes				
< 15	31	21	28	40
15-30	42	46	49	33
> 30	27	33	23	26
Population density (people/ km^2 of land)				
< 15	30	33	33	21
15-30	35	44	23	38
> 30	35	23	44	40
Elevation (m)				
< 250	31	26	31	38
250-300	26	23	33	19
> 300	44	51	36	43
Distance to major road (m)				

	Overall	Heating season (Oct 1-Apr 30)		Non-heating season [1]
		Used wood stove	Did not use wood stove	
	n=137	n=41	n=45	n=47
> 5,000	48	51	41	50
1,000-5,000	39	36	49	33
< 1,000	13	13	10	17

Abbreviations: BMI – body mass index; m – meters; km – kilometers

Missing data in overall cohort: 3 for pre-pregnancy BMI, 15 for education, 2 for parity, 6 for dusted, 7 for burnt candles, 6 for cooking, 6 for fan above cook stove, 8 for use of other fan, 7 for opened windows, 7 for humidifier use, 6 for air purifier, 7 for indoor renovation, 3 for number of rooms, 3 for home age, 4 for freestanding home, 6 for pets, and 13 for census block characteristics

[1] Four participants who used a wood stove during monitoring in the non-heating season are excluded here but included in overall cohort column.

Table 2.

Distribution of average concentrations of household $PM_{2.5}$, black carbon (BC), elemental carbon (EC), organic carbon (OC), and potassium (K), and Spearman correlation coefficients of the air pollutants.

	Average weekly concentrations of household air pollutants [I]				
	$PM_{2.5}$	**BC**	**EC**	**OC**	**K**
Median (IQR)	6.65 (5.02)	0.23 (0.20)	0.12 (0.14)	2.80 (1.60)	41.29 (41.73)
Minimum [II]	0.98 (LOD/√2)	0.06 (LOD/√2)	0.04 (LOD/√2)	0.64	1.39 (LOD/√2)
Maximum	65.23	3.11	2.49	13.78	919.95
	Spearman correlation coefficients				
$PM_{2.5}$	1.00				
BC	0.68	1.00			
EC	0.51	0.70	1.00		
OC	0.75	0.52	0.60	1.00	
K	0.55	0.58	0.42	0.35	1.00

Abbreviations: BC—black carbon, EC—elemental carbon, IQR – interquartile range, K—potassium, OC—organic carbon, PM – particulate matter

[I] $\mu g/m^3$, except for K (ng/m^3)

[II] 3 samples below the LOD for $PM_{2.5}$, 9 for BC, 7 for EC, and 3 for K.

Table 3.

Univariate associations of participant, household, and neighborhood characteristics with average household $PM_{2.5}$, black carbon (BC), organic carbon (OC), and potassium (K).

	% Difference in air pollutant concentration (95% CI)			
	$PM_{2.5}$	**BC**	**OC**	**K**
	n=137	**n=136**	**n=100**	**n=136**
Personal characteristics				
Age at enrollment (years)				
< 30	Reference	Reference	Reference	Reference
30-34.9	−33.5 (−49.0, −13.3)	−38.4 (−55.4, −14.9)	−36.6 (−50.7, −18.5)	−34.5 (−55.4, −3.8)
≥ 35	−11.9 (−35.8, 21.0)	−42.1 (−60.8, −14.6)	−29.5 (−48.2, −4.1)	−14.4 (−46.2, 36.0)
Pre-pregnancy BMI (kg/m^2)				
< 25	Reference	Reference	Reference	Reference
25-29.9	−2.3 (−25.5, 28.1)	1.5 (−26.9, 41.0)	−6.6 (−27.8, 20.9)	−1.8 (−33.1, 44.4)
≥ 30	7.0 (−24.4, 51.4)	25.4 (−17.6, 91.1)	−18.1 (−42.5, 16.7)	17.4 (−28.3, 92.2)
Educational attainment				
Less than college	Reference	Reference	Reference	Reference
College graduate	−13.3 (−37.6, 20.6)	−17.1 (−44.1, 22.8)	−15.0 (−38.8, 18.0)	−13.2 (−45.8, 39.0)
Any post-graduate education	−30.2 (−48.8, −4.9)	−43.1 (−60.7, −17.7)	−13.6 (−36.9, 18.5)	−45.0 (−64.7, −14.3)
Married	−10.4 (−32.7, 19.4)	−6.9 (−34.4, 32.1)	3.6 (−20.6, 35.2)	−12.8 (−42.0, 31.2)
Multiparous	25.4 (−0.5, 58.0)	−1.2 (−25.7, 31.5)	7.2 (−14.8, 34.9)	15.0 (−17.5, 60.4)
Activities during monitoring				
Used wood stove [1]	21.6 (−5.4, 56.4)	71.0 (27.6, 129.3)	24.2 (−2.6, 58.5)	127.3 (63.2, 216.7)
Dusted, swept, or vacuumed (hours/week)				
< 1	Reference	Reference	Reference	Reference
1-3	23.4 (−6.1, 62.1)	47.2 (7.0, 102.4)	0.4 (−22.1, 29.5)	31.5 (−10.7, 93.6)
≥ 4	47.3 (−4.8, 127.7)	130.6 (38.7, 283.3)	10.7 (−27.5, 69.1)	70.2 (−8.2, 215.3)
Burnt candles or incense (hours/week)				
< 1	Reference	Reference	Reference	Reference
1-3	2.6 (−26.5, 43.2)	30.4 (−11.6, 92.5)	8.0 (−21.5, 48.5)	−2.2 (−39.1, 57.1)
≥ 4	7.2 (−21.4, 46.1)	80.9 (26.0, 159.9)	9.0 (−22.2, 52.8)	24.0 (−20.2, 92.8)

