

Exposure of Wildland Firefighters to Carbon Monoxide, Fine Particles, and Levoglucosan

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Wildland firefighters are occupationally exposed to elevated levels of woodsmoke. Eighteen wildland firefighters were monitored for their personal exposure to particulate matter with median aerodynamic diameter of 2.5 microns (PM_{2.5}), levoglucosan (LG), and carbon monoxide (CO) at 30 prescribed burns at the Savannah River Site, South Carolina. Linear mixed effect models were used to investigate the effect on exposure of various factors and to examine whether the firefighters were able to qualitatively estimate their own exposures. Exposure to PM_{2.5} and CO was higher when firefighters performed 'holding' tasks compared with 'lighting' duties, whereas exposures to CO and LG were higher when burns were in compartments with predominantly pine vegetation ($P < 0.05$). Exposures to PM_{2.5} (64–2068 µg m⁻³) and CO (0.02–8.2 p.p.m.) fell within the ranges observed in previous studies. Some recommended shorter term exposure limits for CO were exceeded in a few instances. The very low LG:PM_{2.5} ratios in some samples suggest that the exposures of wildland firefighters to pollutants at prescribed burns may be substantially impacted by non-woodsmoke sources. The association of the qualitative exposure estimation of the firefighters with actual PM_{2.5} and CO measurements ($P < 0.01$) indicates that qualitative estimation may be used to assess exposure in epidemiology studies.

Keywords: carbon monoxide; levoglucosan; occupational exposure; particulate matter; prescribed burn; wildland firefighter

INTRODUCTION

Woodsmoke contains significant amounts of hazardous pollutants including fine particles, free radicals, irritants, and several known carcinogens (Naeher *et al.*, 2007). Exposure to woodsmoke has been associated with a variety of adverse health effects in humans (Kurmi *et al.*, 2010; Naeher *et al.*, 2007). Despite the increasing attention given to woodsmoke exposure and its consequent health effects, very few studies have investigated

woodsmoke exposure among wildland firefighters. Wildland firefighters, due to their proximity to forest fires, are often exposed to elevated levels of pollutants in woodsmoke (Reinhardt and Ottmar, 2004). Previous studies have shown that wildland firefighters could experience occupational exposure to air pollutants, especially particulate matter, above occupational and recommended exposure limits (Reinhardt and Ottmar, 2004). However, most of these exposure studies were conducted in Western and Northwestern United States. Data for other regions of the country where weather, vegetation, and fuel characteristics are different remain limited.

A previous exposure assessment study monitoring the exposure of wildland firefighters to

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particulate matter with median aerodynamic diameter of 2.5 microns ($PM_{2.5}$) and carbon monoxide (CO) had been conducted at forests at the Savannah River Site (SRS), South Carolina, in the Southeastern United States during the dormant prescribed burn seasons of 2003–2005 (Adetona *et al.*, 2011a). Prescribed burns are intentionally set fires that are used to achieve land management objectives including the reduction of wildfire hazards and improvement of wildlife habitats. Dormant winter prescribed burns are typically conducted between late winter and early spring (January to March at SRS) when the woody vegetation is still partially dormant. In this present study, we present exposure characterization from a follow-on study designed to assess the utility of urinary methoxyphenols as biomarkers of occupational exposure to biomass smoke among wildland firefighters. The results of the exposure monitoring of United States Forest Service (USFS) wildland firefighters working at prescribed burns at the SRS are presented in this study; urinary biomarker measurements will be described in a subsequent report. This study builds upon the previous work of Adetona *et al.* (2011a) while addressing some important limitations, including the inability in the earlier study to reliably capture full-shift PM samples. In addition to characterizing exposures to CO and PM, in this present study particulate levoglucosan (LG) was also measured and used to further characterize the exposure of the firefighters to biomass smoke. LG is a pyrolysis product of cellulose and is a major organic compound in the emissions from the combustion of wood (Simoneit *et al.*, 1999; Jordan *et al.*, 2006). It is stable in the environment and is also considered a reliable marker of long-range transport of emissions from biomass combustion (Hays *et al.*, 2002; Jordan *et al.*, 2006).

MATERIALS AND METHODS

Study location and subject recruitment

This study was conducted at the SRS, a National Environmental Research Park in South Carolina. The park's forests comprise 31% hardwood or mixed pine hardwood and 69% pine. USFS forest firefighters apply prescribed burns to ~15 000–18 000 acres annually to restore the native longleaf fire savannah communities and wetland on the site. The personal work-shift exposures of 19 (17 males, 2 females) forest firefighters to CO, $PM_{2.5}$, and LG in woodsmoke were monitored at prescribed burns

during the dormant winter burn seasons (January–March) of 2008 and 2009. The 18 subjects that responded to questions regarding their age at recruitment were between 21 and 54 years (average: 31.5; standard deviation: 8.3). Participation in the study was voluntary. Subjects were selected to participate in the study after the objectives of the study were explained to them, and they had signed the study consent form. This study was approved by the University of Georgia Institutional Review Board for the inclusion of human subjects.

Personal exposure monitoring: $PM_{2.5}$ and CO

A total of 157 person-day full-shift personal exposure samples were collected over 30 prescribed burn days during the study. $PM_{2.5}$ exposure was monitored using SKC Air Check Model 2000 pumps (SKC Inc., Eighty Four, PA, USA) attached to BGI Triplex cyclones (BGI Inc., Waltham, MA, USA). Particulate matter was collected on Gelman 37 mm polytetrafluoroethylene (PTFE) membrane filters that had a pore size of 2.0 μm and a polymethylpentene support ring (Pall Corp, Ann Arbor, MI, USA). The pump flow rate was set at 1.5 l min^{-1} to achieve a 50% aerodynamic cutoff point at 2.5 μm for the cyclone. Pre- and post-sampling flow rates were measured using a Bios Dry Cal DC-Lite Model DCL20K electronic flow meter (Bios International, Butler, NJ, USA). Personal exposure to CO was monitored in real time using Dräger Pac III data-logging single gas monitors (Draeger Safety Inc., Pittsburgh, PA, USA) outfitted with CO sensors. The monitors were calibrated with a 50 p.p.m. CO certified gas standard (Calgaz, Air Liquide America Corp., Cambridge, MA, USA) 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 were set to log data every 30 s. Monitoring was done in the breathing zone of the subject and the samplers were placed in pockets of vests worn by the firefighters.

