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Original Article

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Differences in Fine Particle Exposure and Estimated Pulmonary Ventilation Rate with Respect to Work Tasks of Wildland Firefighters at Prescribed Burns: A Repeated Measures Study

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Abstract

Wildland firefighters (WLFFs) are exposed to a mixture of chemicals found in wildland fire smoke and emissions from nonwildland-fuel smoke sources such as diesel. We investigated compositional differences in exposure to particulate matter and explored differences in ventilation rate and potential inhaled dose relative to the work tasks of WLFFs. Repeated measures on ten professional and two volunteer firefighters were collected on prescribed burn and nonburn days. Personal monitoring consisted of real-time and gravimetric fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and accelerometer measurements to estimate ventilation rate and potential dose of $PM_{2.5}$. The fine particulate matter was analyzed for levoglucosan (LG) and light absorbing carbon as a surrogate for black carbon (BC). Breathing zone personal exposure concentrations of $PM_{2.5}$, LG, BC, and CO were higher on burn days ($P < 0.05$). Differences in exposure concentrations were observed between burn day tasks ($P < 0.05$) with firefighters managing fire boundaries (holders) being exposed to higher CO and LG concentrations and less BC concentrations than those conducting lighting (lighters). While no statistical difference in $PM_{2.5}$ exposure measures was observed between the two tasks, holders in the study tended to be exposed to higher $PM_{2.5}$ concentrations (~1.4×), while lighters tended to have more inhaled amounts of $PM_{2.5}$ (~1.3×). Our findings demonstrate possible diversity in the sources of

What's important about this paper

Exposure of wildland firefighters to respirable particulate matter during prescribed burns is heterogenous. This study demonstrates that heterogeneity in exposure between fireline tasks depends both on the concentration and composition of smoke particles from wood and nonwood combustion sources, and on the pulmonary ventilation rate of firefighters. Therefore, it is important that epidemiology studies consider the particle composition and inhaled dose in exposure-response studies of wildland firefighters.

particulate matter exposure at the fireline and suggest the potential importance of using dose as a metric of inhalation exposure in occupational or other settings.

Keywords: black carbon; exposure; inhaled dose; levoglucosan; light absorbing carbon; particulate matter; wildland firefighters

Introduction

In many regions, wildland firefighters (WLFFs) conduct prescribed burns for ecological benefits and mitigating against the occurrence of catastrophic wildfires. During prescribed burns, firefighters perform two primary work tasks: *lighting* and *holding*. Lighting is typically performed by hand using a diesel-gasoline fueled drip torch. Helicopters may be used to ignite the forest understory for larger burns. During holding, firefighters use water hoses and mule trucks to keep the fire from burning outside designated boundaries. Although prescribed burning is a key tool in forest management, exposures during burns are a concern for health (Adetona *et al.*, 2016). Respiratory protection is not frequently used nor feasible during wildland firefighting (Naeher *et al.*, 2007).

Respirable (including fine) particulate matter (PM) is identified as the primary health hazard of emissions from the combustion of organic matter, including wildland fire smoke (WFS) (Naeher *et al.*, 2007). Previous studies report that particulate matter (PM) exposure varies according to work tasks at prescribed burns (Reinhardt and Ottmar, 2004; Adetona *et al.*, 2011; Adetona *et al.*, 2013; Hejl *et al.*, 2013), and suggest that PM exposure and composition at burns may be impacted by other sources apart from WFS, e.g. drip torches, fire engine exhaust, and soil-derived dust (Adetona *et al.*, 2013; Hejl *et al.*, 2013; Reinhardt and Broyles, 2019). Black carbon (BC) is a component of PM and is formed during the process of incomplete combustion (Sasser *et al.*, 2012), while levoglucosan (LG) is a major pyrolysis product of wood combustion (Mazzoleni *et al.*, 2007). Different amounts of BC and LG may be associated with specific PM sources and different combustion phases at the fireline (Mazzoleni *et al.*, 2007; Sandradewi, Prévôt, Weingartner, et al., 2008; Sandradewi, Prévôt, Szidat, et al., 2008; Reisen *et al.*, 2018). Distinguishing PM sources can help to characterize occupational exposures more accurately for the development of suitable occupational health standards and exposure control for WLFFs.