	% Difference in air pollutant concentration (95% CI)			
	$PM_{2.5}$ n=137	BC n=136	OC n=100	K n=136
Fried, cooked, or baked (hours/week)				
< 5	Reference	Reference	Reference	Reference
5-9	22.8 (−5.0, 58.9)	20.1 (−11.9, 63.9)	3.1 (−19.7, 32.2)	29.6 (−10.0, 86.6)
≥ 10	12.2 (−20.4, 58.2)	22.0 (−19.9, 85.7)	15.4 (−17.1, 60.7)	5.2 (−35.8, 72.3)
Used fan above cook stove (hours/week)				
<1	Reference	Reference	Reference	Reference
1-3	−2.1 (−25.9, 29.4)	4.3 (−25.4, 45.9)	2.4 (−23.5, 37.1)	−20.9 (−46.5, 16.9)
≥ 4	9.4 (−21.1, 51.7)	6.5 (−28.6, 59.0)	16.7 (−12.8, 56.2)	−24.1 (−52.4, 21.1)
Used fan in other location (hours/week)				
0	Reference	Reference	Reference	Reference
1-40	−7.8 (−31.4, 23.9)	−0.7 (−31.0, 42.9)	1.3 (−23.7, 34.5)	−9.5 (−40.1, 36.7)
> 40	−4.0 (−29.6, 30.8)	−10.3 (−38.7, 31.3)	14.6 (−16.8, 57.8)	−9.9 (−41.5, 38.8)
Opened windows (hours/week)				
0	Reference	Reference	Reference	Reference
1-60	5.5 (−20.6, 40.1)	−18.3 (−41.6, 14.4)	−6.7 (−28.5, 21.7)	−15.1 (−43.0, 26.5)
> 60	−1.8 (−29.6, 30.8)	−33.2 (−53.1, −4.8)	−11.1 (−32.9, 17.8)	−28.7 (−53.1, 8.5)
Used humidifier (hours/week)				
0	Reference	Reference	Reference	Reference
1-60	21.9 (−18.8, 82.9)	57.8 (−4.1, 159.6)	108.0 (23.6, 250.0)	15.7 (−34.4, 104.2)
> 60	58.9 (1.8, 148.0)	66.3 (−3.6, 187.2)	65.6 (3.7, 164.4)	80.4 (−3.2, 236.2)
Used air purifier	−25.9 (−53.7, 18.8)	−10.8 (−50.2, 60.0)	−41.4 (−63.6, −4.8)	−2.7 (−49.7, 88.3)
Indoor renovation	20.4 (−20.0, 81.4)	28.3 (−22.5, 112.5)	61.8 (7.3, 144.0)	33.2 (−24.7, 135.3)
Household/neighborhood characteristics				
Number of rooms in home				
< 6 rooms	Reference	Reference	Reference	Reference
6-8 rooms	−5.4 (−32.5, 32.8)	−9.4 (−39.9, 36.5)	−10.5 (−35.5, 24.3)	19.4 (−26.2, 93.2)
> 8 rooms	−15.5 (−39.9, 18.8)	−15.6 (−44.2, 27.7)	−20.7 (−42.9, 10.0)	11.6 (−31.4, 81.3)
Year of construction				
< 1960	Reference	Reference	Reference	Reference