Questionnaire and time–activity diary

A self-administered questionnaire was used to collect background information from the subjects at recruitment. This included the age and gender of the firefighter, length of firefighting career, estimate of the cumulative number of prescribed burns and wildfires at which the firefighter had worked over the firefighting career, and the energy source for residential heat. Following each work shift, subjects completed a second questionnaire

providing information regarding the perception of how severe their exposure was (none to very little, low, medium, medium to high, high), size of the burns, and tobacco smoke exposure. Subjects recorded the job tasks they performed at the fire line in a time-activity diary. 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 activities entail the extinguishing of smoldering fire after the major burning phase, and ignition is the fire lighting process. Wind speed data was obtained from the weather station on site at SRS.

PM_{2.5} gravimetric analysis

The filters were stored in a climate-controlled laboratory for a minimum of 48 h before they were weighed pre- and post-sample collection. Filter weights were measured twice with a Cahn C-35 microbalance with a sensitivity of $\pm 1 \mu\text{g}$ following the guidelines described in the United States Environmental Protection Agency (USEPA)'s Standard Operating Procedures (USEPA, 1998). 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. The time-weighted average (TWA) particulate matter concentration was calculated as the amount of PM_{2.5} collected per cubic meter of air. Mean weight change of field blank was subtracted from each sample weight to determine the final PM_{2.5} concentrations. Twenty-four field blanks representing 15% of the total number of samples were collected with a mean weight of 3.0 μg . Weights of all the PM_{2.5} samples collected were more than three times the standard deviation (4.8 μg) of the field blank weights.

LG analysis

Analysis of filter PM_{2.5} LG by gas chromatography/mass spectrometry (GC/MS) was undertaken at the University of Washington. The protocol for the extraction of LG from filter PM_{2.5} has previously been described (Simpson *et al.*, 2004). Briefly, the PTFE filter membranes were folded in half and placed in silane-treated headspace vials. They were then spiked with the recovery standard, deuterated LG (d7-LG). Filters were extracted by sonication for 1 h in a freshly prepared solution of 3.6 mM triethylamine in ethyl acetate. The volumes of the extracts were then reduced to approximately 0.5 ml in a Turbovap II concentrator under nitrogen. The extracts were filtered through a 0.45 μm

PTFE syringe filter into silanized autosampler vials, and internal standard (triisopropylbenzene) and anhydroheptulose (used to monitor the efficiency of derivatization) were added. The derivatization reagent, methylsilyltrifluoroacetamide together with trimethylchlorosilane and pyridine, was added to the extracts and allowed to react in the dark for at least 6 h. Derivatized extracts were injected into the GC by splitless injection. The GC column that was used for the assay is a RESTEK Rtx-5Sil MS (30 m, 0.25 mm i.d., 0.25 μm thickness; RESTEK Corp., Bellefonte, PA, USA). Quantification was done using the m/z peaks of 204 (LG) and 206 (d7-LG) relative to the response at m/z 189 (triisopropylbenzene) and the calibration curve. The calibration was set to quantify LG concentration within the range of 0.1–100 $\mu\text{g ml}^{-1}$ in the extract. The limit of detection was 0.05 μg per filter. Precision was $\pm 5\%$ for the method and $\pm 2\%$ for the instrument. The recovery of d7-LG for all samples was 69% \pm 13%.

Statistical analysis

Mixed effects models were used to determine factors that may affect exposure. Log-transformed concentrations of PM_{2.5}, CO, and LG and arcsine square root transformed ratio of LG to PM_{2.5} (LG:PM_{2.5}) were the dependent variables in the models. The transformations were applied in order to satisfy model assumptions regarding homoscedasticity of variance. The explanatory variables in the model included tasks undertaken at the fire line by the firefighter (categories: lighting, holding, and unclassified), vegetation type (softwood, mixed hardwood), fuel ignition or lighting procedure (whether lighting was done by hand using drip torch or aerially by a helicopter), size of burn, duration of sampling, and wind speed.

The firefighters usually conducted more than one task at the fire line during a single work shift, so exposure was assigned to a task the firefighters had spent at least 75% of their work time at the fire line doing. An 'unclassified' category was created for exposures that did not meet this criterion. The vegetation of the compartment where the firefighters conducted prescribed burns was classified as softwood if at least 70% of the compartment where the burn occurred was softwood and as mixed hardwood if the compartment was composed of less than 70% softwood.

F-values were used to test whether firefighter exposures differed across the categories of the categorical variables and whether they were associated with the continuous variables in the negative

or positive direction. The tests were essentially *t*-tests for all the categorical variables with one degree of freedom except for task that had two degrees of freedom. Pairwise comparisons among classes of the categorical variables were done using Tukey's honest significant difference (HSD) test.

Mixed effects models were also used to determine whether firefighters were able to qualitatively estimate their own exposure. Self-reported measures of exposure were classified as 1–4 depending on the subject's response in the questionnaire to whether exposure is none to very little to medium to high/high with 1 being none to very little. The last two categories in the original response were collapsed into one new category (medium to high/high) for the purpose of statistical analysis due to small sample sizes.

F-values were used to test whether firefighter exposures differed across the levels of self-estimation. Tests of linear increase in exposures with increasing severity of self-estimation were also performed. Pairwise comparisons were done using Tukey's HSD test. The association among pairs of markers of exposure (PM_{2.5}, CO, or LG) was estimated using rank correlation generated with a mixed effects model. Subject and dates of collection were controlled for and treated as random effects. All analyses were done in SAS version 9.2 (Cary, NC, USA).

