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Indoor particulate matter in rural, wood stove heated homes

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Abstract

Ambient particulate matter (PM) exposures have adverse impacts on public health, but research evaluating indoor PM concentrations in rural homes in the United States using wood as fuel for heating is limited. Our objectives were to characterize indoor PM mass and particle number concentrations (PNCs), quantify infiltration of outdoor PM into the indoor environment, and investigate potential predictors of concentrations and infiltration in 96 homes in the northwestern US and Alaska using wood stoves as the primary source of heating. During two forty-eight hour sampling periods during the pre-intervention winter of a randomized trial, we assessed PM mass (< 2.5 µm) and PNCs (particles/cm^3) in six size fractions (0.30–0.49, 0.50–0.99, 1.00–2.49, 2.5–5.0, 5.0–10.0, 10.0+ µm). Daily mean (sd) $PM_{2.5}$ concentrations were 28.8 (28.5) µg/m^3 during the first sampling period and 29.1 (30.1) µg/m^3 during the second period. In repeated measures analyses, household income was inversely associated with $PM_{2.5}$ and smaller size fraction PNCs, in particular. Time of day was a significant predictor of indoor and outdoor $PM_{2.5}$ concentrations, and infiltration efficiency was relatively low (F_{inf} (sd) = 0.27 (0.20)). Our findings demonstrate relatively high mean PM concentrations in these wood burning homes and suggest potential targets for interventions for improving indoor air quality and health in rural settings.

Keywords

particulate matter; biomass combustion; wood stove; indoor air quality; infiltration efficiency

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1. Introduction

The health effects associated with exposure to particulate matter less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) are well known. To date, much of this research has focused on investigating the effects of ambient exposures in urban areas dominated by industrial and vehicular sources of $PM_{2.5}$. However, emissions from biomass combustion generated from heating of homes are a major source of $PM_{2.5}$ in rural areas of the United States (US).

In many areas of the US, wood stoves are used for home heating with over 11 million homes reporting use of wood as either a primary or secondary heating fuel (U.S. Energy Information Administration, 2009). Over 80% of these wood stoves are old and inefficient (Air Quality Management Work Group, 2005), often generating $PM_{2.5}$ concentrations *indoors* that exceed health based standards such as the US Environmental Protection Agency (US EPA) 24-hr National Ambient Air Quality Standard (NAAQS) of 35 micrograms/meter^3 (μg/m^3) (US EPA, 2011) or the corresponding World Health Organization (WHO) standard of 25 μg/m^3 (WHO, 2006). The setting for the study described here is a randomized controlled trial designed to assess the efficacy of in-home interventions in improving indoor air quality and respiratory health in asthmatic children living in wood stove homes in the rural, western US and Alaska. Although recent calls to improve indoor air quality assessment in the developing world have been made (Clark et al., 2013), comparatively little emphasis has been placed on indoor $PM_{2.5}$ concentrations in wood stove homes in the US, a necessary initial step in improving our understanding of the risks to public health posed by these common residential exposure sources and in developing strategies for their mitigation (Barn, 2014).

Our objectives were to: characterize indoor particulate matter (PM) concentrations and infiltration of PM from outdoor sources in homes using wood stoves as the primary source of heating and examine the relationship between particle mass and count concentrations. Further, we evaluated various wood stove burning practices, activities in the home (e.g. opening of windows), socioeconomic factors (e.g. household income), and home characteristics (e.g. home type, size, and presence of pets) as potential predictors of PM concentrations and infiltration within these wood-burning homes.

2. Materials and methods

2.1. Study setting

The Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) provided the setting in which we evaluated $PM_{2.5}$ and particle number concentrations (PNCs) in homes containing wood stoves located in rural areas of Montana, Idaho, and Alaska. The methods utilized in the parent study have been described in detail elsewhere (Noonan and Ward, 2012). Briefly, during the initial winter of enrollment in the study, participation involved pre-intervention residential indoor air sampling and collection of data on multiple biomarkers including inflammatory cytokines in exhaled breath condensate and urinary cotinine and respiratory health endpoints such as the Pediatric Asthma Quality of Life Questionnaire (PAQLQ) (Juniper et al., 1996) in children with asthma. Interventions designed to improve indoor air quality (installation of improved wood stoves or air filtration units) were implemented during the fall followed by a repetition of exposure and health outcome assessment during the following winter. We present here findings based on the pre-intervention winter exposure assessments. The efficacy of wood stove changeouts and air filtration units in reducing indoor $PM_{2.5}$ concentrations in ARTIS homes will be presented in a separate manuscript.

Recruitment and enrollment of subjects occurred as described previously (Noonan and Ward, 2012). To be eligible, homes had to utilize an older model wood stove as a primary heating source as well as have a child between 7 and 17 years of age with asthma who was expected to reside in the home for the next 2 years. In this context, older model wood stoves include those devices that are fueled by wood, and do not have modern control features focused on emission reduction. Homes with smoking residents were excluded. The first cohort of homes was enrolled for the winter of 2008–2009 with the final group completing pre-intervention sampling during the winter of 2011–2012. Parents or guardians of child participants provided signed permission, and assent was documented among children prior to participating in the study. The study was approved by the Institutional Review Board at the University of Montana.

