Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://oeh.informaworld.com/soeh/title~content=t713657996

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First published on: 15 July 2011

To cite this Article Adetona, Olorunfemi , Dunn, Kevin , Hall, Daniel B. , Achtemeier, Gary , Stock, Allison and Naeher, Luke P.(2011) 'Personal $PM_{2.5}$ Exposure Among Wildland Firefighters Working at Prescribed Forest Burns in Southeastern United States', Journal of Occupational and Environmental Hygiene, 8: 8, 503 — 511, First published on: 15 July 2011 (iFirst)

To link to this Article: DOI: 10.1080/15459624.2011.595257

URL: http://dx.doi.org/10.1080/15459624.2011.595257

Journal of Occupational and Environmental Hygiene, 8: 503–511
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459624.2011.595257

Personal $PM_{2.5}$ Exposure Among Wildland Firefighters Working at Prescribed Forest Burns in Southeastern United States

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This study investigated occupational exposure to wood and vegetative smoke in a group of 28 forest firefighters at prescribed forest burns in a southeastern U.S. forest during the winters of 2003–2005. During burn activities, 203 individual person-day $PM_{2.5}$ and 149 individual person-day CO samples were collected; during non-burn activities, 37 person-day $PM_{2.5}$ samples were collected as controls. Time-activity diaries and post-work shift questionnaires were administered to identify factors influencing smoke exposure and to determine how accurately the firefighters' qualitative assessment estimated their personal level of smoke exposure with discrete responses: "none" or "very little," "low," "moderate," "high," and "very high." An average of 6.7 firefighters were monitored per burn, with samples collected on 30 burn days and 7 non-burn days. Size of burn plots ranged from 1–2745 acres (avg = 687.8). Duration of work shift ranged from 6.8–19.4 hr (avg = 10.3 hr) on burn days. Concentration of $PM_{2.5}$ ranged from 5.9–2673 $\mu g/m^3$ on burn days. Geometric mean $PM_{2.5}$ exposure was 280 $\mu g/m^3$ (95% CL = 140, 557 $\mu g/m^3$, n = 177) for burn day samples, and 16 $\mu g/m^3$ (95% CL = 10, 26 $\mu g/m^3$, n = 35) on non-burn days. Average measured $PM_{2.5}$ differed across levels of the firefighters' categorical self-assessments of exposure ($p < 0.0001$): none to very little = 120 $\mu g/m^3$ (95% CL = 71, 203 $\mu g/m^3$) and high to very high = 664 $\mu g/m^3$ (95% CL = 373, 1185 $\mu g/m^3$); $p < 0.0001$ on burn days). Time-weighted average $PM_{2.5}$ and personal CO averaged over the run times of $PM_{2.5}$ pumps were correlated (correlation coefficient estimate, r = 0.79; CLs: 0.72, 0.85). Overall occupational exposures to particulate matter were low, but results indicate that exposure could exceed the ACGIH®-recommended threshold limit value of 3 mg/m³ for respirable particulate matter in a few extreme situations. Self-assessed exposure levels agreed with measured concentrations of $PM_{2.5}$. Correlation analysis shows that either $PM_{2.5}$ or CO could be used as a surrogate measure of exposure to woodsmoke at prescribed burns.

Keywords exposure, firefighters, particulate matter, prescribed burn, wildland, woodsmoke

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The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the Centers for Disease Control and Prevention (CDC). Mention of company names or products does not constitute endorsement by the CDC.

INTRODUCTION

Wildland firefighters are primarily responsible for wildfire suppression in wildlands, including forests, grasslands, and brush, but also engage in prescribed burning. Prescribed burns, as opposed to wildfires, are intentionally set by firefighters and are used as a land management tool for improving forage value of the forests, and reducing wildfire hazard and competing vegetation.(1) They have become such a mandatory land management practice that as much as 6 to 8 million acres of land are treated with prescribed burns by land managers each year in the southern United States alone,(2) and it is estimated that tens of thousands of firefighters across the country work at these burns annually.(3)

Although very careful planning always precedes prescribed burns, wildland firefighters can be exposed to high levels of contaminants in woodsmoke. These include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides, respirable particulate matter (RPM), total suspended particulates (TSP), polycyclic aromatic hydrocarbons (PAH), benzene, aldehydes, and others.[4,5] Carbon monoxide, RPM, TSP, and aldehydes have been identified as the chief woodsmoke exposure hazards among firefighters.[4] Firefighters working at prescribed burns often work extended shifts (up to 18 hr) while engaged in hard physical labor[4] and wearing no respiratory protection. Physical labor increases minute ventilation and total exposure of the respiratory tract to particles, gases, and vapors. Therefore, firefighters are potentially at risk of serious acute and chronic health effects. Health effects that have been associated with occupational exposure to woodsmoke among wildland firefighters include reduced lung function and pulmonary and systemic inflammation.[6,7]