RESULTS AND DISCUSSION

Personal exposure of wildland firefighters to CO, PM_{2.5}, and LG

A total of 157 person-days of samples were collected from 18 subjects over 30 burn days during the study. Burn size ranged from 80 to 3300 acres and averaged 910 acres, whereas work-shift duration of the wildland firefighters ranged between 3.0 and 13 h and averaged 7.9 h. The duration of the work time of the firefighters at the fire line as estimated from the time–activity diary ranged from 2.0 and 11 h and averaged 5.5 h. Twenty-seven PM_{2.5} samples were excluded from all statistical analyses: 15 because of pump failures, 7 because pumps were removed from the breathing zone, and 5 for other reasons including torn filters. Seventeen CO samples were excluded because the CO samplers failed before monitoring was completed (*n* = 10) or vests were not worn properly (*n* = 7). The overall unadjusted geometric means and ranges of exposure for PM_{2.5}, CO, and LG are presented in Table 1.

In a previous exposure assessment study conducted between 2003 and 2005 at SRS among

wildland firefighters working at prescribed burns, TWA personal exposure to PM_{2.5} averaged over the work shift ranged between 5.9 and 2673 µg m⁻³, whereas exposure to CO ranged between <1 and 14 p.p.m. (Adetona *et al.*, 2011a). The previous study was also conducted during dormant winter prescribed burn seasons. Although the geometric means for PM_{2.5} and CO exposures in the current study are higher, exposures in the current study fell within the ranges observed in the previous study. Geometric mean TWA work-shift exposures were also comparable with those measured in studies in Western United States (Reinhardt and Ottmar, 2004). Limitations of our previous study (Adetona *et al.*, 2011a) regarding the monitoring of the firefighters for exposure to PM_{2.5} were corrected in this present study. Longer running pumps were used in this present study to ensure that samples were not lost due to incomplete measurements.

Similar to the previous study, results of the current study indicate that neither the Occupational Safety Health Administration's (OSHA) permissible exposure limits (PEL) nor the lower American Conference of Governmental Industrial Hygienists' (ACGIH) threshold limit value (TLV) for 8-h TWA exposure for PM and CO were exceeded by the firefighters. A PEL of 5 mg m⁻³ is defined for respirable particles (PM_{3.5}) (OSHA, Code of Federal Regulation, Title 29), whereas a TLV of 3 mg m⁻³ is defined for PM₄ (ACGIH, 2003). However, PM_{2.5} was monitored in this study because the aerodynamic diameter of particles in woodsmoke is mainly below 1 µm (Kleeman *et al.*, 1999; Silva *et al.*, 1999; Leonard *et al.*, 2007) and most studies of the health effects of PM have used PM_{2.5} as their exposure metric. PM_{2.5} was also monitored in the previous study at SRS. Furthermore, respirable PM is more likely than PM_{2.5} to include larger soil dust and ash particles that are not part of the woodsmoke mixture. A 12% difference between the mass concentrations of PM_{2.3} and PM_{3.5} had been reported in small, open burning greenhouse experiments using a 10-mm nylon cyclone (McMahon and Bush, 1992). Adjusting the largest PM_{2.5} exposure (2068 µg m⁻³) measured in this study by the difference still places the exposure below the ACGIH TLV. The ACGIH TLV was still not exceeded when the PM_{2.5} exposures were converted to the 8-h TWA (normal work day length assumed for ACGIH TLV), in addition to adjusting them for the 12% difference between the mass concentrations of PM_{2.3} and PM_{3.5} (Table 1). Nonetheless,

Table 1. Unadjusted geometric means for exposure components and burn characteristics (arithmetic mean for LG/PM_{2.5} ratio).

Exposure	Average (95% lower, upper CLs)	Minimum	Maximum	N
Overall				
PM _{2.5} (µg m ⁻³) ^a	530 (476, 591)	64	2068	130
8-h adjusted PM _{2.5} (µg m ⁻³) ^a	525 (466, 590)	66	2456	130
CO (p.p.m.)	1.5 (1.3, 1.7)	0.02	8.2	140
LG (µg m ⁻³)	20 (16, 29)	0.04	291	122
LG/PM _{2.5} ratio (%)	6.9 (5.4, 8.5)	0.008	61	122
Size of burns (acres)	910	80	3300	
Duration of work shift (h)	7.9	3.0	13	
Duration of work time at fire line (h)	5.5	2.0	11	
2008				
PM _{2.5} (µg m ⁻³) ^a	509 (446, 579)	64	1466	72
8-h adjusted PM _{2.5} (µg m ⁻³) ^a	483 (420, 556)	66	1574	72
CO (p.p.m.)	1.7 (1.3, 2.1)	0.02	7.5	76
LG (µg m ⁻³)	19 (15, 23)	1.43	97	65
LG/PM _{2.5} ratio (%)	4.2 (3.8, 4.7)	0.99	9	75
Size of burns (acres)	831	80	1895	
Duration of work shift (h)	7.6	3.0	11	
Duration of work time at fire line (h)	5.6	2.0	11	
2009				
PM _{2.5} (µg m ⁻³) ^a	559 (465, 671)	140	2068	58
8-h adjusted PM _{2.5} (µg m ⁻³) ^a	581 (475, 710)	102	2456	58
CO (p.p.m.)	1.3 (1.0, 1.6)	0.10	8.2	64
LG (µg m ⁻³)	22 (13, 36)	0.04	291	57
LG/PM _{2.5} ratio (%)	10 (6.9, 13)	0.008	61	57
Size of burns (acres)	1012	160	3300	
Duration of work shift (h)	8.1	3.4	13	
Duration of work time at fire line (h)	5.4	2.3	9.5	

^aThe exposures are also reported as 8-h TWAs in addition to reporting them as work-shift TWAs.

exposure to PM_{2.5} from biomass combustion at levels similar to those measured for the firefighters in this study, and also at lower levels of exposure, has been associated with various adverse health effects in the general population (Mott *et al.*, 2002; Naeher *et al.*, 2007; Delfino *et al.*, 2009). Most of the 24-h PM_{2.5} exposures observed for these firefighters during the days they worked at prescribed burns would also still be higher than the USEPA 24-h national ambient air quality standards by one factor or more, even if the improbable assumption that they had no PM_{2.5} exposure at the times when they are away from firefighting is made. Furthermore, wildland firefighters often work extended shifts while engaged in hard physical activities and wearing no respiratory protection (Reinhardt and Ottmar, 2004). The subjects in this study also did not wear respiratory protection. Reduced lung function and pulmonary and

systemic inflammations are among the adverse health effects that have been associated with occupational woodsmoke exposure among wildland firefighters (Betchley *et al.*, 1997; Gaughan *et al.*, 2008; Swiston *et al.*, 2008; Adetona *et al.*, 2011b).