2.2. Indoor and outdoor air exposure assessment

PM air sampling instruments were placed approximately 5 feet off of the ground in the living or common room (which usually contained the wood stove) of participating homes. In addition, outdoor $PM_{2.5}$ sampling occurred outside the home using a DustTrak 8520 housed in a portable DustTrak Environmental Enclosure 8535 (TSI Inc., Shoreview, MN, USA), which enabled it to operate during cold temperatures. Indoor $PM_{2.5}$ concentrations were assessed using either a DustTrak 8520 or 8530, the primary model deployed for indoor monitoring during later years of the study. PM concentrations were assessed continuously and recorded as 1-minute averages throughout each of two 48-hour sampling periods that occurred during the pre-intervention winter. The DustTrak measures $PM_{2.5}$ concentrations by calculating the forward scattering of an infrared diode laser beam in the airflow. Each instrument was zero calibrated prior to each sampling event. Calibration and field maintenance of the device was performed as described previously (McNamara et al., 2013). Due to the sensitivity of measurements obtained from optical scatter instruments to particle size and material properties and thus combustion sources, we applied a wood smoke-specific correction factor of 1.65 to all indoor and outdoor $PM_{2.5}$ concentrations (McNamara et al., 2011). PNCs were assessed using a Lighthouse 3016-IAQ particle counter (Lighthouse Worldwide Solutions, Fremont, CA) that continuously measured particle counts within six size fractions (0.30–0.49, 0.50–0.99, 1.00–2.49, 2.5–5.0, 5.0–10.0, 10.0+ µm).

Summary PM concentrations over each 48-hour sampling period are reported. For $PM_{2.5}$, we also calculated the percentage of homes with 48-hour averages exceeding WHO and US EPA health-based 24-hour ambient air quality guidelines (WHO, 2006) and standards (US EPA, 2011). We included only those averages that were generated from data that was at least 80% complete to ensure that the averages were representative of concentrations experienced during the entire sampling event. Temporal patterns over the course of each sampling event also were evaluated. Six four-hour time periods (10 pm–2 am, 2 am–6 am, 6 am–10 am, 10 am–2 pm, 2 pm–6 pm, and 6 pm–10 pm) were chosen *a priori* and were expected to correspond approximately to times when the residents of participating homes would be sleeping (10 pm–6 am), at home and actively using their wood stoves (6 am–10 am and 6 pm–10 pm), or not at home (10 am–6 pm).

2.3. Covariate ascertainment

QTRAKs (TSI Inc.), co-located with the DustTraks and particle counters, were used to record 1-minute averages of indoor temperature and humidity throughout the sampling periods. In addition, adult residents reported the usage of the wood stove during each sampling event including the number of times that the wood stove was loaded/stoked, burn intensity (none, light, average, or heavy), source of wood, and approximate age of wood. We also ascertained the occurrence of activities in the home that are potential predictors of elevated $PM_{2.5}$ concentrations (i.e. cooking, cleaning, pets, etc.). Demographic and home characteristics data also were captured from an adult resident. We expected that home characteristics such as square footage would not change throughout the study. Thus, we used data from the most recent visit or from a subsequent visit when home characteristics information was missing for a particular visit since no participants moved between visits during the pre-intervention winter. Meteorological data including temperature, relative humidity, precipitation, and wind speed were obtained from the Western Regional Climate Center (2013) and averaged over the first, second, and third calendar days of each sampling event. Lastly, during each sampling event (with the exception of the first year of the study), household caregivers recorded the times that the child was actually in the home during the scheduled sampling events to more accurately quantify in-home exposure for the child.

2.4. Infiltration estimation

Infiltration efficiency (F_{inf}) is defined as the fraction of the outdoor concentration that penetrates indoors and remains suspended. It depends on particle penetration and deposition, as well as the air exchange rate, and in the absence of indoor sources F_{inf} is equal to the indoor-outdoor concentration ratio. Continuous indoor and outdoor $PM_{2.5}$ sampling during each of two 48-hour winter visits was exploited to quantify F_{inf} in homes using a well-validated recursive model approach (Allen et al., 2003; Allen et al., 2007). Hourly indoor and outdoor concentration averages were calculated from 1-minute averages, and any hourly average generated from less than thirty minutes of data was excluded. The recursive modeling approach used here involves a censoring algorithm that identifies indoor source periods as those during which indoor concentrations increase without a corresponding increase outdoors. We excluded homes in which the 25th percentile indoor measurement exceeded the 75th percentile outdoor measurement, because these situations represent either a constant indoor source or instrument calibration problems, both of which prevent the recursive model from being applied (Allen et al., 2003). F_{inf} was set to 0 for homes with negative values for F_{inf} (n = 6) and to 1 with F_{inf} exceeding 1 (n = 1). Winter estimates of F_{inf} were calculated for a total of 90 homes with sufficient indoor and outdoor $PM_{2.5}$ measurements.

2.5. Statistical analysis

We calculated summary statistics of potential predictors of $PM_{2.5}$, PNCs, and infiltration. Spearman correlation coefficients were calculated to examine the relationship between indoor $PM_{2.5}$ mass measured by the DustTrak and PNCs for each size fraction of interest. Mean and standard deviation (sd) indoor air concentrations for each 48-hour sampling event were calculated as were summary statistics for the times that the child was in the home during the sampling period. We utilized generalized estimating equations (GEE) with an exchangeable correlation structure and robust standard errors, adjusted for the number of days since the first visit, in bivariate and multivariate analyses of potential predictors and $PM_{2.5}$ and PNCs. $PM_{2.5}$ and PNC distributions were right-skewed, and, as a result, these variables were log-transformed in analyses. We used GEE assuming an exchangeable correlation structure with robust standard errors to examine the influence of time of day on indoor and outdoor $PM_{2,5}$ concentrations, accounting for multiple measures within each home. Temporal patterns of PNCs also were explored graphically. Potential predictors of F_{inf} were evaluated using linear regression. Finally, based on estimated F_{inf}, we calculated the percentage of indoor $PM_{2.5}$ accounted for by outdoor-generated $PM_{2.5}$ (i.e., $PM_{2.5}$ infiltrating from local ambient sources including smoke emissions from a given home's stove flue) versus indoor-generated $PM_{2.5}$ (e.g., $PM_{2.5}$ escaping from wood stoves due to leaky seals and/or poor venting). The outdoor-generated indoor concentration was equal to F_{inf} multiplied by the outdoor concentration, and the indoor-generated indoor concentration was equal to the indoor concentration minus the outdoor-generated concentration. All analyses were conducted using SAS 9.3 (Cary, NC) and STATA 9.2 (College Station, TX).