Studies of exposures among wildland firefighters have been conducted mainly in the western United States, which has different vegetation and weather characteristics compared with other parts of the country. These studies show exposure to particulate matter and CO could exceed occupational health standards, and that exposures were higher among firefighters working at prescribed burns compared with those working at wildfires.[4,8,9] Although conducted in a completely different environment, a study of exposure to vegetative smoke from bushfire at prescribed burns in Australia also points to the possibility of elevated exposure to RPM among wildland firefighters.[10] We assessed occupational woodsmoke exposure in wildland firefighters working at prescribed burns in a southeastern U.S. forest during the dormant (winter) burn seasons of 2003–2005. The objective of this study was to examine the association between particulate matter with median aerodynamic diameter of 2.5 μm ($PM_{2.5}$) and duration and sizes of burns, job tasks, and weather variables to identify the factors that influence exposure. We also assessed whether the firefighters could qualitatively estimate their level of exposure.

METHODS

Study Location and Population

This study was conducted at the Savannah River Site (SRS), a 198,000-acre National Environmental Research Park located in the southeastern coastal area of the United States. The U.S. Department of Agriculture Forestry Service (USFS) manages the complex's natural resources. The forest is composed of 31% hardwood or mixed pine hardwood, and 69% pine. USFS fire personnel apply prescribed burns to approximately 15,000 to 18,000 acres annually to restore the native longleaf pine/savannah communities and wetland on the site.[11] A total of 29 Forest Service firefighters working at prescribed burns participated in the study during the winters of 2003 to 2005. The group included 25 men and 4 women between 21–46 years (average: 29.8; standard deviation: 6.3) who had worked an average of 7.5 years as firefighters at the time of recruitment. Participation in the study was voluntary. A consent form was signed after the study was explained and a firefighter had agreed to participate. The study protocol was reviewed and approved by the University of Georgia Institutional Review Board for the inclusion of human subjects.

Exposure Assessment: Personal $PM_{2.5}$ and Carbon Monoxide Sampling

Full-shift personal $PM_{2.5}$ firefighter exposures were measured during prescribed burns (burn day) and on several days when firefighters did not work at burns (controls). A total of 240 samples (6.5 per day) were collected during the study, with 203 on prescribed burn days (6.7 per day). The samples were collected using Air Check Model 224-PCXR pump (SKC, Inc., Eighty Four, Pa.) attached to GK2.05 KTL Respirable/Thoracic cyclone (BGI International, Waltham, Mass.). Particulates were collected on Gelman 37-mm Teflo filter (Pall Corp., Ann Arbor, Mich.) that was loaded into the cyclone. The filter had a 100% PTFE (polytetraflouroethylene) Teflon membrane with a 2.0 μm pore size and a polymethylpentene support ring. The system is designed to have a 50% aerodynamic cutoff point of 2.5 μm.[12] Pre- and post-sampling flow rates of the pumps were measured with a Dry Cal DC-Lite Model DCL20K (Bios International, Butler, N.J.). The flow rate for the sampling unit was set at 4.0 L/min. $PM_{2.5}$ was measured in the breathing zone with the pumps attached to each firefighter's gear pack. In all, 149 real-time person-shift CO samples were collected on 19 burn days from 20 firefighters during the 2004 and 2005 burn seasons. CO samples were not collected on non-burn days. Real-time CO was measured using Pac III single-gas monitors (Draeger Safety Inc., Pittsburgh, Pa.) outfitted with CO sensors and calibrated with a 200 ppm CO certified gas standard (Calgaz, Air Liquide America Corp., Cambridge, Mass.) prior to the start of the study. Subsequently, Draeger CO monitors were zeroed with ambient air at the forest station at the beginning of each shift, and response was checked with 200 ppm calibration gas at the end of each shift. $PM_{2.5}$ samples were collected in 2003–2005, while CO was measured in 2004 and 2005.

Exposure Assessment: Questionnaire and Time-Activity Diary

A post-shift questionnaire was administered daily to the firefighters to collect data on burn characteristics, tobacco smoke exposure, and self-reported qualitative estimation of woodsmoke exposure: whether their exposure at the prescribed burns was "none to very little, low, medium, medium to high, or very high." A daily activity diary administered alongside the questionnaire was used to determine the tasks and schedule of the firefighters during their work shifts. Possible job tasks included holding, lighting, mop-up, and other activities that do not belong to these major groupings. Briefly, holding involves the maintenance of fire within boundary lines, mop-up entails the extinguishing of smoldering fire after the major burning phase, and ignition is the fire lighting process.