The maximum work-shift TWA CO exposure measured in this study (8.2 p.p.m.) was well below the OSHA PEL of 50 p.p.m. and the ACGIH TLV of 25 p.p.m. However, some recommended shorter term exposure limits were exceeded in a few instances. The National Institute of Occupational Safety and Health's (NIOSH) ceiling limit of 200 p.p.m. was exceeded for 99 thirty-second-averages over a total of 9 person-days. The highest 30-s average that was recorded among the firefighters was 1450 p.p.m., which is greater than the immediately dangerous to life or health (IDLH) value of 1200 listed by NIOSH (NIOSH, 1994). OSHA has not defined a short-term exposure limit (STEL), typically measured

over a 15-min period, for CO. However, a STEL of 75 p.p.m. (three times the ACGIH TLV) has been recommended for use for wildland firefighters (Reinhardt and Ottmar, 2004). This threshold was exceeded on a total of 4 person-days for periods lasting between 13 and 76 min during the study.

Although results indicate that exposures to PM do not exceed available occupational exposure standards, levels observed are elevated and may warrant further investigation, especially since wildland firefighting is a physically demanding occupation that requires increased minute ventilation. Work-shift TWA exposures to CO were low and well below available 8-h occupational standards. However, shorter term exposure limits (IDLH and 15-min STEL) were exceeded in a few instances.

Qualitative self-estimation of exposure

Consistent with the results of the previous study conducted at SRS (Adetona *et al.*, 2011a), the firefighters were able, within a wide range of variability, to qualitatively self-estimate their own level of exposure to woodsmoke as indicated by the comparison of the qualitative self-estimation with the actual measurements of exposure to PM_{2.5}, CO,

and LG. Exposures to PM_{2.5} ($P = 0.0009$) and CO ($P < 0.0001$) were different across the levels of self-estimation (Figs 1 and 2). There was also a linear trend of an increase in exposure to PM_{2.5} ($P < 0.0001$) or CO ($P = 0.0002$) with increasing severity of self-estimation (from none to very little to medium to high/high). This result indicates that self-estimation of exposure may be of use in epidemiological studies. Although we note that the results are from a study conducted at one location and have not been validated by similar studies elsewhere, it is noted that an exposure assessment protocol such as this has been successfully utilized for municipal firefighters in a study of the effects of smoke exposure on pulmonary inflammation among municipal firefighters in the Netherlands (Greven *et al.*, 2012).

Correlation between exposures to CO, PM_{2.5}, and LG

The rank correlation coefficients between personal exposures to PM_{2.5}, CO, and LG are statistically significant but low ($r = 0.35$ for CO versus LG, 0.37 for PM_{2.5} versus LG, and 0.45 for PM_{2.5} versus CO). The association between personal exposure to CO and PM_{2.5} ($r = 0.45$) was weaker

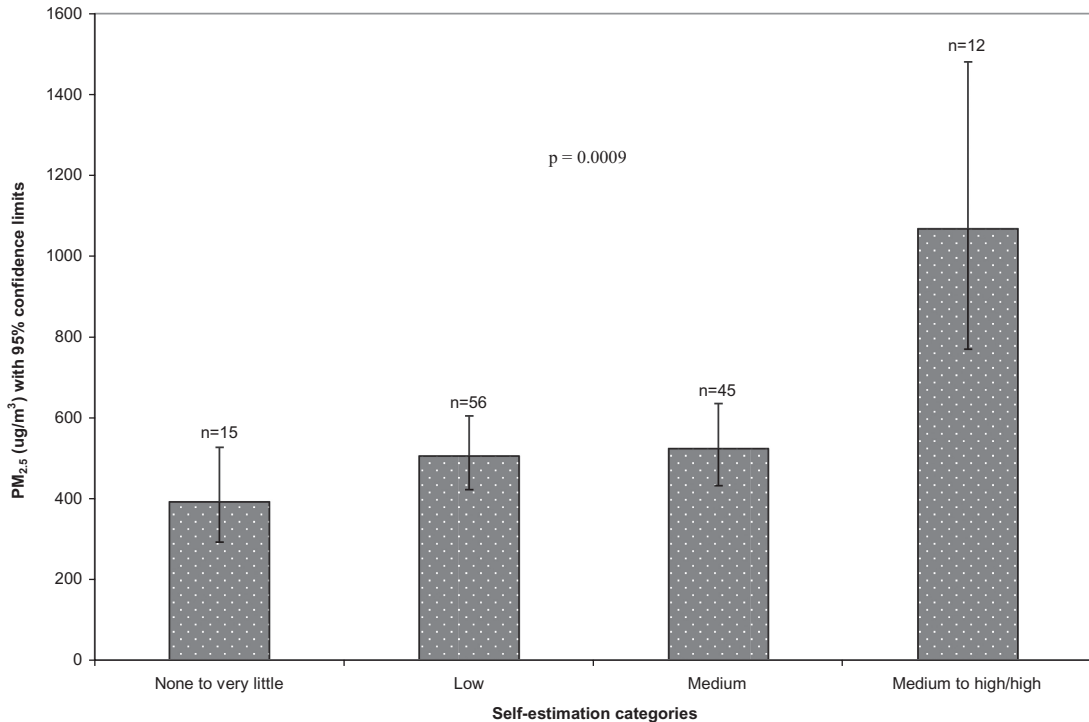


Fig. 1. Geometric mean personal work-shift TWA exposure to PM_{2.5} according to the categories of the qualitative estimation of the firefighter. n = number of person-days.