3. Results

A total of 96 homes with 80% complete data for at least one sampling day were included in the final analyses. Table 1 presents selected pre-intervention characteristics of wood stove homes participating in ARTIS by sampling visit. Nearly 60% of homes reported a total household income of less than $50,000 per year. As illustrated in Table 1, summaries of potential predictors of indoor $PM_{2.5}$ and PNCs including demographic and home characteristics information did not change substantially from visit to visit. Not surprisingly, the home activity and wood stove usage responses exhibited the most temporal variability. The number of times the stove was opened as well as the intensity of burning reported by the subject's caregiver varied over time. Adult residents reported that the child study participants were in the home for 64.8 and 66.0% of the first and second 48-hour sampling periods, respectively.

Smaller fraction PNCs, averaged over each 48-hour sampling period, were most strongly correlated with $PM_{2.5}$ (Table 2). Spearman correlation coefficients describing the relationship between $PM_{2.5}$ and PNCs ranged from 0.94 to 0.34 for 0.3–0.49 μm to 10.0+ μm particle size fractions, respectively. These relationships persisted during the second sampling visit (results not shown).

As presented in Table 3, daily mean indoor $PM_{2.5}$ concentrations were 28.8 (sd: 28.5) $\mu g/m^3$ for the first visit and 29.1 (sd: 30.1) $\mu g/m^3$ for the second visit. The mean one-minute maximum for all homes for each sampling event exceeded 600 $\mu g/m^3$, and approximately

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30% of homes had 48-hour averages exceeding the WHO's ambient $PM_{2.5}$ guideline of 25 μg/m^3 during at least one of the two sampling periods. PM concentrations averaged over the time the child was in the home (Table 3) were generally higher than those calculated for the entire sampling event. PNCs decreased with increasing size fractions.

In analyses evaluating potential contributors to indoor air quality measures, income was a strong predictor of reduced $PM_{2.5}$ concentrations and PNCs in the 0.30–0.99 size range (Table 4). A reported household income of greater than $50,000 per year was associated with a 51% (95% CI: 34%, 64%) reduction in geometric mean $PM_{2.5}$. Results were similar for the 0.30–0.49 and 0.50–0.99 PNC size fractions. The relationship was weaker for the 1.0–2.49 size fraction (0.69; 95% CI: 0.51, 0.93) but remained significant. A 100 square foot increase was associated with small, but significant, decreases in PM_{25} and PNCs in the 0.30–0.99 μm range. Residing in a home, relative to a mobile home or apartment, was associated with 36% (95% CI: 5%, 57%) lower $PM_{2.5}$ concentrations, 40% (95% CI: 14%, 58%) lower PNC 0.30–0.49 concentrations, and reduced concentrations of all fine fraction PNCs combined. Associations between household income and indoor air quality measures persisted, and were attenuated only slightly, after adjustment for size of home and residing in a home, relative to a mobile home or apartment (results not shown). The number of children in the home was associated only with the 1.0–2.49 and coarse PNC size fractions with each additional child living in the home linked to a 13% (95% CI: 1%, 26%) increase in 48-hour mean coarse PNC.

The reported number of times the wood stove was opened was not associated with $PM_{2.5}$ or any PNC size fraction, nor was the reported intensity of burning. Reported use of wood that was seasoned for at least two years before burning was associated with reduced concentrations of particles of the smallest size fraction measured (25% reduction; 95% CI: 1%, 43%), and was borderline significantly associated with the all fine fraction PNCs combined. A number of reported activities in the home were associated with higher air pollutant concentrations including not using a supplemental source of heating (e.g. electrical or propane) (PNC 0.50–2.49), burning of any type (e.g. candles or incense) (PNC 0.3–0.49 and PNC fine), and having an open window or door during the sampling event (all PM size fractions reported in Table 4). A 1-percent increase in indoor relative humidity was associated with a 2% (95% CI: 0%, 4%) elevation in PM2.5, PNC 1.0–2.49, and PNC coarse, possibly due to a change in the light scattering properties of PM at higher relative humidity rather than a true increase. Ambient meteorological variables generally were not associated with indoor air quality metrics with the exception of a 1-degree increase in mean outdoor temperature during the sampling event, which was linked to a 3% (95% CI: 1%, 4%) elevation in PNC coarse.

Both indoor and outdoor $PM_{2.5}$ concentrations varied over each sampling visit (Table 5). Median indoor concentrations were 8.4 μg/m^3 between 2 and 6 am and 25.4 μg/m^3 between 6 and 10 pm. The former represents a 47% reduction (95% CI: 39%, 55%) and the latter more than a doubling (95% CI: 73%, 133%) of median outdoor $PM_{2.5}$ relative to indoor concentrations observed between 10 pm and 2 am. In contrast, outdoor concentrations peaked between 10 pm and 2 am with all other time periods, except for 6 pm to 10 pm, having significantly lower $PM_{2.5}$. In general, PNCs of all size fractions followed a similar temporal pattern to indoor $PM_{2.5}$ as shown for the representative home in Figure 1 with larger size fractions decaying more rapidly than smaller size fractions.