$PM_{2.5}$ Gravimetric Analysis

The PTFE filters were packed and stored in a refrigerator (approximately –4C) until shipment on dry ice to the University of Georgia. The filters were stored in a climate-controlled lab for a minimum of 48 hours before they were weighed pre- and post-sample collection. Both weights were measured twice with a Cahn C-35 microbalance with a sensitivity of ± 1 μg following the guidelines set in the U.S. Environmental Protection Agency's (USEPA) standard operating procedures.[13] The weight of the $PM_{2.5}$ collected on the filter was determined by subtracting the average pre-weight of the filter from its average post-weight. Adjustments were made for minor variations in temperature, barometric pressure, and humidity for all the pre- and post-weights. The time-weighted average (TWA) particulate matter concentration was calculated as the amount of $PM_{2.5}$ collected per cubic meter (m^3) of air. Field blank concentrations were subtracted from each sample to determine the final $PM_{2.5}$ concentrations.

Statistical Analysis

All analyses were done in SAS version 9.1 (SAS Institute, Inc., Cary, N.C.).

Linear mixed-effect models were used to analyze the effect of various factors on $PM_{2.5}$ exposure. A plot of residuals using the untransformed TWA $PM_{2.5}$ concentrations revealed that the constant variance assumption was not satisfied, so $PM_{2.5}$ data were log transformed before model fitting. Firefighter tasks were included in the model as dichotomous variables. Zero was assigned to a task on control days or on burn days when the firefighter had spent less than 75% of total work time on the task; 1 was assigned on burn days when at least 75% of total work time was spent working on the task. The model included terms for plot size, wind speed, shift length (all of which were centered on their means), dichotomous variables for tasks, and the interactions between the tasks and the other variables. Interaction terms were excluded for tasks that were done on very few occasions. In addition, random subject effects were included in the model to account for longitudinal within-subject correlation among the data, and random effects for the date of sample collection were included to account for possible heterogeneity in meteorological and burn conditions from day to day.

A mixed-effect model was also used to analyze how well firefighter estimation predicted actual exposure. Self-reported measures of exposure were classified as 1 to 4 depending on the subject's response in the questionnaire regarding his/her perceived level of exposure, with 1 being "none to very little," 2 being low, 3 being moderate, and 4 being "high" or "very high." Exposures classified as high and very high were collapsed into one new category because of the small sample sizes in these categories.

Finally, it was desired to measure the correlation between $PM_{2.5}$ and CO and to test whether this correlation was equal to 0. This task is complicated by the presence of longitudinal correlation within this sample from repeated measures on the subjects and because of day-to-day heterogeneity. These features preclude a simple correlation analysis. Instead, inference on the correlation between these variables was performed by fitting a bivariate linear mixed-effect model to $PM_{2.5}$ and CO simultaneously, in which random subject-specific effects and random sampling date effects for each response variable were included, and contemporaneous correlation between the two response variables was allowed and estimated.

RESULTS

In total, 240 individual $PM_{2.5}$ work shift samples were collected over the 3-year period: 203 of these were collected on days when prescribed burns were done. Thirty-seven non-burn activity samples were collected as controls from subjects working away from burns: 35 were collected on non-burn days, 2 of which were from subjects carrying out high exposure fire mop-up duties. The other two control samples were collected on a burn day from firefighters who did not work at prescribed burns. In all, 28 samples were excluded from the analyses, leaving 177 burn day and 35 non-burn day samples. Seven of the burn day samples were excluded because they were collected with pumps having stop flows more than 5% below or above the calibrated volume of 4 L/min. Sixteen burn day samples were compromised because of a problem with the cyclone, pump flow faults, or torn filters, and were also excluded. Two non-burn day samples were excluded because they were collected during high exposure fire mop-up duties. In addition, three samples collected on burn days were not used in the models because data were missing for the acreage of burn the firefighters conducted. The average duration of work shift was 10.3 hr (range = 6.8 to 19.4 hr) on burn days and 9.3 hr (range = 7.0 to 11.5 hr) on non-burn days. Samples were collected on 30 burn days with an average of 6.7 firefighters monitored per burn. The size of burn plots ranged from 1 to 2745 acres (avg = 697). Seven non-burn (control) days were monitored. The difference between average exposures on burn and non-burn days was significant. The geometric mean $PM_{2.5}$ exposure calculated from a linear mixed-effect model adjusted for firefighter task, wind speed, length of work shift, and size of burn was 280 $\mu g/m^3$ (95% CL = 140, 557 $\mu g/m^3$, n = 177) for burn day samples, and 16 $\mu g/m^3$ (95% CL = 10, 26 $\mu g/m^3$, n = 35) for non-burn day samples (Table I). The unadjusted arithmetic and geometric means by year and for all samples are also presented in Table I. Overall, $PM_{2.5}$ exposure ranged from 5.9 to 2673 $\mu g/m^3$, and there was no difference in exposure across the 3 years for all samples and neither for burn or non-burn day samples alone. A plot of the cumulative frequency distribution of $PM_{2.5}$ exposure is presented in Figure 1.

