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Residential indoor $PM_{2.5}$ in wood stove homes: follow-up of the Libby changeout program

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Abstract

In 2005 through 2008 a small rural mountain valley community engaged in a wood stove changeout program to address concerns of poor ambient air quality. During this program we assessed changes to indoor air quality before and after the introduction of a new, lower emission wood stove. We previously reported a greater than 70% reduction in indoor $PM_{2.5}$ concentrations in homes following the installation of a new EPA-certified stove within the home. We report here on follow-up of the experiences in these and other homes over three winters of sample collection. In 21 homes, we compared pre-changeout $PM_{2.5}$ concentrations (mean (sd) = 45.0 (33.0) $\mu g/m^3$) to multiple post-changeout measures of $PM_{2.5}$ concentrations using a DustTrak. The mean reduction (and 95% confidence interval) from pre-changeout to post-changeout was −18.5 $\mu g/m^3$ (−31.9, −5.2), adjusting for ambient $PM_{2.5}$, ambient temperature, and other factors. Findings across homes and across years were highly variable, and a subset of homes did not experience a reduction in $PM_{2.5}$ following changeout. Reductions were also observed for organic carbon, elemental carbon, and levoglucosan, but increases were observed for dehydroabietic acid and abietic acid. Despite overall improvements in indoor air quality, the varied response across homes may be due to factors other than the introduction of a new wood stove.

Keywords

Intervention; wood smoke; wood stove; biomass; particulate matter; Libby; Montana

INTRODUCTION

A limited number of epidemiological studies in communities with elevated levels of residential biomass smoke exposure have found morbidity and mortality impacts that are similar to those observed in communities with primarily industrial and mobile sources of PM (Fairley, 1999; Hales et al., 2000; Lipsett et al., 1997; McGowan et al., 2002; Sanhueza et al., 2009; Schwartz et al., 1993; Boman et al., 2003). Wood burning stoves can be

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significant sources of air pollution in cold-climate communities, emitting known toxic compounds including polyaromatic compounds, benzene, aldehydes, carbon monoxide, nitrogen oxides, and respirable PM (Naeher et al., 2007). The PM emitted from wood combustion are predominantly smaller than 1 μm, and have a peak mass size distribution ranging from 0.1 to 0.4 μm (Kleeman et al., 1999; Hays et al., 2002). This small size allows biomass PM to penetrate deep into the lung tissue, leading to adverse health outcomes such as airway inflammation or susceptibility to respiratory infection, and increased emergency department visits and hospitalizations (Naeher et al., 2007).

There are currently over 11 million homes in the United States that use wood as either a primary or secondary heating source (U.S. Department of Energy, 2009). Wood stoves are the most intensively used type of space heater with an average annual usage per heater of 2,100 hours, and more than 80% of existing wood stoves are old, inefficient models (Air Quality Management Work Group, 2005). Emission estimates vary greatly among stoves, but older models emit approximately 15 to 30 grams of fine particulate per hour (g/h) compared to 2 to 7 g/h for certified EPA-certified wood stoves. EPA-certified stoves comply with the 1988 standards of performance limits and often feature a catalytic element or other design features to create more complete combustion conditions (U.S. Environmental Protection Agency, 2010).

Community-wide wood stove use coupled with topographical and meteorological conditions that allow for sustained periods of stagnant air inversions can result in non-compliance with the Environmental Protection Agency's (EPA) National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$. One such community was Libby, Montana, which was designated non-attainment for $PM_{2.5}$ in 2004. The results of a Chemical Mass Balance (CMB) source apportionment model revealed that residential wood combustion was the single major source of $PM_{2.5}$ throughout the winter months in Libby, contributing an average of 82% of the measured $PM_{2.5}$ throughout the winter sampling program (Ward et al., 2006; Ward et al., 2010b). With support from local, state and federal agencies in addition to private interests the community initiated a large-scale wood stove changeout program to replace over 1,100 older model wood burning devices with new EPA-certified wood stoves (or similar heating appliances). A comprehensive registry program was also established to monitor long-term compliance.