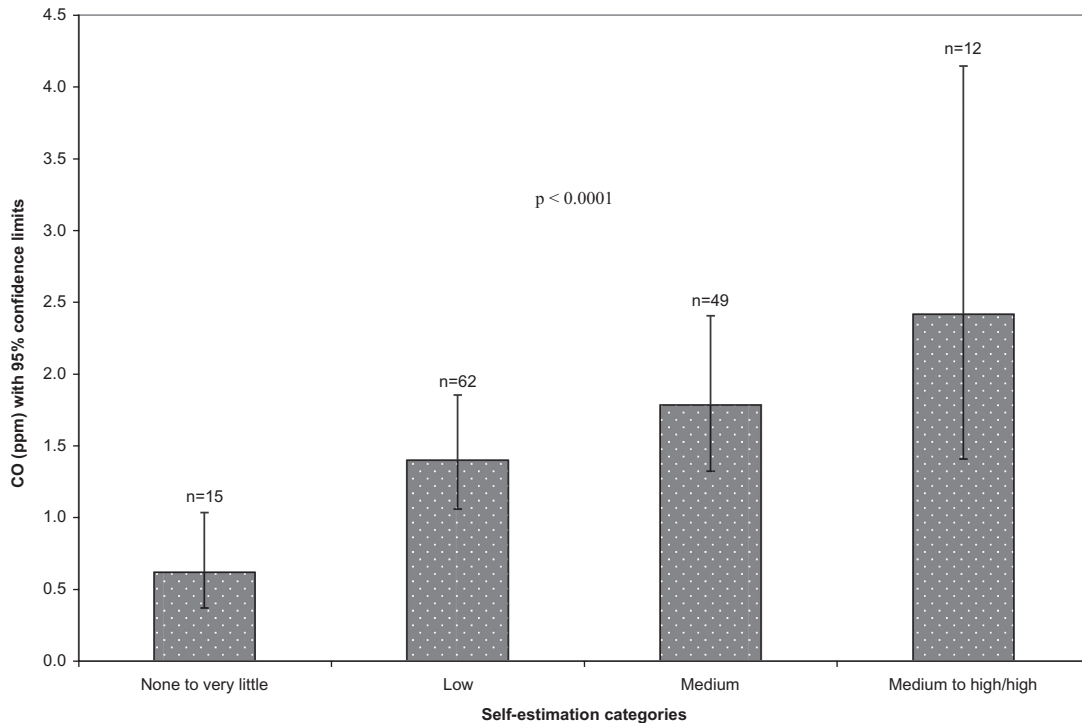


Fig. 2. Geometric mean personal work-shift TWA exposure to CO according to the categories of the qualitative estimation of the firefighter. n = number of person-days.

than was observed in the previous study at SRS ($r = 0.79$) (Adetona *et al.*, 2011a) and in older studies conducted among wildland firefighters working at prescribed burns and wildfires (Reinhardt and Ottmar, 2004). The reason for the disparity in the results is unclear but could have been due to some of the PM exposures being impacted substantially by non-combustion sources. During prescribed burns at SRS, firefighters rely on four-wheel and utility vehicles to perform tasks including holding and mop-up. This may result in the suspension of particles and lead to disproportionate exposure to increased levels of PM, especially in completely burnt and flamed-out areas. On the other hand, substantial exposure to the exhaust from the vehicles may lead to higher exposure to CO than the firefighters would otherwise have had. For instance, the LG:PM_{2.5} ratios of nine of the samples were below 1%, indicating a substantial source of PM_{2.5} exposure other than woodsmoke. The correlation between personal exposure to PM_{2.5} and particulate LG was also very low ($r = 0.37$).

Factors affecting exposure

The statistical significance of the explanatory variables in the model for the wildland firefighters

exposure to PM_{2.5}, CO, and LG and the LG:PM_{2.5} ratio is presented in Table 2. The exposures were not affected by the size of the burn, lighting procedure, or wind speed. The personal exposures of the wildland firefighters to both PM_{2.5} ($P = 0.007$) and CO ($P = 0.01$) were significantly different according to the task conducted by the firefighters. Exposures to CO ($P = 0.04$) and LG ($P = 0.045$) were also significantly different according to the type of vegetation that was burnt, whereas exposure to CO significantly was associated with the work-shift length ($P = 0.04$).

Exposures to PM_{2.5}, CO, and LG according to the task of the firefighters are presented in Figs 3–5. The firefighters who were monitored in this study typically conducted more than one task during their work time at the fire line. Consequently, the TWA work-shift exposures were assigned to the task that the firefighters spent at least 75% of their work time at the fire line performing. Exposures that did not meet this criterion were categorized as ‘unclassified’. It should also be noted that no exposure was assigned to mop-up under this criterion since all the firefighters that were monitored did not spend up to 75% of their work time doing this task at

Table 2. Parameter estimates and *P*-values for the effect of explanatory variables on exposure to environmental markers woodsmoke.