TWA $PM_{2.5}$ above 1000 $\mu g/m^3$ was experienced in 11% (n = 18) of all samples included in data analysis, while exposure was above 2000 $\mu g/m^3$ and 2500 $\mu g/m^3$ in 3% (n = 5) and 1% (n = 2) of these samples, respectively. There was no consistency within these samples regarding the subject or sample day. Filter $PM_{2.5}$ differed significantly across levels of the firefighters' self-assessed exposure ($p < 0.0001$ for samples collected on burn days), with a significant linear trend of increasing personal $PM_{2.5}$ exposure being observed at higher

TABLE I. Work Shift TWA Personal Exposure to $PM_{2.5}$ and CO

	Unadjusted				Adjusted[A]
	2003	2004	2005	Total	Total
Burn Day					
$PM_{2.5}$ Arithmetic mean (CLs) ($\mu g/m^3$)	353 (242, 464)	491 (365, 617)	507 (385, 629)	462 (389, 535)	
$PM_{2.5}$ Geomean (CLs) ($\mu g/m^3$)	215 (154, 300)	248 (184, 333)	347 (265, 456)	264 (221, 316)	280 (140, 557)
CO Geomean (CLs) (ppm)[B]		1.0 (0.07, 13)	1.1 (0.14, 9.2)	1.0 (0.09, 11.6)	
Duration of work shift- Mean (Min, Max) (hr)	9.0 (6.8, 10.5)	11.0 (7.8, 19.4)	10.1 (7.9, 14.5)	10.3 (6.8, 19.4)	
Size of Burn- Mean (Min, Max) (acres)	411 (1.0, 1900)	758 (5.0, 2745)	837 (345, 1898)	697 (1.0, 2745)	
N	43	82	52	177	
Non-Burn Day					
$PM_{2.5}$ Arithmetic mean (CLs) ($\mu g/m^3$)	26 (12, 39)	24 (14, 35)	12 (10, 15)	20 (15, 25)	
$PM_{2.5}$ Geomean (CLs) ($\mu g/m^3$)	23 (13, 43)	18 (12, 27)	12 (9.0, 15)	16 (12, 20)	16 (10, 26)
Duration of work shift-Mean (Min, Max) (hr)	8.6 (7.0, 9.0)	9.2 (9.0, 9.8)	9.9 (7.8, 11.5)	9.3 (7.0, 11.5)	
N	5	17	13	35	

Notes: N = 87 in 2004, N = 62 in 2005, N = 149 for all samples.
[A]Results were adjusted for plot size, wind speed, shift length, tasks, and the interactions between the tasks and the other variables.
[B]CO was measured only on burn days and in 2004 and 2005 alone.

levels of self-assessed exposure ($p < 0.0001$). The adjusted geometric mean exposures for all sample days estimated as none to very little by the firefighters was 120 $\mu g/m^3$ (95% CL = 71, 203 $\mu g/m^3$), and 664 $\mu g/m^3$ (95% CL = 373, 1185 $\mu g/m^3$) for exposures estimated as high or very high on samples collected on burn days (Figure 2). Only the difference between exposures estimated as moderate and those estimated as high or very high was insignificant ($p = 0.06$). Exposure