The community-wide intervention resulted in a 27% reduction in winter ambient $PM_{2.5}$ concentrations (Ward et al., 2010b; Noonan et al., 2011) and a 64% reduction in the summed concentrations of selected polycyclic aromatic hydrocarbons (Ward et al., 2009). We have previously described reductions in reporting of childhood wheezing and respiratory infections with respect to these ambient changes (Noonan et al., 2012). Given that most people spend the majority of their time indoors (≈ 87% for all indoor environments and 69% for residential only) (Klepeis et al., 2001), we recognize the importance of evaluating the impact of this wood stove intervention program on indoor residential air quality. In this manuscript, we expand upon an earlier study conducted during the winter of 2006/2007 that measured $PM_{2.5}$ and other parameters within 16 Libby homes prior to and directly following the changeout of older stoves with new EPA-certified stoves (Ward et al., 2008). We present here the findings from a multi-winter study designed to evaluate the continued effectiveness of wood stove changeouts within homes over multiple winter seasons.

METHODS

Residential Indoor Air Sampling

Air sampling was conducted in a convenience sample of 26 homes prior to wood stove replacement, and at least one post-changeout sampling was conducted in 24 of these homes.

Selection was limited to those homes with a completed inspection and approval for changeout per the county's program guidelines. The presence of a non EPA-certified wood stove as the main heating source was the primary criterion for residential participation in the community changeout program. Among these participants we recruited homes with plans to replace their stove during the winter. This criterion enabled us to measure pre- and post-changeout indoor air during the same winter period. Only homes without resident tobacco smokers were eligible for selection.

In our original residential study we focused on 16 homes evaluated during the winter of 2006/2007. Initial 24-hour post-changeout sampling was conducted during the same winter as the 24-hour pre-changeout sampling (Ward et al., 2008). At the community level, approximately 58% of the stoves had been changed out prior to this winter, but this remained a highly active period for the overall wood stove changeout program. For more than half of the homes sampled during winter 2006/2007, the difference in ambient temperature between the pre-changeout measure and the post-changeout measures was greater than 12.2 °C. There was concern that ambient temperature discrepancies on sample days would impact burning behavior in wood stove homes, thereby obscuring the impact of new wood stoves on indoor air quality.

As presented in this study, additional 24-hour post-changeout sampling during the subsequent two winter periods (winters 2007/2008 and 2008/2009) was conducted in an attempt to match the sampling day as closely as possible to ambient temperature of both the pre-changeout and the initial post-changeout sample days for the corresponding homes. Altogether the residential sampling program included five phases: phase 1 = pre stove change (winter 2006/2007); phase 2 = post change (winter 2006/2007); phase 3 = post change (2^{nd} winter, 2007/2008) matched on phase 1 ambient temperature; phase 4 = post change (2^{nd} winter, 2007/2008) matched on phase 2 ambient temperature; and phase 5 = post change (3^{rd} winter, 2008/2009), no temperature match.

During each 24-hour residential sampling event, there were two sampling instruments operating within the same room as the wood stove. The instruments were always set up within 20 feet of the woodstove. Field sampling personnel were always instructed to place the air samplers in the common area of the house as far away from stove as possible yet still in the same room. To eliminate any sampling variability or bias due to sampling location within each home, the air samplers were always placed in the same locations. A DustTrak (Model 8520, TSI, Inc., Shoreview, MN, USA) was used to continuously measure $PM_{2.5}$ at 60-second intervals, while a Leland legacy pump/personal environmental monitor (PEM) sampler (SKC, Inc., Eighty Four, PA, USA) collected $PM_{2.5}$ on a prefired 37-mm quartz filter. This filter was then analyzed for Organic Carbon, Elemental Carbon (OC/EC), and organic markers of wood smoke (vanillin, acetovanillone, guaiacol, 4-ethylguaiacol, levoglucosan, abietic acid, and dehydroabietic acid). The analytical procedures, including Quality Assurance/Quality Control (QA/QC) methodologies, have been described previously (Ward et al., 2008).

During sampling residents were not instructed to alter their indoor behaviors, but we asked them to monitor and record activities that may affect indoor air quality. For each residential indoor air sampling event, residents recorded information on wood usage and the frequency of wood stove loading (wood burning records). Residents also recorded information on home characteristics or activities that would impact indoor air quality (activity records). Variables that were recorded during each sampling event included: cooking modes, usage of secondary heating sources or indoor fans, any burning of candles, incense or oil lamps, occurrence of various cleaning activities, outdoor or indoor construction, open windows or doors, and presence of household pets. These factors were evaluated as categorical variables

in the analysis. For activities associated with specific times recorded by the resident (i.e., loading of wood stove, burning of candles or incense, and cleaning or cooking activities) the corresponding $PM_{2.5}$ peak was captured from the air sampling trace.