Exposure marker	Variable	Parameter estimate	<i>P</i>
PM _{2.5}	Intercept	6.53	<0.0001
	Burn size ^a	0.000035	0.82
	Work-shift length ^a	0.00054	0.31
	Wind speed ^a	0.0023	0.97
	Vegetation (overall) ^b		0.25
	Vegetation (mixed hardwood)	-0.22	0.25
	Vegetation (pine)	0.00	
	Lighting procedure (overall) ^b		0.97
	Lighting procedure (aerial)	0.21	0.92
	Lighting procedure (hand)	0.00	
	Job task (overall) ^b		0.007
	Job task (lighting)	-0.35	0.007
	Job task (holding)	0.042	0.76
	Job task (unclassified)	0.00	
CO	Intercept	0.37	0.09
	Burn size	0.000011	0.96
	Work-shift length	0.0013	0.04
	Wind speed	0.043	0.53
	Vegetation (overall)		0.04
	Vegetation (mixed hardwood)	-0.49	0.04
	Vegetation (pine)	0.00	
	Lighting procedure (overall)		0.23
	Lighting procedure (aerial)	0.35	0.21
	Lighting procedure (hand)	0.00	
	Job task (overall)		0.01
	Job task (lighting)	-0.43	0.02
	Job task (holding)	0.17	0.44
	Job task (unclassified)	0.00	
LG	Intercept	3.64	<0.0001
	Burn size	0.00038	0.26
	Work-shift length	-0.0015	0.21
	Wind speed	0.064	0.56
	Vegetation (overall)		0.045
	Vegetation (mixed hardwood)	-0.77	0.045
	Vegetation (pine)	0.00	
	Lighting procedure (overall)		0.89
	Lighting procedure (aerial)	-0.041	0.92
	Lighting procedure (hand)	0.00	
	Job task (overall)		0.06
	Job task (lighting)	-0.61	0.05
	Job task (holding)	0.11	0.77
	Job task (unclassified)	0.00	
LG:PM _{2.5} ratio	Intercept	0.31	<0.0001
	Burn size	0.000033	0.31
	Work-shift length	-0.00023	0.047
	Wind speed	0.00041	0.97

(Continued)

Table 2. *Continued*

Exposure marker	Variable	Parameter estimate	<i>P</i>
	Vegetation (overall)		0.05
	Vegetation (mixed hardwood)	-0.075	0.05
	Vegetation (pine)	0.00	
	Lighting procedure (overall)		0.92
	Lighting procedure (aerial)	0.014	0.75
	Lighting procedure (hand)	0.00	
	Job task (overall)		0.22
	Job task (lighting)	-0.042	0.15
	Job task (holding)	0.0061	0.85
	Job task (unclassified)	0.00	

^aContinuous variable: parameter estimate is the amount in log units by which exposure marker (PM_{2.5}, CO, LG, LG:PM_{2.5}) increases per unit increase in the variable.

^bCategorical variable: parameter estimate is the difference in the exposure marker (PM_{2.5}, CO, LG, LG:PM_{2.5}) in log units between the category of the variable and the intercept/default category of the variable.

any time during the study. Firefighters who had conducted holding for at least 75% of their work time at the fire line had the highest geometric mean exposures of 633 µg m⁻³ (95% confidence limits (CLs): 461, 869 µg m⁻³) and 2.0 p.p.m. (CLs: 1.3, 3.1 p.p.m.) for PM_{2.5} and CO, respectively (Figs 3 and 4). These were significantly different from the exposures experienced by the firefighters when most of their work time at the fire line was spent conducting lighting. However, it should be noted that holding and mop-up were conducted by various means including the use of four-wheel vehicles, utility vehicles, and on foot. The different means were classified together as single tasks for simplicity of analysis and sample size reasons.

Further analyses were conducted in order to examine whether the results would change when the exposure assignment criterion was modified. Whether the exposures were assigned to the tasks the firefighters had spent at least 51% or 100% of their time at the fire line performing, the exposures to both PM_{2.5} and CO when they were mostly conducting holding at the fire line remained higher than when they were mostly conducting lighting. As in the original analysis, exposures that did not meet either of the criteria were categorized as 'unclassified'. Since the firefighters spent at least 51% conducting mop-up during measurements (*n* = 4, 5, and 4 person-days for PM_{2.5}, CO, and LG, respectively), these exposures were assigned to mop-up under this criterion. Although not significantly different probably due to the small numbers of sample days, exposures to PM_{2.5}, CO, and LG when the firefighters spent at least 51% of their time at the

fire line conducting mop-up were also higher than when they spent at least 51% of the time lighting. [Supplementary Figs S1–S3](#) (available at *Annals of Occupational Hygiene* online) show the exposures by task and dominant vegetation of the compartment where the prescribed burn occurred when the 51% threshold was used for assigning exposures to task.

The lighting protocol at SRS involves lighting in strips perpendicular to the wind starting from the downwind side of the burn and progressing upwind. This in effect enables the firefighter performing lighting to consistently move slightly upwind of the resultant smoke plume. However, holding involves the maintenance of the fire within set boundaries, a task that often places firefighters in the path of the plume. Exposures when firefighters conduct mop-up are also expected to be higher than when they are lighting since this job task occurs after the major burning phase when smoldering is occurring. Geometric mean exposures to PM_{3.5} and CO were also higher for firefighters who conducted holding or mop-up in exposure assessment studies conducted during prescribed burns and wildfires in Western United States (Reinhardt and Ottmar, 2004).

The LG:PM_{2.5} ratio averaged 6.9% (95% CLs: 5.4, 8.5%) for all the person-day samples (*N* = 122; Table 1). The LG:PM_{2.5} ratios were variable among species of hardwoods or softwoods in experimental stove and fireplace wood-log combustion studies (Fine *et al.*, 2001, 2002a,b, 2004). However, Hays *et al.* (2002) had reported that the predominant fuel component consumed during prescribed fires consists of foliage, litter, and herbaceous matter. This is