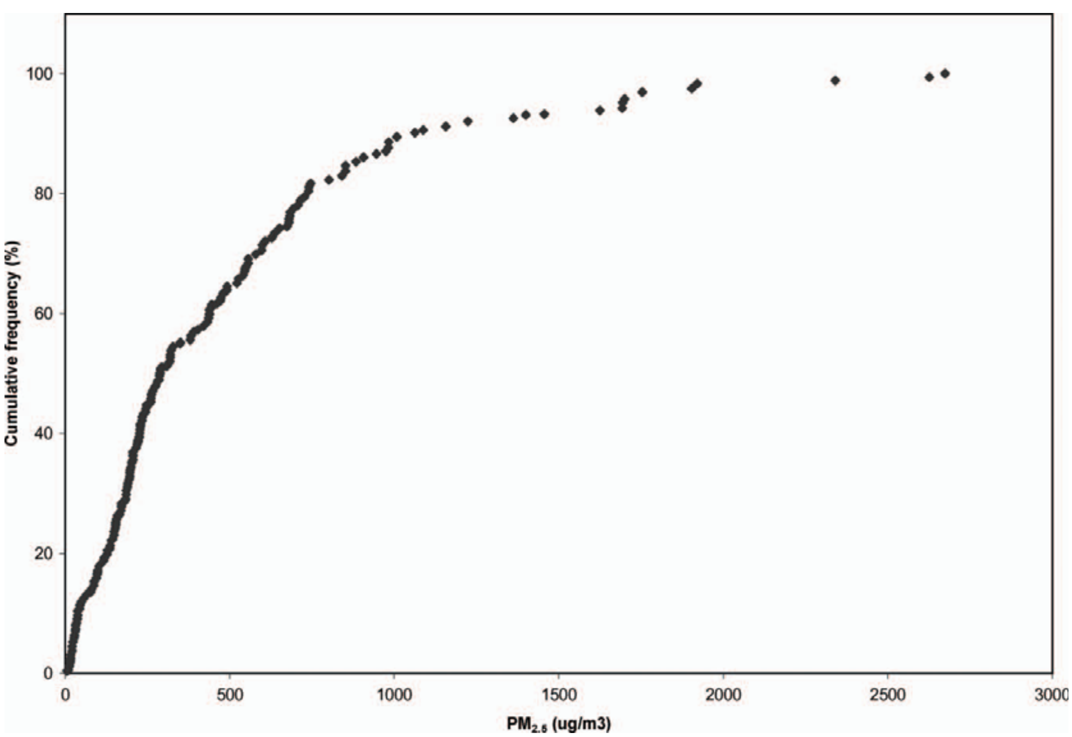

FIGURE 1. Cumulative frequency distribution for $PM_{2.5}$ exposure on burn days (N = 177)

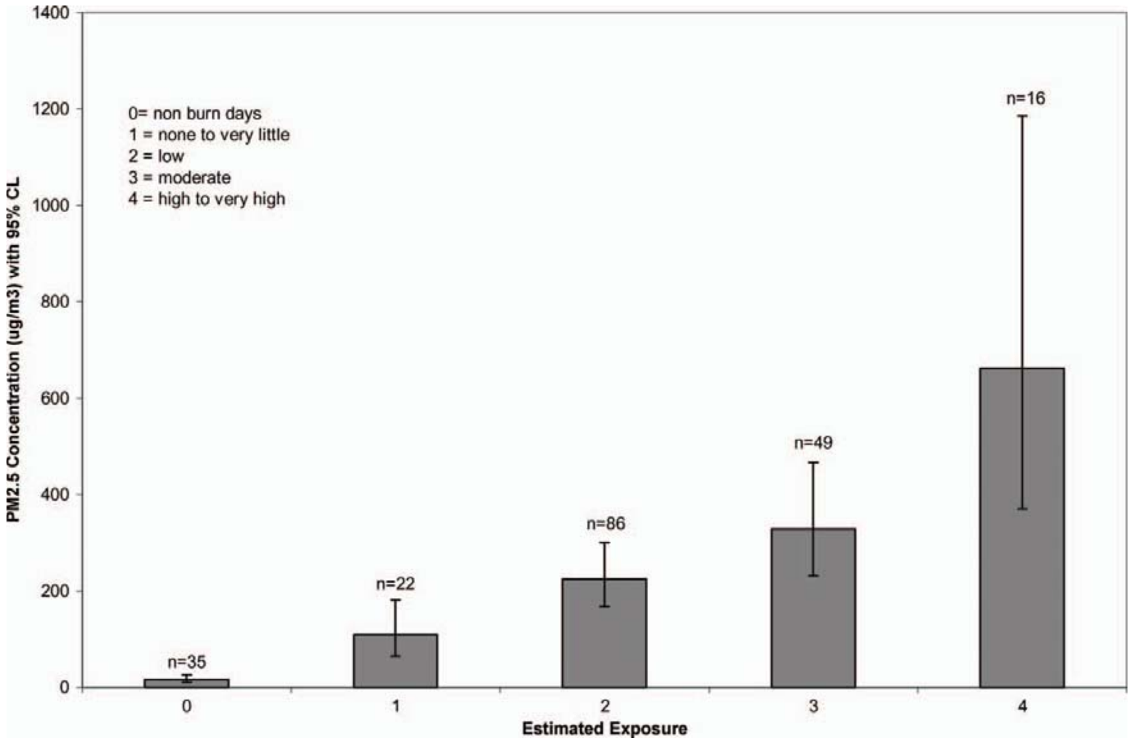

FIGURE 2. Geometric mean estimates of $PM_{2.5}$ at self-estimated exposure levels (N = 208) (N is less than 212 because some samples did not have data filled in for the self-estimation variable) ($p < 0.0001$)

was not dependent on size of burn, wind speed, or length of work time. Results of analyses suggest that type of task has an effect on exposure. However, the observed effect is solely due to tasks classified as "other" (tasks performed by the burn boss, from helicopters, or not directly at the burn). The differences between pairs of job tasks excluding the "other" category were insignificant. Figure 3 shows geometric mean $PM_{2.5}$ exposure on burn days classified according to the job task taking up at least 75% of the firefighters' work time.