Mean (sd) estimated F_{inf} was 0.27 (0.20) during the heating season in the 90 homes with indoor and outdoor $PM_{2.5}$ measurements (results not shown). As described in Table 6, a number of factors were examined as potential predictors of mean cold season F_{inf}. Participating homes in Butte, Montana exhibited significantly lower F_{inf}, relative to other western Montana homes although study community was not a significant predictor of F_{inf} (P = 0.18). Living in a single family home, relative to a mobile home or apartment, (β=0.11; 95% CI: 0.03, 0.20) was associated with higher F_{inf}, and the relationship between increased square footage and F_{inf} was borderline significant (β=0.05; 95% CI: 0.00, 0.11). On average, 70% (sd = 21%) of indoor $PM_{2.5}$ was indoor-generated (results not shown).

4. Discussion

4.1. Significance and context of findings

This study is the first to characterize both $PM_{2.5}$ mass and PNCs of various size fractions and to describe relationships between these measures of indoor air quality in wood stove homes across the western US and Fairbanks, Alaska. We observed significant temporal variability over each 48-hour sampling visit in indoor and outdoor $PM_{2.5}$. Indoor $PM_{2.5}$ peaked between 6 pm and 10 pm, when we generally would expect residents to be at home and awake, and was lowest between 2 am and 6 am when residents would be sleeping and not actively using their wood stove. In contrast, outdoor $PM_{2.5}$ peaked between 10 pm and 2 am and was lowest between 10 am and 2 pm. PNCs, particularly the smaller size fraction PNCs, closely followed indoor $PM_{2.5}$ patterns, with steep decays observed as the size fraction increased.

As expected, mean concentrations over the entire sampling period were lower than those typically observed in homes utilizing biomass cookstoves in the developing world, settings that can yield indoor $PM_{2.5}$ concentrations of several hundred μg/m^3 (Naeher et al., 2007). Indoor exposures observed in this study were similar to previous observations in rural wood stove homes performed by our group (Noonan et al., 2012; Ward et al., 2011; Ward et al., 2008). Importantly, the results show that PM concentrations consistently approached US EPA NAAQS during each of the sampling events occurring during the pre-intervention winter of ARTIS, leading to significant and prolonged indoor PM exposures for the asthmatic children. Of particular note, when $PM_{2.5}$ concentrations were restricted to the times when the child was reported to be in the home, exposures were, on average, 4 μg/m^3 higher compared to the 48-hour indoor average, indicating that full sampling event measures underestimate indoor, residential PM exposure concentrations for school-aged children in these settings.

Overall, when classifying particle counts as either “fine” or “coarse” fraction particles, we saw more of the measured particles in the smaller size fractions. On average, we measured more particle counts/cm^3 in the 0.3–0.49 and 0.50–0.99 fractions compared to the 1.0–2.49 fractions. This is consistent with what is known about the sizes of wood smoke particles, which are generally smaller than 1 μm, with a peak in the size distribution between 0.15 and

0.4 μm (Hays et al., 2002; Kleeman et al., 1999). The smaller size fractions measured within the homes also suggest they were generated from a combustion source, most likely the wood stove within the home or neighboring homes. In the context of our randomized trial, examining particle counts of various size fractions will allow us to evaluate which size fractions are influenced by the interventions, and, if health changes among participating children are dependent upon reductions in specific PM size fractions.

Indoor PM associated with biomass combustion could be attributed to a combination of indoor smoke escape from wood stove use (e.g., leaky seals from older model wood stoves and/or poor venting) and infiltration of PM from local ambient sources including smoke emissions from a given home's stove flue. We did not observe an association between the number of times a stove was opened during sampling events, an indicator of wood stove use, and average indoor concentrations. The lack of association between stove opening and indoor PM concentrations likely suggests that this measure does not adequately capture all possible wood stove generated contributors to $PM_{2.5}$ concentrations including escaped smoke due to improper venting.

Other studies have noted the importance of local ambient influences on indoor residential smoke exposures (Allen et al., 2004; Barn et al., 2008). We observed a strong association between open windows or external doors and higher indoor PM concentrations, and some evidence of higher F_{inf} with door/window opening. This could suggest an important influence from local ambient sources or, alternatively, that high indoor $PM_{2.5}$ concentrations associated with stove usage, for example, resulted in residents opening doors or windows. In rural settings with a high proportion of wood-heated homes, the ambient source is likely a combination of emissions from the same home and emissions from nearby wood-burning homes. Interestingly, based on infiltration efficiency estimation, 70% of indoor $PM_{2.5}$ was indoor-generated, indicating it is critically important that interventions aimed at reducing indoor $PM_{2.5}$ concentrations in these settings target the factors leading to smoke escape from wood stoves as well as outdoor sources.

The average infiltration efficiency of outdoor PM into the wood stove homes included in our study was relatively low at 0.27, an estimate similar to that observed in a study conducted during winter in a northern Canadian community (Barn et al., 2008), but lower than estimates observed in studies conducted in settings with milder winters (Allen et al., 2003; Hystad et al., 2009). Lower F_{inf} in colder temperatures has been observed in other studies (Allen et al., 2012), and we observed significantly lower F_{inf} in Butte, Montana, one of the coldest communities in our study. The relationship between temperature and F_{inf} may be explained by less frequent window opening during the winter. Air exchange rates decrease when windows are closed resulting in lower F_{inf} (Wallace et al., 2002). Somewhat surprisingly, residing in a home, versus a mobile home or apartment, and increased square footage were related to significantly higher F_{inf} values.