	% Difference in air pollutant concentration (95% CI)			
	$PM_{2.5}$	BC	OC	K
	n=137	n=136	n=100	n=136
1960-1989	−3.5 (−29.1, 31.3)	−1.4 (−32.3, 43.6)	−4.7 (−28.6, 27.3)	−2.0 (−36.5, 51.3)
≥ 1990	−14.7 (−37.0, 15.3)	−3.7 (−33.3, 38.9)	6.8 (−19.0, 41.0)	−28.9 (−53.5, 8.5)
Freestanding home	3.1 (−38.6, 73.1)	−18.1 (−55.9, 52.1)	−30.3 (−55.9, 10.0)	49.9 (−27.9, 211.7)
Pets in household	19.7 (−9.1, 57.5)	6.6 (−24.0, 49.5)	−12.9 (−32.9, 13.1)	31.8 (−11.1, 95.4)
Census block characteristics				
Median household income (USD)				
< 60,000	Reference	Reference	Reference	Reference
60,000-75,000	−7.5 (−30.5, 23.1)	−28.2 (−50.1, 3.3)	−22.1 (−42.0, 4.6)	−13.8 (−43.3, 31.0)
> 75,000	−32.3 (−49.3, −9.5)	−25.3 (−48.5, 8.4)	−15.7 (−36.5, 12.1)	−43.0 (−62.8, −12.6)
Percent of wood-fuel heated homes				
< 15	Reference	Reference	Reference	Reference
15-30	0.4 (−23.4, 33.2)	−12.4 (−39.3, 26.3)	4.1 (−22.1, 39.2)	62.1 (7.2, 145.1)
> 30	45.2 (6.2, 98.5)	10.1 (−26.5, 64.9)	21.5 (−11.0, 65.9)	91.6 (21.4, 202.6)
Population density (people/km^2 of land)				
< 15	Reference	Reference	Reference	Reference
15-30	−4.8 (−29.9, 29.2)	6.4 (−29.2, 59.8)	−14.0 (−36.0, 15.7)	3.2 (−33.6, 60.3)
> 30	−8.6 (−32.6, 23.8)	−18.2 (−43.0, 17.3)	−7.5 (−31.4, 24.7)	−28.1 (−53.7, 11.8)
Elevation (m)				
< 250	Reference	Reference	Reference	Reference
250-300	−2.2 (−29.1, 34.9)	6.4 (−29.2, 59.8)	9.3 (−21.4, 52.0)	−7.2 (−42.0, 48.4)
> 300	−22.9 (−41.9, 2.5)	−18.2 (−43.0, 17.3)	0.0 (−25.8, 34.9)	−33.6 (−56.2, 0.7)
Distance to primary road (m)				
> 5,000	Reference	Reference	Reference	Reference
1,000-5,000	0.7 (−22.6, 31.0)	15.2 (−17.3, 60.3)	−1.5 (−23.6, 27.0)	−11.5 (−39.9, 30.2)
< 1,000	21.0 (−17.4, 77.3)	38.5 (−14.1, 123.2)	9.6 (−33.3, 80.0)	23.4 (−29.3, 115.6)
Season				
Heating season (Oct 1-Apr 30)	12.8 (−10.9, 42.8)	53.6 (16.0, 103.4)	19.3 (−4.5, 49.2)	67.7 (20.9, 132.6)

Abbreviations: BC—black carbon, K—potassium, OC—organic carbon, PM – particulate matter

[1] Analyses of wood stove use and air pollutant concentrations excluded four participants who used a wood stove during monitoring in the non-heating season.

Table 4.

Covariate-adjusted associations of household and neighborhood characteristics with average household $PM_{2.5}$, black carbon (BC), organic carbon (OC), and potassium (K).

	% Difference in air pollutant concentration (95% CI)			
	$PM_{2.5}$	**BC**	**OC**	**K**
	n=113	**n=110**	**n=79**	**n=120**
Activities during monitoring				
Used wood stove	20.6 (−10.6, 62.6)	61.5 (11.6, 133.6)	23.5 (−7.0, 63.9)	104.4 (35.5, 208.3)
Dusted, swept, or vacuumed (hours/week)				
< 1		Reference		
1-3		40.5 (−2.0, 101.6)		
≥ 4		101.0 (13.9, 254.9)		
Burnt candles or incense (per 24 hours/week)		79.4 (−2.7, 164.3)		
Used humidifier (per 24 hours/week)	8.2 (−2.6, 15.6)	5.1 (−6.2, 16.4)	21.3 (7.0, 35.8)	
Opened windows (per 24 hours/week)		1.4 (−7.0, 9.8)		
Used air purifier			−59.9 (−77.8, −27.4)	
Indoor renovation			77.7 (18.4, 166.7)	
Census block characteristics				
Percent of wood-fuel heated homes (per 5% increment)	7.9 (2.7, 13.1)	2.8 (−3.6, 9.3)	3.1 (−1.6, 7.9)	8.9 (1.9, 16.0)
Season				
Heating season (Oct 1-Apr 30)	−4.6 (−28.6, 27.4)	18.1 (−24.4, 84.3)	9.9 (−15.2, 42.3)	15.1 (−23.1, 72.2)

Abbreviations: BC—black carbon, K—potassium, OC—organic carbon, PM – particulate matter

Associations are adjusted for wood stove use, heating season, percent of wood-fuel heated homes in census block, and other sources of the pollutant with global $p < 0.10$ in univariate associations (Table 3).

Four participants who used a wood stove during monitoring in the non-heating season were excluded.