In all, 149 real-time person-shift CO samples were collected during the 2004 and 2005 burn seasons. The geometric mean CO exposure (n = 149) is presented in Table I. Some pumps used for $PM_{2.5}$ sampling stopped before the end of the work shift, so for the purpose of the correlation analysis, the average CO samples were calculated for the periods for which the pumps ran. In addition, because some $PM_{2.5}$ samples were excluded from the analysis, only 134 CO/$PM_{2.5}$ pairs were used for the analysis. TWA $PM_{2.5}$ was correlated with TWA CO averaged over the run times of the $PM_{2.5}$ pumps (Pearson correlation coefficient estimate, $r = 0.79$; CLs: 0.72, 0.85; average duration, $t = 9.3$ hr) (Figure 4), and the correlation coefficient was significantly different from zero ($p < 0.0001$). Due to the increase in variance with increasing concentrations in both variables, we decided to fit the bivariate linear mixed-effect model to log-transformed values of $PM_{2.5}$ and CO simultaneously. The estimate for the Pearson correlation coefficient for this analysis was not substantially different: $r = 0.73$ (CLs: 0.64, 0.82).

DISCUSSION

Studies of occupational exposures to woodsmoke among wildland firefighters in the United States have revealed that they could be exposed to levels of particulate matter exceeding the OSHA permissible exposure limit (PEL) for respirable particulates (particulates with median size 3.5 μm, $PM_{3.5}$) of 5 mg/m^3 (OSHA, *Code of Federal Regulations*, Title 29) or the ACGIH threshold limit value (TLV for PM_4) of 3 mg/m^3.[14] These studies have been done mostly in forests in the western United States. The current study examines exposure among wildland firefighters in a forest in the southeastern United States where the vegetation and climate are very different.

It is difficult to make comparisons between this and other studies or the exposure standards because of the different size of particulate matter used in this study. Most of the previous forest firefighter exposure studies in the United States and the exposure standards are based on respirable particulates (with median aerodynamic diameter of 3.5 or 4 μm), while this study used particulate matter with median aerodynamic diameter of 2.5 μm ($PM_{2.5}$), defined by the U.S. Environmental Protection Agency (USEPA) as respirable particles. Various studies have shown that the aerodynamic diameter of particles in woodsmoke is mainly below 1.0 μm,[15–17] and most studies of the health effects of respirable particles have used $PM_{2.5}$ as a measure of exposure. Furthermore, we do not expect the weight concentration of $PM_{2.5}$ measured in this study to

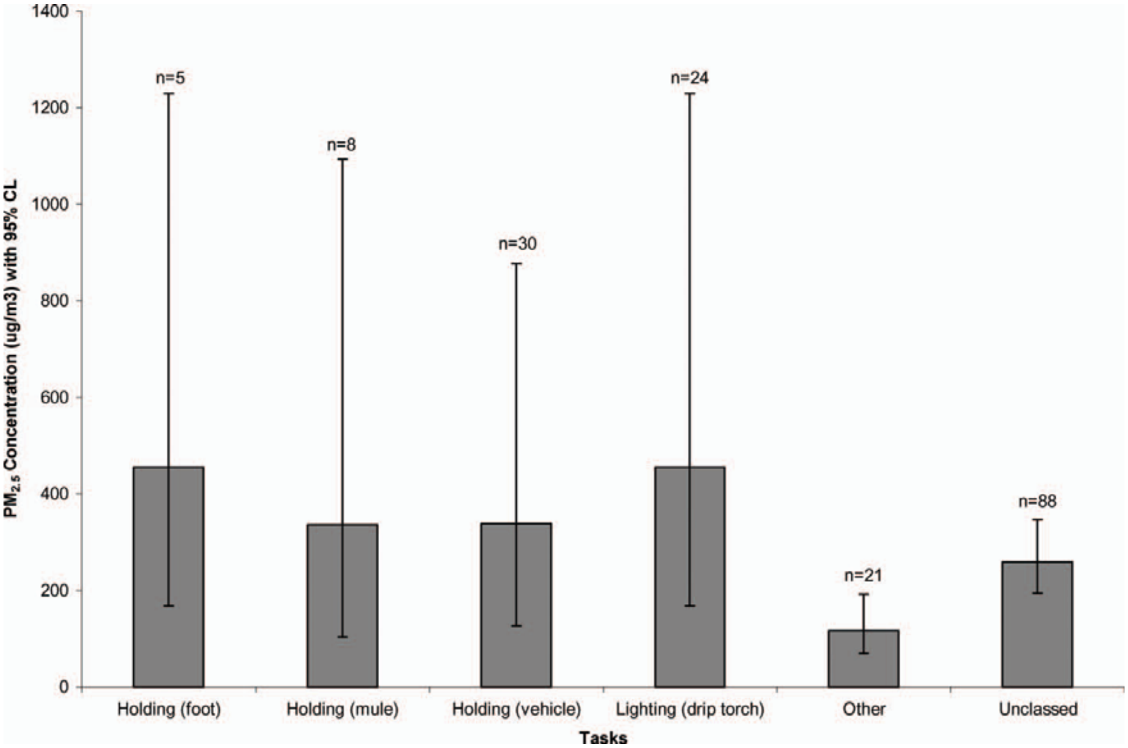

FIGURE 3. Geometric mean estimates of $PM_{2.5}$ exposure on burn days across different tasks with at least 75% of firefighter work time. Holding was done on foot, on a mule (utility vehicle), or with a 4-wheel car (vehicle). Lighting was done with a drip torch. Tasks not under the major classifications are categorized as "other," while the "unclassed" category is for exposures with the proportion of work shift time spent on all tasks during the particular work shift being below 75%.