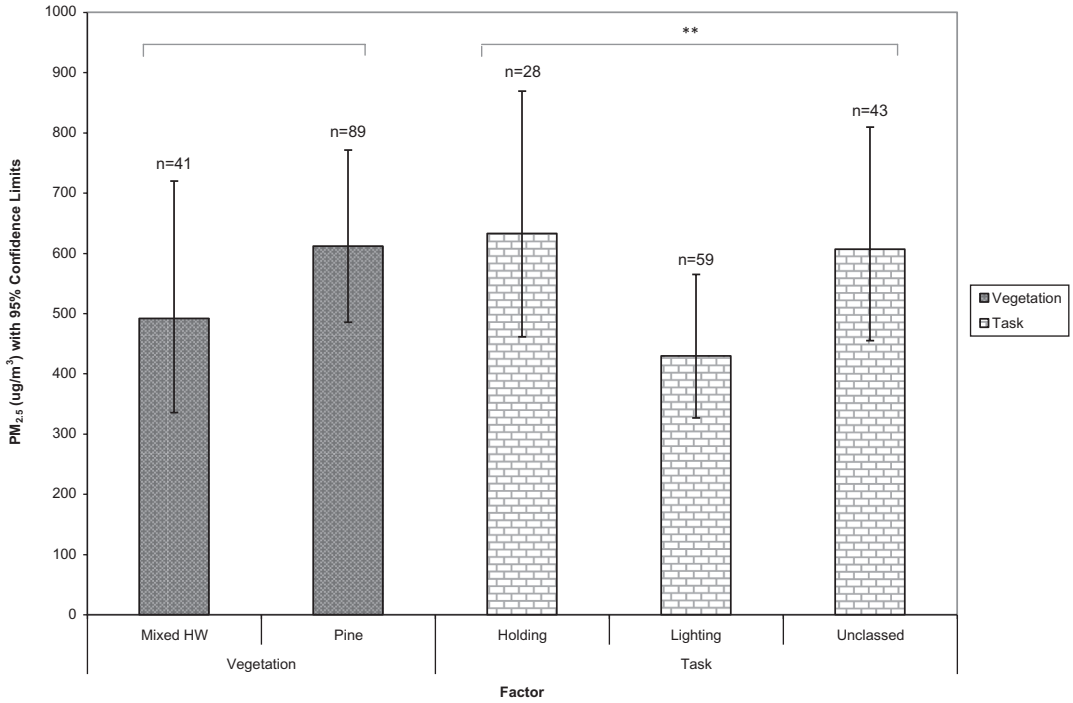


Fig. 3. Geometric mean personal work-shift TWA exposure to PM_{2.5} according to the vegetation type in the compartment of burn and according to the task the firefighter spent at least 75% of the work-shift duration performing. **, Difference is significant at $P = 0.01$. n = number of person-days.

consistent with the observation that prescribed fires at SRS are maintained on the ground and consumption of live wooded vegetation is avoided during the dormant winter season. The average LG:PM_{2.5} ratios that were observed for the vegetation types (7.3% and 3.8% for pine and mixed hardwood compartments, respectively) for this present study are comparable but higher than those reported for the experimental combustion of foliar fuels including biomass litter from forests in Florida (Hays *et al.*, 2002). The ratios observed in this study are also more variable, possibly due to the non-experimental nature of the study and the availability of other sources of PM at prescribed burns. Additionally, it has been shown in experimental studies that in addition to fuel type, combustion conditions such as the fire behavior (heading or backing fire) could affect the emission factors of LG when biomass is combusted (Engling *et al.*, 2006; Mazzoleni *et al.*, 2007). In this present study, the ratio was higher when burns were conducted in compartments with pine vegetation (7.3%; 95% CLs: 5.0, 10%) compared with when burns were conducted in the compartments with mixed hardwood

vegetation (3.8%; 95% CLs: 1.6, 7.1%). However, the difference was only marginally significant ($P = 0.05$). This result is consistent with the findings of an experimental study in which emission factors (LG:PM_{2.5}) from the combustion of foliar fuels of softwoods and biomass litter from forests dominated by softwoods were higher than the emission factor from the combustion of litter from a mixed hardwood forest (Hays *et al.*, 2002).

Geometric mean exposures to LG, PM_{2.5}, and CO were also higher when firefighters conducted prescribed burns in the pine forest compartments compared with the mixed hardwood forest compartments (Figs 3–5), although the difference for PM_{2.5} was not statistically significant ($P = 0.25$). Geometric mean exposures to CO and LG were significantly higher when the burn was conducted in compartments with pine vegetation (2.0 p.p.m.; CLs: 1.5, 2.6 p.p.m. and 30 $\mu\text{g m}^{-3}$, CLs: 18, 50 $\mu\text{g m}^{-3}$, respectively) compared with when the burns were conducted in compartments with mixed hardwood vegetation (1.2 p.p.m., CLs: 0.77, 1.9 p.p.m. and 14 $\mu\text{g m}^{-3}$, CLs: 6.4, 30 $\mu\text{g m}^{-3}$). Emission factors in the experiment involving the combustion