Meteorological and ambient $PM_{2.5}$ data

Daily temperature, wind speed, relative humidity, and precipitation data were obtained from the Western Regional Climate Center, a division of the National Oceanic and Atmospheric Administration (Western Regional Climate Center, 2010). The measurement station was located in Libby, at latitude 48° 23′ 00″ and longitude 115° 34′ 00″. Hourly ambient $PM_{2.5}$ concentrations (as measured by a Met One BAM, Grants Pass, OR, USA) on the days of indoor sampling were measured at the Montana Department of Environmental Quality's $PM_{2.5}$ compliance monitoring site for the town of Libby.

Data Analysis

For comparing indoor $PM_{2.5}$ concentrations and other variables across the multiple home sampling visits, we fit a generalized estimating equation using the identity link and exchangeable covariance matrix. The dependent variable was indoor 24-hour average $PM_{2.5}$ concentration. The primary independent variable was an indicator of changeout, indicating either a pre-changeout sampling or a post-changeout sampling. Other explanatory variables included in the model were ambient $PM_{2.5}$ concentration corresponding to the same 24-hour indoor sampling period and ambient temperature. Various activities were recorded by the resident during the sampling period through the use of wood burning and activity records, and included in the model: cleaning (i.e., vacuuming, sweeping or dusting); cooking (i.e., frying, fat frying, in-home grilling or baking); and burning of candles or incense. The presence of dogs or cats in the home was also included in the model. Type of residence (i.e., trailer versus single family dwelling) and other home characteristics (i.e., secondary types of heating, open windows or doors and construction) were not found to be associated with indoor $PM_{2.5}$ and were not included in the final model.

To evaluate the impact of the changeout within homes over multiple winters we compared post-changeout indoor $PM_{2.5}$ (as well as speciated carbon components) during follow-up winters (phases 3 and 4, 2007/2008 and phase 5, 2008/2009) to post-changeout indoor $PM_{2.5}$ during the initial winter (phase 2, 2006/2007). We fit a generalized estimating equation, adjusting for the same variables described above.

RESULTS

Home Characteristics

Post-changeout sampling was completed from one to four times in 24 of the 26 homes for which we had pre-changeout sampling. One of the homes was abandoned and could no longer be accessed after the wood stove changeout, while a second home switched to a pellet stove rather than a wood stove and was excluded from subsequent sampling. Of those 24 residences with both pre- and post-changeout sampling, there was a fairly wide spatial distribution throughout the Libby valley, with residents located from 0.8 to 13.7 kilometers from the central ambient air monitoring site. All but one of the homes was owner occupied, and most of the homes (19/24) were single family fixed residences with the remainder being trailers. Estimated winter period wood use by residents averaged 5.8 cords, ranging from 1.5 to 10 cords. Resident-reported size of homes was almost 138.5 square meters on average (55.7 to 278.7 m^2). Despite efforts to exclude homes with residents who smoked tobacco, smoking was reported during one or more of the sampling events for three of the 24 homes. Homes with reported tobacco smoking during any of the sampling events were excluded from the final data analyses. The 21 homes used in the final analysis are presented in Table

1 according to sampling period (phase), average indoor and ambient $PM_{2.5}$, and ambient temperature.

Temperature Matching

Attempts to match sampling on temperature were reasonably successful, but this strategy was imperfect (**see** Table 1). When matching post-changeout sample days (phase 3) to ambient temperature of the prior winter's pre-changeout sample day (phase 1), the absolute temperature difference ranged from 0.2°C to 6.3°C. When matching post-changeout sample days (phase 4) to ambient temperature of the prior winter's post-changeout sample day (phase 2), the absolute temperature difference ranged from 0.2°C to 10.9°C (and 95% CI) was 1.33°C (−2.40, 5.06). When including the final winter of sampling (phases 2 through 5), the mean ambient temperature on all post-changeout sample days was slightly lower than the ambient temperature on the pre-changeout sample days (−2.7°C versus 0.48°C, respectively).