We observed that socioeconomic status defined by household income was the strongest predictor of nearly all measures of PM assessed in this study. This is of particular note from a public health standpoint as residents of lower income households also may be more susceptible to the health effects of indoor air pollution. Indeed, low-income households were the focus of a recent study estimating the number of Americans at risk of exposure to household air pollution generated from indoor stoves (Rogalsky et al., 2014). Although lower socioeconomic status has been linked to higher indoor PM exposures in developing country settings in which cookstove use is prevalent (Kulshreshtha et al., 2008; Zhou et al., 2011), this is the first study to note an inverse relationship between household income and biomass combustion derived PM exposures in relatively higher income homes using wood stoves as a primary heating source in the US. The reason for this association is not clear. It is possible that higher income homes are more likely to have properly installed and maintained wood stoves with higher combustion efficiencies. Income could also co-vary with other factors found to be inversely associated with lower indoor PM concentrations such as size of home (although inclusion of this factor in analyses attenuated the relationship between income and $PM_{2.5}$ only modestly). Several additional household characteristics and activities unrelated to home heating were linked to higher indoor PM concentrations and point to the importance of considering these contextual factors in rural residential settings. For example, the burning of incendiary devices such as candles was strongly associated with indoor exposures, particularly the smaller fraction particle counts.

4.2. Strengths and limitations

Our study benefited from repeated observations on a relatively large sample of homes located in diverse regions of the northwestern US and Fairbanks, Alaska with extensive information on potentially important predictors and covariates. However, several limitations deserve mention. First, biomass combustion likely was not the only source of PM in participating homes. Our findings suggest, however, that it is an important contributor. PM concentrations were higher when the participating child was in the home and lowest during the night, likely due to the wood stove being in use more frequently when residents occupy the home and are awake. Also, the methods for assessing indoor PM concentrations were not conducted using US EPA-certified methodologies although our group has demonstrated a strong correlation between $PM_{2.5}$ assessed by DustTraks and a Federal Equivalency Method sampler through a continued QA/QC program (McNamara et al., 2011). Information collected on potential predictors largely was self-reported; however, we expect that misclassification would have been nondifferential with respect to indoor air quality measures. Information was missing on a number of covariates of interest although restricting analyses to homes with complete information did not change overall findings, indicating that selection bias is not a major concern. Finally, we performed multiple statistical tests and, as a result, would expect to observe associations by chance alone.

4.3. Conclusions

In summary, study homes exhibited average indoor $PM_{2.5}$ concentrations exceeding WHO ambient air quality guidelines and approaching the US EPA 24-hour standard (NAAQS), which are based upon a wide range of PM-associated acute and chronic health effects. The lower concentrations of the smallest size fraction PNC associated with well-aged wood compared to newer wood indicate the potential benefits of behavioral- or education-based interventions on best-burn practices. Such approaches have been promoted recently by federal, state and local agencies (Nez Perce Tribe ERWM Air Quality, 2011b; Washington Department of Ecology, 2012; US EPA, 2011a), but the intervention strategies have not been formally tested. Our findings suggest that interventions targeting wood smoke reductions have the potential to improve both indoor air quality and health, particularly for children and other sensitive populations.

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Highlights

- Mean $PM_{2.5}$ levels in wood stove homes in the US exceed WHO air quality guidelines.
- Household income was the strongest predictor of nearly all measures of PM assessed.
- Interventions that reduce wood smoke may improve indoor air quality and health.

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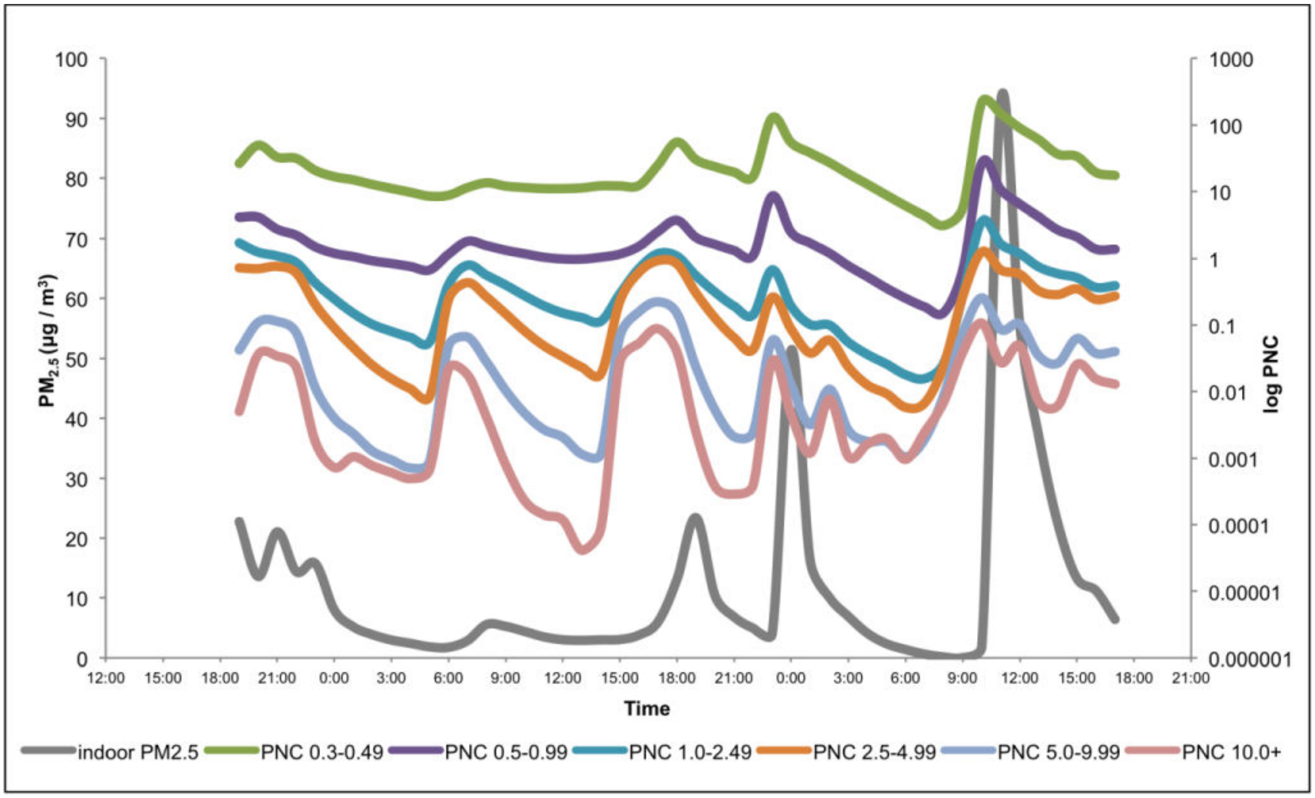