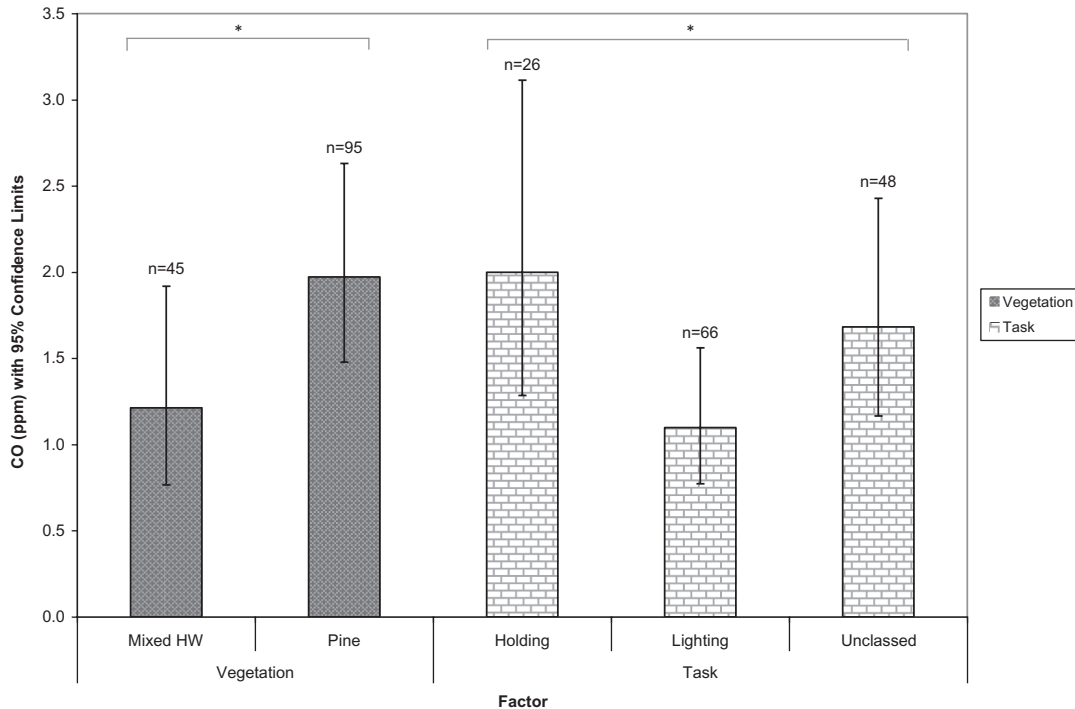


Fig. 4. Geometric mean personal work-shift TWA exposure to CO according to the vegetation type in the compartment of burn and according to the task the firefighter spent at least 75% of the work-shift duration performing. *, Difference is significant at $P = 0.05$. n = number of person-days.

of foliar fuels also resulted in higher emission of $PM_{2.5}$ per kilogram of biomass combusted for softwood compared with mixed hardwood (Hays *et al.*, 2002).

Work-shift length was associated with exposures to CO (positively) and the LG: $PM_{2.5}$ ratio (negatively). However, it is difficult to explain these results in terms of the burn characteristics since the firefighters often spent portions of their time at work away from the fire line. Therefore, the length of time spent at the fire line as reported by the firefighters in the time-activity diaries was not always equal to the length of the work shift over which exposure measurements were collected (Table 1). Exposure measurements were collected over the work-shift duration for logistical reasons as the researchers did not go to the fire line with the firefighters. Obvious periods of the work shift that was not spent at the fire line included the drive between the locations of the prescribed burns and the office base at the start and end of the work shift. In contrast to work-shift length, the fire line work time estimated from the time-activity diaries was not associated with any of the exposure markers when

it was included in the model instead of the work-shift length.

CONCLUSION

The work-shift exposures of wildland firefighters to particulate matter and CO did not exceed occupational exposure limits. However, these results, as those of previous studies, confirm that wildland firefighter experience elevated exposures to particulate matter. Furthermore, shorter term exposure limits for CO was exceeded in some instances. The exposures of the firefighters were affected by their job task and dominant vegetation of the compartment that was burned at the prescribed burns. Firefighters who performed holding or mop-up for the majority of their work time at the fire line had higher $PM_{2.5}$ and CO exposures than those who performed lighting and also exposures were higher when compartments that are dominated by pine were burned. Finally, the low ratios of LG to $PM_{2.5}$ for some of the samples suggest that their exposures to pollutants at prescribed burns could be substantially affected by non-woodsmoke sources.

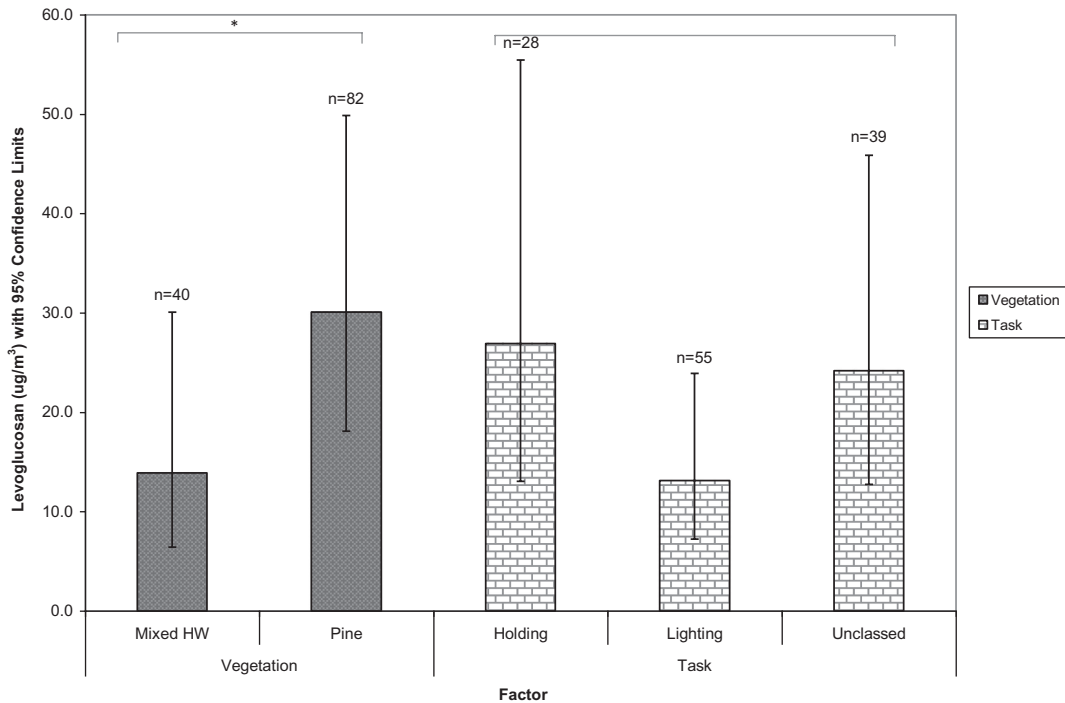


Fig. 5. Geometric mean particulate LG according to the vegetation type in the compartment of burn and according to the task the firefighter spent at least 75% of the work-shift duration performing. *, Difference is significant at $P = 0.05$. n = number of person-days.

SUPPLEMENTARY DATA

Supplementary data can be found at <http://annhyg.oxfordjournals.org/>.

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