Indoor $PM_{2.5}$ Concentrations

Pre-changeout indoor concentrations and the combined average of all post-changeout concentrations for 21 homes are presented in Table 2. The average (sd) indoor $PM_{2.5}$ for the pre-change sampling was 45.0 $\mu g/m^3$ (33.0). The average (sd) indoor post-changeout $PM_{2.5}$ (one to four sampling events per home) was 21.0 $\mu g/m^3$ (19.2), resulting in a crude overall $PM_{2.5}$ reduction of 53%. The modeled mean reduction (and 95% CI) from pre-changeout to post-changeout was −18.5 $\mu g/m^3$ (−31.9, −5.2), adjusting for ambient $PM_{2.5}$, ambient temperature, presence of indoor pets, and reported cooking, cleaning or lighting of candles or incense during the sampling period. Average reductions following wood stove changeout were observed in 16 of 21 homes.

High variability was observed for post-changeout sampling within some homes, but 14 of the 21 homes still had lower $PM_{2.5}$ concentrations for all post-changeout sampling compared to pre-changeout $PM_{2.5}$ concentrations (**see** Figure). Several activities reported by the resident and corresponding peak $PM_{2.5}$ measures are reported in Table 3. The number of stove loadings before and after wood stove changeout were similar. The peak $PM_{2.5}$ concentrations associated with stove loadings were generally high. Surprisingly, the median peak $PM_{2.5}$ during this activity was higher among post-changeout stoves compared to pre-changeout stoves. The maximum observed value during this activity (2,333 $\mu g/m^3$) was observed within a home that still demonstrated an average $PM_{2.5}$ reduction following changeout. Among the homes with no average $PM_{2.5}$ reduction the peak concentrations associated with stove loadings were similar for pre- and post-changeout sample periods, median (range) = 45 $\mu g/m^3$ (29–98) and 42 $\mu g/m^3$ (10–133), respectively.

Other recorded activities not directly related to wood stove usage were also found to contribute to indoor $PM_{2.5}$ concentrations. Among these recorded activities the times corresponding to cooking yielded high $PM_{2.5}$ peaks (Table 3). Cooking peaks were higher in pre- compared to post-changeout sampling periods. However, the highest cooking-related pre-changeout peaks (median (range) = 510 $\mu g/m^3$ (43 – 1,230)) were observed among homes that still showed an average reduction in $PM_{2.5}$. Cleaning activities and burning of candles or incense were not commonly reported, nor do these activities appear to explain the why some homes demonstrated average reductions in $PM_{2.5}$ following stove changeout and some did not. For example, during post-changeout sampling periods $PM_{2.5}$ peaks associated with reported cleaning activities were 10, 108 and 114 $\mu g/m^3$ among homes that showed average $PM_{2.5}$ reductions following changeout and 9 and 112 $\mu g/m^3$ among homes that did not show average $PM_{2.5}$ reductions following changeout.

To determine if the impact of newly introduced wood stoves on reducing indoor $PM_{2.5}$ was attenuated over multiple years of use we evaluated the post-changeout measures across three winter seasons. During the initial winter the post-changeout average (sd) indoor $PM_{2.5}$ concentration in 18 homes was 12.8 $\mu g/m^3$ (14.8). The average (sd) indoor $PM_{2.5}$ during the second winter increased to 27.4 $\mu g/m^3$ (22.0), an increase (and 95% CI) of 17.2 $\mu g/m^3$ (8.9, 25.5), adjusting for ambient $PM_{2.5}$, ambient temperature, baseline wood number of cords burned in a winter, presence of indoor pets, and various reported activities during the sampling event. In the final winter, however, the post-changeout measures were similar to the initial post-changeout sampling, 18.0 $\mu g/m^3$ (14.5) or an adjusted increase (and 95% CI) of only 4.34 $\mu g/m^3$ (−6.31, 15.0).

OC/EC and organic markers of wood smoke

Table 2 presents pre- versus post-changeout comparisons for OC/EC and polar organics. Consistent with the findings for $PM_{2.5}$, significant reductions were observed for indoor OC (−39%) and EC (−41%). Among the chemical markers often used for wood smoke, a crude reduction of 44% was observed for levoglucosan. However, the resin acids actually showed increases following wood stove changeouts (+81% for dehydroabietic acid and +219% for abietic acid). The observed reductions for OC, EC, and levoglucosan, as well as the observed increases for the resin acids remained robust after adjusting for ambient $PM_{2.5}$, ambient temperature and other factors. We did not observe any meaningful changes in the methoxyphenol markers for wood smoke throughout the program. This may have resulted from the fact that we were only able to measure particulate-bound concentrations of these semi-volatile compounds.