Figure 1.

PNCs, by size fraction, over a 48-hour sampling visit for a western Montana home during the winter of 2009–2010

Table 1

Selected pre-intervention characteristics of wood stove homes participating in ARTIS, by sampling visit (N = 96 homes)

	Visit 1 (N = 88)			Visit 2 (N = 84)		
	n[b]	n[a]	%[a]	n[b]	n[a]	%[a]
Demographic characteristics						
Community, pre-intervention winter years	88			84		
Hamilton, 2008–09		11	13		9	11
Missoula, 2009–10		20	23		21	25
Nez Perce, 2009–10		6	7		6	7
Butte, 2010–11		7	8		8	10
Fairbanks, 2010–11		8	9		8	10
western MT, 2011–12		36	41		32	38
Household income $50,000 or more	81	33	41	76	32	42
Caregiver's education college degree or more	79	34	43	74	34	46
Children in home, mean(sd)	82	2.5	1.3	77	2.5	1.3
Wood, wood stove and usage						
method of acquiring wood	79			79		
harvest		50	63		50	63
purchase		29	37		29	37
wood age	85			83		
< 1 year		31	36		27	33
1 year		28	33		27	33
2 years+		26	31		29	35
woodstove opened, mean(sd)	88	10.8	7.4	83	10.1	6.8
burn intensity	85			80		
none/light		20	24		22	28
average/heavy		65	76		58	72
Activities in or near the home						
use of other source of heating	88	53	60	83	50	60
burning (smoke, incense, candle, etc.)	88	29	33	83	24	29

	Visit 1 (N = 88)			Visit 2 (N = 84)		
		n[a]	%[a]		n[a]	%[a]
	n[b]			n[b]		
open door or window	88	29	33	83	32	39
Home characteristics						
house	87	61	70	83	61	73
square footage of home, mean(sd)	74	1932	856	70	1968	842
dog	87	68	78	83	65	78
cat	81	42	52	78	44	56
indoor temperature (° Celsius), mean (sd)	76	22.1	2.5	79	21.9	2.7
indoor humidity (%rh), mean (sd)	74	28.5	8.1	79	28.7	8.0
Meteorology						
temperature (° Celsius)	87	−3.6	9	81	−2.1	7.7
humidity (%rh)	87	73.2	12.1	81	74.9	11.8
precipitation (inches)	87	0.03	0.05	81	0.02	0.05
wind (miles per hour)	87	3.5	2.6	81	3.3	2.3
% of day spent in home by child, mean(sd)	78	64.8	16.4	76	66	16.0

Abbreviation: sd, standard deviation

[a] Numbers refer to the number and percentage of homes with a given characteristic except where otherwise specified.

[b] Number of homes with information on a specified characteristic for each visit.

Table 2

Spearman correlation coefficients describing the relationship between $PM_{2.5}$ mass and PNCs for the first pre-intervention sampling visit

		Particle number concentration (particles/cm^3)					
	indoor $PM_{2.5}$	**0.3–0.49**	**0.5–0.99**	**1.0–2.49**	**2.5–4.99**	**5.0–9.99**	**10.0+**
indoor $PM_{2.5}$	1.00						
PNC 0.3–0.49	0.94	1.00					
PNC 0.5–0.99	0.93	0.94	1.00				
PNC 1.0–2.49	0.67	0.56	0.67	1.00			
PNC 2.5–4.99	0.46	0.35	0.45	0.86	1.00		
PNC 5.0–9.99	0.35	0.26	0.35	0.67	0.84	1.00	
PNC 10.0+	0.34	0.23	0.31	0.59	0.76	0.89	1.00

Table 3

48-hour concentrations of $PM_{2.5}$ and particle counts of various size fractions, by sampling visit