be substantially different from that of $PM_{3.5}$. McMahon and Bush[18] reported a 12% difference in weight concentration between $PM_{3.5}$ and $PM_{2.3}$ from small, open burning greenhouse experiments using a 10-mm nylon cyclone. Subsequently, the measured exposures (geometric mean = 0.28 mg/m^3) seem to be lower than those reported by Reinhardt and Ottmar[8] (for $PM_{3.5}$: geometric mean = 0.63 mg/m^3; n = 200). Furthermore, higher exposures were observed among wildland firefighters during prescribed burns in an older study in the state of Georgia (for $PM_{2.3}$: median = 1.3 mg/m^3; range = 0.2–3.7 mg/m^3; n = 48).[18] However, exposure in the Georgia study was monitored only at the fire line and not over the entire work shift. In comparison, time spent performing tasks away from the fire during the work shift would have resulted in reduced TWA concentrations.

Although the geometric mean presented here indicates that the OSHA PEL or the ACGIH TLV for particulate matter is not exceeded among this group of firefighters, exposures may exceed the TLV as a few firefighters had a $PM_{2.5}$ exposure above 2500 μg/m^3. Exposure to such elevated levels of particulate matter may elicit various adverse health effects.[19–21] More specifically, woodsmoke exposure has been linked to respiratory symptoms and diseases,[5,22–26] and systemic inflammation.[27,28] Lung function decline and inflammation have also been observed among wildland firefighters post-exposure to woodsmoke.[6,7]

Daily average ambient 24-hr $PM_{2.5}$ concentrations measured by EPA monitors closest to the study site—those in South Carolina at Aiken: 1 mile NW, Edgefield: 25 miles NW, Richland: 50 miles NE, and Orangeburg: 37 miles NE, and in Augusta, Georgia: 16 miles NW—during the periods of the study were well below most of the personal exposures of the firefighters. The maximum concentration measured by any of the monitors was less than 30 μg/m^3 throughout the periods of the study.[29] Magnitudes of $PM_{2.5}$ exposure similar to those measured in this study have been observed for persons living in homes in which wood is used for cooking in rural communities in developing countries[30,31] and in ambient air in areas impacted by wildfires in the United States.[32,33]

As observed by Reinhardt and Ottmar,[8] average work shift particulate matter and CO are correlated in this study confirming that either of these two environmental markers might be used as surrogate measure of exposure to the other across a prescribed burn work shift. However, the slope of the relationship in this study appears to be steeper. This could be explained by the lower carbon monoxide exposure that was observed and, possibly, the difference in the aerodynamic size of the particles measured. Average exposure was not significantly affected by wind speed, wind direction, size of burn, or length of the work shift of the firefighter. Results show that firefighters tended to be able to predict their exposure.