DISCUSSION

As noted earlier, the results presented here are a continuation of a program that was initially conducted during the winter of 2006/2007 (noted as phases 1 and 2 in this manuscript) in which the indoor air of 16 homes were evaluated when old stoves were replaced with EPA-certified woodstoves. $PM_{2.5}$ and other variables were measured prior to and directly following the changeout within the homes. Results showed that average $PM_{2.5}$ concentrations and maximum $PM_{2.5}$ concentrations were reduced by 71% and 76%, respectively (Ward et al., 2008).

One of the shortcomings of this original study was that only one 24-hour measurement was conducted within the home following the changeout, with this post-measurement occurring during the same winter as the changeout (usually 2-3 weeks following installation of the new EPA-certified stove). The original findings demonstrated that the changeout provided significant and immediate improvements to the indoor air, but did not provide any information on the sustainability of these effects over time. Our findings with repeated post-changeout measures suggest that average reductions in indoor $PM_{2.5}$ remained evident, but were slightly attenuated (53% reduction compared to the original 71% reduction). Conducting multiple post-changeout sampling events also revealed substantial variability. Five of the 21 homes demonstrated no average reduction in indoor $PM_{2.5}$, and 7 homes had at least one post-changeout sampling with higher indoor $PM_{2.5}$ than the concentrations observed during pre-changeout sampling.

The reasons for this lack of consistent reduction in indoor $PM_{2.5}$ across all homes are difficult to discern with the available data. To further understand some of the resident behaviors that may have contributed to indoor air quality we asked residents to record specific activities. Activities specifically related to wood stove use (i.e., loading of stoves) did not appear to determine whether homes demonstrated average reductions in $PM_{2.5}$ following stove changeout or failed to do so. Indeed, the highest peaks associated with stove

loading were observed post-changeout among homes that showed an average reduction in $PM_{2.5}$. This was a surprising finding as newer technology stoves should have better combustion efficiencies and draft than older stoves. The cases of higher $PM_{2.5}$ values associated with post-changeout stove loadings may indicate improper burning technique among residents.

Several other indoor activities not associated with wood stove use could also impact indoor air quality. Residents recorded some of these activities, including cooking, cleaning and burning of candles or incense. An attenuation of effect following wood stove changeout may be expected if, by chance, such non-stove related activities and the corresponding $PM_{2.5}$ peaks were more common during post-changeout sampling periods. Our data offer little evidence to support this with some of the highest $PM_{2.5}$ peaks observed during pre-changeout sampling among homes that nevertheless demonstrated an average $PM_{2.5}$ reduction following stove changeout. It should be noted that these activities were reported during only a limited number of sampling episodes. We are uncertain whether this indicates that these few non-wood stove activities identified a priori had limited effect on indoor air quality changes attributed to wood stove changeout or if this is reflective of under-reporting for these activities.

Chemical markers of wood smoke

In the original 2006/2007 Libby residential study (Ward et al., 2008), OC and levoglucosan were reduced by 26% and 45%, respectively, following the introduction of the new woodstove within the home. However, the concentrations of resin acids, natural chemicals found in the bark of resinous soft woods, were increased following the introduction of the new woodstove. The predominant wood species harvested in the study area are resinous soft woods: Douglas fir, ponderosa pine, and larch. There is no reason to expect any significant change in the type of wood harvested or burned during the course of our study, nor any reason to expect the sort of increase in the use of resinous wood needed to result in such substantial increases in resin acids in the PM. Specifically, abietic acid increased by 292%, while dehydroabietic acid increased by 133%. When evaluating additional winter seasons as part of this study, these same trends were found to continue throughout the three winter seasons of sampling. Multi-winter OC and levoglucosan were still found to be reduced compared to the pre-changeout measurements (OC, −39%; levoglucosan, −44%), and the resin acids were still elevated (abietic acid, +219%, dehydroabietic acid +81%). Similar findings were observed in the ambient air in this community. Following the changeout program, ambient levels of OC and levoglucosan decreased by ~25%, while abietic and dehydroabietic acid increased by 291% and 562% respectively when comparing baseline winter 2003/2004 and post-changeout winter 2008/2009 (Ward et al., 2011). The increased levels of resin acids post-changeout indicated that these chemically stable compounds may continue to survive the combustion conditions in the modern stoves, and may actually be released at higher levels due to increased combustion temperatures. Unlike other pyrolysis products, resin acids are reported to be released with the same or very similar structure as that which they appear in the wood, and are likely released through volatilization with steam (Corin et al., 2000; Rogge et al., 1998). This distinction in the process of release vs. formation during combustion may explain the observed differences in behavior. This suggests that even though on average there were observable reductions in indoor $PM_{2.5}$ mass following the replacement of an old stove with an EPA-certified stove, there potentially could be an increase in some volatile and semi-volatile compounds due to the difference in burning conditions or some other factors (Jordan and Seen, 2005; Purvis et al., 2000). These findings also suggest that the chemistry of the emissions have changed as a result of the wood stove changeout-both in the indoor and ambient environments.