The potential inhaled dose of air pollutants is related to physical exertion and minute ventilation that vary, and is dependent on the breathing route and the aerodynamic particle size. Therefore, risk estimations can be improved if potential dose rather than personal breathing zone measures is used to quantify PM exposure (Rodes *et al.*, 2012). A previous study piloted the use of a dual functioning personal aerosol monitor that measures fine particulate matter ($PM_{2.5}$) in real-time and gravimetrically, and collects accelerometry data that can be used to estimate pulmonary ventilation rate (Rodes *et al.*, 2012). Results indicated that linear regression could be used to predict ventilation rate from the accelerometer data over a range of activities, and that the approach could be applied for estimating the inhaled PM dose. Therefore, we investigated whether occupational exposure to fine PM and its components (BC and LG) differ with respect to work tasks, and explored the integration of accelerometry data and concentration measured in the breathing zone for estimating inhaled PM dose of WLFFs to WFS as part of a larger study of the occupational health impact of prescribed burns (Adetona *et al.*, 2017; Adetona *et al.*, 2019; Wu *et al.*, 2020).

Methods

Study design and population

Repeated measures were collected from 10 WLFFs employed by the United States Forest Service-Savannah River (USFS-SR), South Carolina and two volunteer firefighters. Subjects were healthy, currently nonsmokers, not pregnant, and at least 18 years old. Subjects signed an informed consent form approved by the Institutional Review Board at the University of Georgia (UGA), Athens, Georgia. Subjects were monitored for $PM_{2.5}$ and CO exposures on days when prescribed burning was conducted and work days when no prescribed burning occurred during the months of January–July 2015 at the United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina. Vegetation at the 800 km^2 site is mostly comprised of pines and mixed pines and hardwoods (Kilgo and Blake, 2005).

Questionnaires

Baseline questionnaires were administered to capture relevant information (e.g., age, weight, height, smoking status, etc.). Subjects responded to additional questionnaires each sampling day regarding their primary work task (defined as comprising > 50% of the work duration) and potential confounders (e.g., second-hand cigarette exposure). On burn days, lighting and holding were the tasks that were monitored. Activities on nonburn days included office work, patrolling, engine maintenance, and field prep. These were collectively categorized as 'nonburn day work tasks'. Duration of work-shifts, and size and date of burn were recorded by field technicians.

Gravimetric $PM_{2.5}$ sample collection and instantaneous real-time $PM_{2.5}$ measurement

Personal real-time and gravimetric $PM_{2.5}$ measurements were measured in the breathing zone of the subjects during their work-shifts using the MicroPEM (RTI International, Research Triangle Park, NC, USA). The MicroPEM measures continuous relative humidity-corrected $PM_{2.5}$ concentrations by nephelometry using a laser diode with a wavelength of 780 nm and collects $PM_{2.5}$ samples for subsequent off-line gravimetric determination. The upper detection limit of the real-time measurement is approximately 15 000 µg/m^3 but does vary with the size distribution and optical properties of sampled PM (i.e. 10 000 – > 30 000 µg/m^3). MicroPEMs were zero-calibrated before each sample was collected using a low-pressure drop HEPA filter and were set to run for 20 s/min (33% duty cycle) at a flow rate of 0.4 L/min using a mass flowmeter (TSI 4100 flowmeter; TSI Incorporated, Shoreview, Minnesota, USA). Gravimetric $PM_{2.5}$ samples were collected on pre-weighed 25-millimeter polytetrafluoroethylene (PTFE) membrane filters with a porosity of 3.0 µm (Pall Life Sciences, Ann Arbor, MI, USA). Integrated real-time $PM_{2.5}$ concentrations were calculated by averaging the nephelometer measurements over the sample duration. The instantaneous real-time measurements of each MicroPEM were adjusted with the ratio of its gravimetric $PM_{2.5}$ concentration for the sample to the integrated real-time $PM_{2.5}$ as a correction factor. Peak exposure concentrations were estimated as the 95th percentile of the filter-corrected real-time $PM_{2.5}$.

Gravimetric analysis

Pre- and post-sample filters were stored in a climate-controlled laboratory (20°C; 40% relative humidity) at UGA for 48 hours prior to weighing using a Cahn C-35 microbalance (sensitivity of ±1.0 µg; Thermo Electron, Waltham, MA, USA). The sample $PM_{2.5}$ weights were adjusted by subtracting the mean weight change of field blanks. Eleven field blanks (about 15% of all filter samples) had a mean weight change of 1.5 µg (standard deviation [SD]: 0.8 µg). Gravimetric $PM_{2.5}$ concentrations were determined as the weight of $PM_{2.5}$ on the filter per unit volume of air sampled. All gravimetric analyses followed United States Environmental Protection Agency (USEPA) specifications (USEPA, 2009).