	Visit 1		Visit 2	
	48 hour (n = 88)	**child in home (n = 78)**	**48 hour (n = 84)**	**child in home (n = 76)**
$PM_{2.5}$ mass (μg/m^3)				
48-hr mean	28.8 (28.5)	33.4 (37.4)	29.1 (30.1)	32.6 (37.3)
48-hr max	627.7 (1113.7)	454.7 (904.0)	821.0 (1683.3)	499.8 (1191.1)
> 25 μg/m^3, n (%)[a]	31 (35)	29 (37)	29 (35)	31 (41)
> 35 μg/m^3, n (%)[a]	25 (28)	25 (32)	21 (25)	23 (30)
PNC (particles/cm^3)				
0.3–0.49 μm				
48-hr mean	64.4 (57.6)	67.2 (59.5)	55.5 (52.2)	60.2 (56.4)
48-hr max	485.8 (326.0)	340.7 (300.5)	475.5 (323.6)	334.1 (272.6)
0.50–0.99 μm				
48-hr mean	8.8 (8.4)	9.7 (10.2)	7.6 (7.0)	8.5 (8.6)
48-hr max	135.5 (166.8)	100.3 (150.8)	148.0 (193.9)	84.3 (121.6)
1.0–2.49 μm				
48-hr mean	1.1 (1.3)	1.1 (1.5)	0.7 (0.6)	0.8 (0.8)
48-hr max	27.8 (60.9)	19.0 (43.3)	20.2 (26.9)	10.4 (15.6)
fine				
48-hr mean	74.2 (65.3)	78.1 (68.2)	63.8 (58.3)	69.6 (63.7)
48-hr max	609.6 (450.9)	439.3 (426.8)	615.7 (461.5)	418.5 (358.7)
coarse				
48-hr mean	0.6 (0.8)	0.6 (0.6)	0.4 (0.4)	0.4 (0.5)
48-hr max	11.4 (19.7)	7.4 (11.1)	6.7 (8.0)	3.6 (3.6)

Abbreviation: SD, standard deviation

[a]Indicates the number and percentage of ARTIS homes with 48-hr averages exceeding WHO guidelines or US EPA standards.

Table 4

Associations between characteristics of wood stove homes and % change in indoor $PM_{2.5}$ concentrations and PNCs

			$PM_{2.5}$		PNC 0.3–0.49		PNC 0.50–0.99		PNC 1.0–2.49		PNC fine		PNC coarse	
	N[a]	n[b]	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI
Demographic characteristics														
Household income $50,000 or more	88	157	0.49	0.36, 0.66	0.56	0.41, 0.76	0.52	0.38, 0.71	0.69	0.51, 0.93	0.55	0.41, 0.75	0.79	0.58, 1.08
Caregiver's education college degree or more	86	153	0.78	0.51, 1.01	0.75	0.54, 1.05	0.72	0.52, 1.01	0.72	0.53, 0.96	0.74	0.53, 1.03	0.65	0.48, 0.88
Children in home	89	159	1.06	0.95, 1.18	1.04	0.93, 1.16	1.05	0.94, 1.17	1.11	1.01, 1.23	1.04	0.93, 1.16	1.13	1.01, 1.26
Wood, wood stove and usage														
purchase vs. harvest	88	158	1.29	0.89, 1.87	1.08	0.75, 1.55	1.04	0.71, 1.52	1.08	0.76, 1.54	1.08	0.76, 1.54	1.09	0.76, 1.56
wood age	93	168												
< 1 year			ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
1 year			0.87	0.69, 1.10	0.89	0.69, 1.15	0.84	0.65, 1.08	0.72	0.55, 0.94	0.88	0.69, 1.13	0.75	0.57, 0.99
2 years +			0.88	0.67, 1.16	0.75	0.57, 0.99	0.84	0.62, 1.13	0.84	0.64, 1.11	0.77	0.59, 1.00	0.83	0.65, 1.06
number of times wood stove opened	96	171	1.01	0.99, 1.02	1.00	0.98, 1.02	1.00	0.98, 1.02	1.00	0.98, 1.01	1.00	0.98, 1.02	0.99	0.98, 1.01
burn intensity, average/heavy vs. none/light	95	165	1.13	0.87, 1.47	1.18	0.93, 1.50	1.10	0.88, 1.38	1.08	0.86, 1.35	1.18	0.94, 1.48	1.14	0.93, 1.39
Activities in or near the home														
use of other source of heating	96	171	0.92	0.74, 1.14	0.83	0.67, 1.02	0.76	0.61, 0.96	0.76	0.60, 0.96	0.82	0.66, 1.02	0.83	0.66, 1.04
burning (incense, candle, etc.)	96	171	1.27	0.99, 1.65	1.30	1.01, 1.66	1.25	0.97, 1.61	1.07	0.85, 1.35	1.29	1.01, 1.64	1.03	0.80, 1.34
open door or window	96	171	1.51	1.20, 1.90	1.46	1.16, 1.83	1.55	1.22, 1.96	1.39	1.16, 1.68	1.46	1.17, 1.83	1.38	1.13, 1.69
Home characteristics														
house vs. other	95	170	0.64	0.43, 0.95	0.60	0.42, 0.86	0.69	0.47, 1.01	1.05	0.76, 1.44	0.61	0.43, 0.87	1.06	0.78, 1.43
home square footage (100 unit increase)	81	144	0.97	0.95, 0.98	0.98	0.96, 1.00	0.97	0.95, 0.99	0.98	0.97, 1.00	0.98	0.96, 1.00	0.99	0.98, 1.01
dog	95	170	1.14	0.82, 1.58	1.13	0.80, 1.61	1.22	0.87, 1.71	1.26	0.93, 1.70	1.15	0.81, 1.62	1.25	0.89, 1.77
cat	89	159	1.12	0.83, 1.51	1.09	0.82, 1.44	1.14	0.85, 1.55	1.12	0.86, 1.48	1.10	0.83, 1.45	1.08	0.81, 1.43
indoor temperature (° Celsius)	92	155	1.01	0.96, 1.07	1.03	0.98, 1.09	1.04	0.99, 1.10	1.00	0.95, 1.06	1.03	0.98, 1.09	1.01	0.96, 1.07
indoor humidity (%rh)	92	153	1.02	1.00, 1.04	1.01	0.99, 1.03	1.01	0.99, 1.03	1.02	1.00, 1.04	1.01	0.99, 1.03	1.02	1.00, 1.04
Meteorology														
temperature (° Celsius)	95	168	1.01	0.99, 1.02	1.00	0.99, 1.02	1.00	0.98, 1.02	1.01	0.99, 1.02	1.00	0.99, 1.02	1.03	1.01, 1.04