Comparison with other studies

In the study presented here, reductions following wood stove changeout were observed in 16 of 21 homes. The observed variable impact on indoor $PM_{2.5}$ following wood stove replacement was consistent with previous work in other wood smoke impacted communities. A similar in-home study conducted on the Nez Perce Reservation (Ward et al., 2010a) found improved indoor air quality in 10 of the 16 homes following a wood stove replacement. Despite an overall mean 36% reduction of indoor $PM_{2.5}$, five of the homes had increased indoor $PM_{2.5}$ concentrations following the changeout (one home did not have final $PM_{2.5}$ results for comparison). A similar study in northern British Columbia did not find a consistent relationship between stove technology upgrades and indoor air quality improvements (Allen et al., 2009). With one pre-changeout and one post-changeout comparison only 9 of 15 homes experienced reduced indoor $PM_{2.5}$.

Limitations

In this study we were only able to capture one pre-changeout sample per home, so we were unable to estimate the variability in pre-changeout concentrations of indoor $PM_{2.5}$. Ideally, we would have collected additional samples within each home over longer periods of time (for both pre- and post-changeout winters), thereby capturing some of the temporal variability in the $PM_{2.5}$ concentrations. Under EPA guidelines ambient air monitoring programs include 24-hour measures repeated every three days for the duration of the sampling program. We did not have adequate resources to conduct indoor air sampling at this frequency. Nevertheless, additional samples within each home over longer periods of time (for both pre- and post-changeout winters) would have enabled us to more accurately estimate the temporal variability in the indoor $PM_{2.5}$ concentrations.

The generalizability of our findings is limited as the sampled homes were not randomly selected from among the residences in the study area that participated in the wood stove changeout program. The observations in this study were based on a convenience sample of homes that met minimal eligibility criteria. To the degree possible we captured information regarding home characteristics and resident behaviors, but it is possible that these homes were not representative of the housing stock in the community or in other similar communities.

When considering the results from this study, it is also not clear how ambient $PM_{2.5}$ and residential air infiltration may have influenced our indoor measurements. Air infiltration can impact indoor environments either locally due to re-entry of emitted $PM_{2.5}$ from the home, or from other ambient sources of $PM_{2.5}$ (Allen et al., 2003; Barn et al., 2008). In previous analyses comparing indoor changes in $PM_{2.5}$ stratified on whether homes experienced increases or decreases in ambient $PM_{2.5}$ on pre- versus post-changeout sampling days, results did not suggest a strong influence from ambient PM concentrations (Ward et al., 2008). In addition, our present study adjusted indoor $PM_{2.5}$ reduction estimates for central site ambient $PM_{2.5}$ levels. Thus, the large decreases in indoor $PM_{2.5}$ following stove changeout are likely the result of lower indoor escape of wood smoke (during loading/stoking activities or vent/flue leakage) or lower levels of local PM re-entry due to greater burn efficiencies and the associated lower chimney emissions.

As noted in our original study (Ward et al., 2008), it is important to note that the DustTrak utilized for $PM_{2.5}$ mass measurements in this study is not a Federal Reference Method (FRM) sampler, and any comparisons with the National Ambient Air Quality Standards for $PM_{2.5}$ should be viewed with caution. To address the accuracy of the DustTraks utilized in wood smoke settings, we have carried out multiple studies (both field and laboratory) comparing the DustTrak results to results from FRMs while sampling in wood smoke

impacted environments (McNamara et al., 2011). These studies determined that the DustTrak over-reports $PM_{2.5}$ mass measurements by a factor of ~1.65. In an effort to be consistent with our previous Libby study, we did not correct the DustTrak $PM_{2.5}$ data reported in this manuscript. Although the DustTrak $PM_{2.5}$ data may overestimate indoor concentrations, the overall findings reported in this manuscript regarding relative differences before and after changeout are not affected.