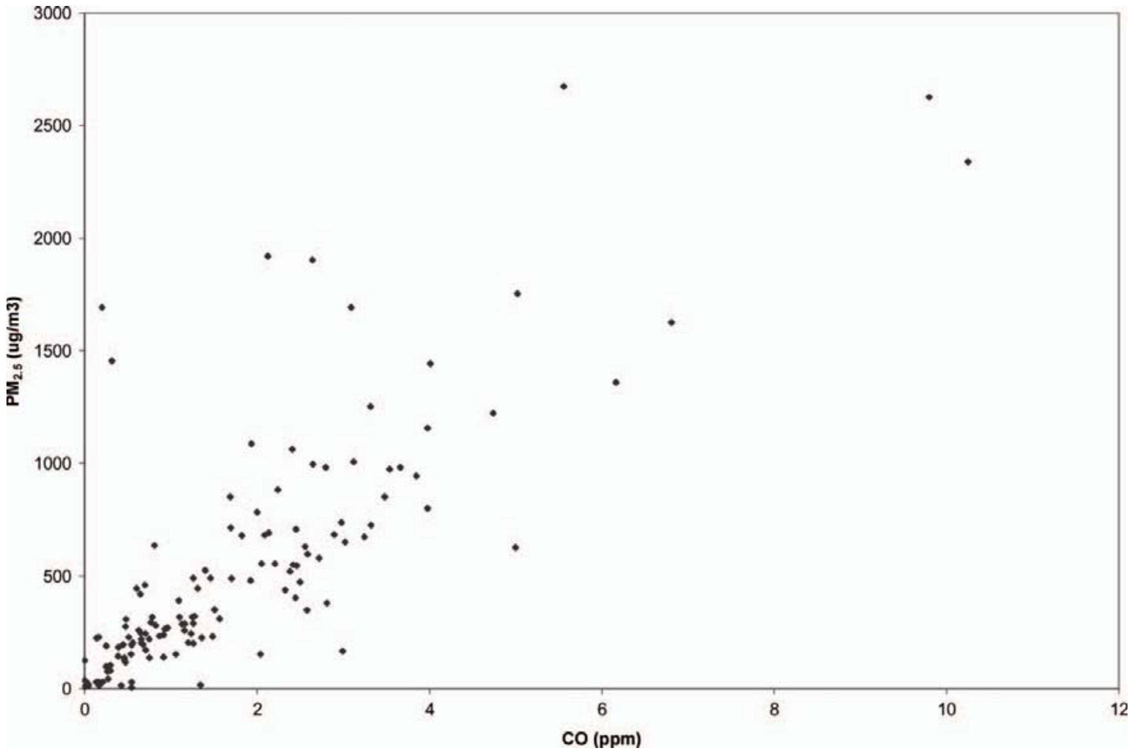

FIGURE 4. Association (scatterplot) between $PM_{2.5}$ and CO. Pearson correlation coefficient = 0.79; $p < 0.0001$ (estimated from bivariate linear mixed-effect model fitted simultaneously to $PM_{2.5}$ and CO) (N = 134).

However, the variation within each estimation class is large. The observed difference in exposure across job task was solely due to tasks relatively remote from the fires. However, the comparison was not precise because firefighters often worked multiple tasks during each work shift, making the attribution of exposure during a shift to a particular task difficult. Also, very few person-hours satisfied our criterion requiring at least 75% of the work shift to be spent doing the task, resulting in small sample sizes for most of the tasks in the analyses, but results did not change when the analysis was done with a relaxed classification and exposures were assigned to tasks the firefighters spent the majority of their time performing. Exposure was not completely captured in a few cases as some pumps failed to run the entire duration of the work shift. Also, exposure may be underreported in a few cases because firefighters sometimes put away their gear packs while working at some tasks in the field. However, we do not envisage that this would have impacted our results substantially, as there was good compliance among the subjects, and the firefighters only put away their gear packs for very short periods and only a few feet away when they did. We also kitted the subjects in this study with the samplers to minimize hindrance without compromising the results of the study. The use of time-integrated samplers to monitor exposure across the entire work shift precluded the calculation of TWA exposure at the fire line, which would have been higher than the result presented here.

CONCLUSIONS

Although the overall geometric mean $PM_{2.5}$ exposure indicates that the OSHA PEL or the ACGIH TLV for particulate matter was not surpassed, these limits may be exceeded, as some of the firefighters were exposed to very high levels of $PM_{2.5}$. The correlation between CO and $PM_{2.5}$ is potentially an exposure assessment tool for research and exposure management for firefighters working at prescribed burns.

RECOMMENDATIONS

As indicated above, the correlation between CO and $PM_{2.5}$ may be used for exposure control among wildland firefighters. CO monitors with alarms set at certain thresholds could, for example, be used to alert firefighters to a high/very high exposure situation. This could be particularly because firefighter exposure to woodsmoke may be dominated by momentary peaks.[34] However, the relationship between CO and PM may vary as indicated by the difference in the slope of the relationship in our study compared with those reported by Reinhardt and Ottmar.[8] Therefore, future studies are needed to better understand the relationship between the two pollutants/exposure proxies. For future studies, we recommend that real-time particulate matter samplers should be used, or where they are unavailable, time-integrated samplers should be run for the duration when the firefighters are at the fire line. The completion of time-activity diaries by researchers detailed to monitor the activities of firefighters at the fire line instead of self-administered diaries, together with the use of real-time samplers, would present the researcher with data to better understand the relationship between job tasks and exposure. The use of real-time particulate matter samplers could also facilitate a better understanding of the relationship between particulate matter and CO. We also recommend that samplers be worn directly on the firefighter to avoid underreporting in cases where firefighters put away their gear packs. Some of these corrections have been and are being made in subsequent studies among this group of wildland firefighters.

ACKNOWLEDGMENTS

We acknowledge the support of John Blake, Dan Shea, Jason Demas, Mark Frizzel, Paul Linse, and Jeff Prevey of the United States Forest Service and David Macintosh of the Environmental Resource Management Inc., Needham, Massachusetts. Funding was provided by the Department of Energy–Savannah River Operations Office through the U.S. Forest Service Savannah River under Interagency Agreement DE-AI09-00SR22188.

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