	N[a]	n[b]	$PM_{2.5}$		PNC 0.3–0.49		PNC 0.50–0.99		PNC 1.0–2.49		PNC fine		PNC coarse	
			exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI	exp(β)[c]	95 % CI
humidity (%rh)	95	168	1.00	0.99, 1.02	1.01	1.00, 1.02	1.01	1.00, 1.02	1.00	0.99, 1.01	1.01	1.00, 1.02	0.99	0.98, 1.01
precipitation (inches)	95	168	1.46	0.18, 11.69	2.64	0.49, 14.13	2.41	0.42, 13.82	1.44	0.25, 8.18	2.56	0.50, 13.17	2.19	0.52, 9.14
wind (miles per hour)	95	168	1.01	0.95, 1.08	0.98	0.91, 1.06	1.00	0.93, 1.06	1.02	0.97, 1.07	0.99	0.92, 1.06	1.04	0.99, 1.09

Abbreviations: exp(β), exponentiated coefficient describing relationship between potential predictor and indoor air quality measure; CI, confidence interval; ref, reference category.

[a]Subjects.

[b]Observations.

[c]Exponentiated coefficients from repeated measures analyses represent the ratio of geometric mean PM2.5 or PNC associated with a specified change in the value of the predictor variable. For example, exp(β) = 0.46 indicates a 54% reduction in geometric mean $PM_{2.5}$ or PNC. Associations are reported as a one unit increase in continuous predictors except where otherwise specified.

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Table 5

The effect of time of day on indoor and outdoor $PM_{2.5}$ concentrations (N = 96)

Time of day	Median	Range	exp(β)[a]	95 % CI
10pm–2am				
indoor	14.9	3.0, 117.5	ref	ref
outdoor	23.0	2.0, 202.3	ref	ref
2am–6am				
indoor	8.4	1.2, 122.4	0.53	0.45, 0.61
outdoor	14.9	0.2, 193.1	0.60	0.52, 0.68
6am–10am				
indoor	15.4	1.3, 716.8	0.92	0.76, 1.12
outdoor	15.9	0.7, 167.1	0.72	0.64, 0.82
10am–2pm				
indoor	13.3	0.1, 201.6	0.85	0.68, 1.08
outdoor	11.1	0.1, 112.1	0.47	0.38, 0.58
2pm–6pm				
indoor	14.3	0.4, 457.0	1.09	0.90, 1.32
outdoor	12.6	0.2, 106.2	0.51	0.43, 0.62
6pm–10pm				
indoor	25.4	3.9, 374.5	2.01	1.73, 2.33
outdoor	21.2	1.7, 84.0	0.93	0.85, 1.02

Abbreviations: exp(β), exponentiated coefficient describing relationship between potential predictor and indoor air quality measure; CI, confidence interval; ref, reference category.

[a] Time of day was included in analyses as a 6-level categorical variable.

[b] Exponentiated coefficients from repeated measures analyses represent the ratio of geometric mean $PM_{2.5}$, natural log-transformed in analyses, associated with time of day. 10pm–2am was used as the reference category.

Table 6

Predictors of heating season F_{inf} in wood stove homes

	N	β[a]	95 % CI
Demographic characteristics			
Community, pre-intervention winter years	90		
Hamilton, 2008–09		0.04	−0.09, 0.17
Missoula, 2009–10		−0.02	−0.13, 0.08
Nez Perce, 2009–10		0.01	−0.16, 0.18
Butte, 2010–11		−0.19	−0.36, −0.02
Fairbanks, 2010–11		−0.09	−0.24, 0.06
western MT, 2011–12		ref	ref
Household income $50,000 or more	82	0.02	−0.07, 0.11
Caregiver’s education college degree or more	80	−0.01	−0.10, 0.08
Activities in or near the home			
use of other source of heating	90	−0.004	−0.09, 0.09
open door or window	90	0.07	−0.01, 0.15
Home characteristics			
house vs. other	89	0.11	0.03, 0.20
home square footage (1000 unit increase)	76	0.05	0.00, 0.11
indoor temperature (° Celsius)	87	−0.01	−0.02, 0.01
indoor humidity (%rh)	87	0.001	−0.004, 0.006
Meteorology			
temperature (° Celsius)	89	0.002	−0.003, 0.007
humidity (%rh)	89	0.002	−0.002, 0.006
precipitation (inches)	89	−0.52	−1.54, 0.51
wind (miles per hour)	89	−0.002	−0.021, 0.018

[a]Linear regression coefficient describing the change in F_{inf} associated with a one-unit increase in each potential predictor, except where otherwise specified.