CONCLUSIONS

From a regulatory point of view, the Libby wood stove changeout community-wide intervention was shown to be an effective tool in lowering ambient $PM_{2.5}$ throughout the winter months. When comparing post-changeout ambient winter $PM_{2.5}$ levels to pre-changeout measurements, ambient concentrations were 30% lower in the final winter following the changeout program, compared with the baseline pre-changeout years (Noonan et al., 2012). After replacing ~95% of the older, high-polluting wood stoves with more efficient certified wood stoves or similar non-wood burning devices, the community was in attainment for the ambient $PM_{2.5}$ standard.

This study suggests the impact of the wood stove changeout on indoor air quality is potentially larger but more variable than its impact on ambient $PM_{2.5}$ concentration. We observed a 53% reduction when comparing pre- and post-changeout $PM_{2.5}$ concentrations, with decreased indoor $PM_{2.5}$ concentrations observed in 16 of the 21 homes of nonsmoking residents. There was substantial variability in the measurements within and between homes. In addition, the average concentrations across homes varied over subsequent winters, and several homes actually showed increased concentrations in some subsequent winters. This variability could be due to incorrect stove operation (e.g., non-optimal burn temperatures), improper fuel source (e.g., wet wood), other indoor sources of pollution (e.g., cooking/cleaning events), or as yet unidentified factors. Considering these findings in a more global context, there is currently a large and important public health movement in many developing countries to introduce improved technology cookstoves (The World Bank, 2011). The settings and interventions in these developing countries are quite distinct from the community and biomass smoke burning devices investigated for this study. Nevertheless, further understanding the sources of variability, behavioral and otherwise, and the efficacy of biomass burning interventions may be translatable to other settings.

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Practical Implications

Biomass combustion is a common source of ambient $PM_{2.5}$ in many cold-climate communities. The replacement of older model wood stoves with newer technology wood stoves is a potential intervention strategy to improve air quality in these communities. In addition to ambient air, wood stove changeouts should improve residential indoor air quality. We present results from a multi-winter study to evaluate the efficacy of wood stove changeouts on improving indoor air quality. Reductions in indoor $PM_{2.5}$ were evident, but this observation was not consistent across all homes. These findings suggest that other factors beyond the introduction of an improved wood burning device are relevant to improving indoor air quality in wood burning homes.

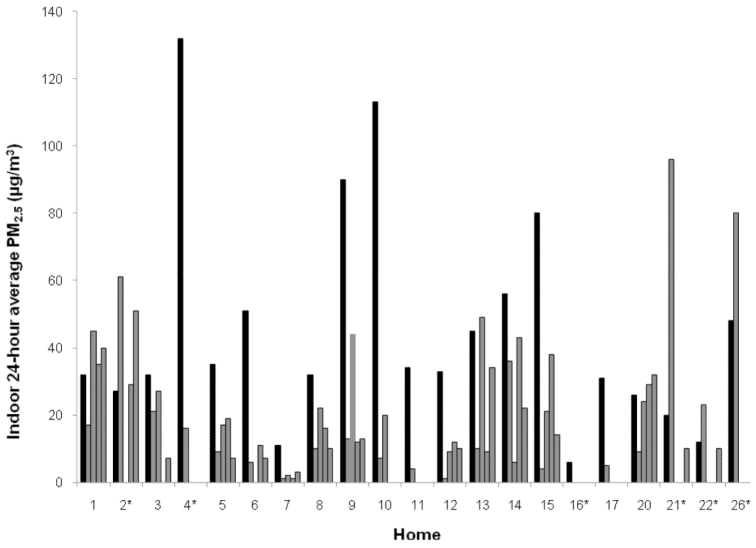

Figure.

Indoor $PM_{2.5}$ concentrations pre- (black bars) and post- (grey bars) wood stove changeout for non-smoking homes. *Homes that were not included in the previous analysis (Ward et al., 2008).

Table 1

Indoor residential $PM_{2.5}$ sampling[a] and corresponding ambient $PM_{2.5}$ and temperature on sample days.

Wood stove status (Phase)	Winter sampled relative to pre-change sample	Number of homes	Average indoor $PM_{2.5}$	Average ambient $PM_{2.5}$	Average ambient temperature, °C
Pre-change (1)	--	21	45.0 (33.0)	25.3 (12.4)	0.48 (5.62)
Post-change (2)	Same winter	21	20.4 (26.5)	18.3 (8.12)	−3.74 (4.23)
Post-change[b] (3)	2nd winter	12	23.8 (15.3)	18.5 (6.76)	−0.22 (6.36)
Post-change[c] (4)	2nd winter	12	21.2 (13.3)	19.5 (3.53)	−2.13 (5.29)
Post-change (5)	3rd winter	15	18.0 (14.5)	17.7 (6.85)	−2.55 (2.71)

[a]For non-smoking homes with at least one post-changeout sample.

[b]Post-change sample day chosen to match closely to ambient temperature of pre-change sample day.

[c]Post-change sample day chosen to match closely to ambient temperature of 1st winter post-change sample day.

Table 2

Comparison of indoor PM2.5, OC/EC, and polar organics during single pre- and post- changeout sampling.

	Pre		Post		Change	
	Homes sampled	**Mean (sd)**	**Homes sampled**[1]	**Mean (sd)**	**Adjusted difference**[2] **(95% CI)**	**p-value**
PM2.5 (μg/m^3)	21	45.0 (33.0)	59	21.0 (19.2)	−18.5 (−31.9, −5.2)	0.007
Organic Carbon (μg/m^3)	21	17.0 (9.5)	60	10.3 (5.4)	−6.3 (−10.0, −2.5)	0.001
Elemental Carbon (μg/m^3)	21	0.87 (0.83)	60	0.51 (0.53)	−0.26 (−0.51, −0.20)	0.048
Levoglucosan (ng/m^3)	21	957 (804)	60	539 (489)	−303 (−579, −27)	0.032
Dehydroabietic acid (ng/m^3)	21	102 (73.2)	61	185 (119)	+80.0 (+35.8, +123.9)	<0.001
Abietic acid (ng/m^3)	21	8.83 (20.2)	61	28.2 (23.1)	+17.7 (+6.8, +123.9)	0.002
Vanillin (ng/m^3)	21	2.63 (6.79)	56	2.74 (7.74)	−1.43 (−5.07, +2.21)	0.441
Acetovanillin (ng/m^3)	21	1.78 (5.27)	56	0.33 (0.79)	−1.73 (−4.21, +0.75)	0.172
Guaiacol (ng/m^3)	21	0.39 (0.47)	50	0.58 (0.75)	+0.04 (−0.33, +0.41)	0.842
4-ethyl guaiacol (ng/m^3)	21	1.05 (1.09)	50	0.69 (1.25)	−0.52 (−1.17, +0.13)	0.115

[1] Homes sampled one to four times post-changeout.

[2] Adjusted for ambient $PM_{2.5}$, ambient temperature, presence of pets in the home, and burning of candles or incense, cleaning and cooking activities during sampling.

Table 3

Reported activities and corresponding $PM_{2.5}$ peak measures.

	Pre		Post	
	Reported activity	**Median $PM_{2.5}$ (range)**	**Reported activity (No. of Homes)[1]**	**Median $PM_{2.5}$ (range)**
Number of stove loadings during sampling period	19	5 (1 – 10)	54 (21)	5 (2 – 12)
$PM_{2.5}$ peaks during stove loadings ($\mu g/m^3$)	19	111 (12 – 472)	54 (21)	386 (3 – 2,333)
$PM_{2.5}$ peaks during cleaning activities ($\mu g/m^3$)	1	28 (28 – 28)	5 (4)	108 (9 – 114)
$PM_{2.5}$ peaks during burning of candles or incense ($\mu g/m^3$)	1	70 (70 – 70)	9 (5)	62 (4 – 522)
$PM_{2.5}$ peaks during cooking activities ($\mu g/m^3$)	4	305 (43 – 1,230)	15 (10)	135 (6 – 301)

[1] Total across all sampling events (homes sampled one to four times post-changeout) followed by number of homes reporting any activity.