Reflectance analysis

After gravimetric analysis, PTFE filters were shipped to the University of Washington for measurement of light absorbing carbon (LAC), which is a surrogate for BC. The reflectance of all sample filters was determined using the Evans Electroselenium Limited smoke stain reflectometer (Model 43D, Diffusion Systems Ltd, London, UK), which measures the reflection of incident light (linear scale; 0–100% reflectance). The instrument was recalibrated after each sample using the standard calibration plate with reference white and gray spots provided by the manufacturer. Absorption coefficient was calculated according to ISO 9835 (ISO, 1993):

$$a = \left(\frac{A}{2V}\right) \ln\left(\frac{R_b}{R_s}\right) \tag{1}$$

where a = absorption coefficient (m^{-1}), A = area of the sample (m^2), V = volume sampled (m^3), R_b = reflectance of a field blank filter, R_s = reflectance of a sample filter. Since pre-exposure measurements for the filters were not collected, R_b in equation (1) was determined as the average reflectance value of the field blank filters (69.3%; SD = 0.9%; percent coefficient of variation [%CV] = 1.3%). Absorption coefficients were multiplied by 10^5 to make the values more comprehensible (ISO, 1993). In addition, we calculated $PM_{2.5}$ mass absorption efficiencies in ×10^{-}5 m^2/µg as absorption (coefficient) per unit concentration of total $PM_{2.5}$. Precision of replicate measurements of reflectance on twenty-eight filters was determined (SD: 0.2; % CV: 0.5%), and samples with replicate measurements were averaged.

LG measurements

The procedure for levoglucosan analysis has been reported previously (Adetona *et al.*, 2013). In brief, after LAC analysis, filters were cut and placed in silane-treated headspace vials, spiked with a deuterated LG (d7-LG) internal standard, and then extracted by sonication in methylene chloride. The solvent was evaporated under N_2 in a Turbovap II concentrator, and the samples were reconstituted in a 3.6 mM solution of triethylamine in ethyl acetate containing anhydroheptulose, which was used to monitor the efficiency of derivatization. The extracts were filtered through a 0.2 µm PTFE syringe into silanized amber glass autosampler vials, then derivatized using methylsilyltrifluoroacetamide together with trimethylchlorosilane and pyridine and allowed to react in the dark for at least 6 hours. The derivatized extracts were introduced by splitless injection into the GC with a RESTEK Rtx-5sil column (RESTEK Corp., Bellefonte, PA, USA). LG was quantified using m/z peaks of 204 (LG) and 206 (d7-LG). The calibration range was 0–100 µg/ml. The limit of detection was 0.0025 µg per filter. LG recovery based on spiked quality control filters was 98%, and precision was ±6%.

CO measurements

Real-time CO was measured in the breathing zone using Dräger Pac III single gas monitors equipped with CO sensors (DrägerSafety Inc., Pittsburgh, PA, USA). The sensors were calibrated using pure nitrogen gas and a 100 ppm CO certified gas standard, and were programmed to log data in 30-s intervals.

Estimated pulmonary ventilation rate and inhaled dose

The MicroPEM's triaxial accelerometer activity measurements were used to estimate minute ventilation rate (L/min) according to the previously published linear regression equation ($V = m \times ACCEL + b$ where V = ventilation rate, m = experimentally determined slope, $ACCEL$ = composite variable computed from the triaxial accelerometer measurements, and b = intercept) (Rodes *et al.*, 2012). The accelerometer composite, which is a vector magnitude, was determined by the square root of the sum of the squares of accelerometer data in x-, y-, and z-axes in units of g (gravity) (Rodes *et al.*, 2012). Rodes *et al.* regressed the accelerometer data against a gold standard-derived ventilation rate using the Oxycon Mobile metabolic measurement system (Carefusion, Yorba Linda, CA, USA). MicroPEM accelerometer data were not calibrated against ventilation rates of firefighters in the current study. Therefore, we adopted the intercept of 10.7 L/min reported by Rodes *et al.* as the median resting ventilation rate (Rodes *et al.*, 2012). We also took a conservative approach to estimate the slope for the equation by setting the 95th percentile average ventilation rate by age, gender, and activity level reported by the USEPA in the Exposure Factor Handbook against values approximating the mean 95th percentile accelerometer composite (i.e. USEPA 95th percentile average ventilation rate = $m \times peak\ ACCEL + 10.7$) (USEPA, 2011). The mean 95th percentile accelerometer composite for nonburn day tasks, holding, and lighting were 0.22 ± 0.09, 0.24 ± 0.06, and 0.41 ± 0.06, respectively. Therefore, 0.2 for holding and non-burn day activities and 0.4 for lighting were substituted for '*peak ACCEL*' in the equation. To account for the added weight of backpacks and drip torches used by firefighters lighting fires, we used USEPA's 95th percentile average ventilation rate for high intensity activities (Metabolic Equivalents [METS] > 6.0). Since holding, which involved patrol of the burn boundary in fire trucks and occasional wetting of the fireline, and nonburn work day activities had similar peak accelerometer composites, we used USEPA's 95th percentile average ventilation rate for light intensity activities (1.5 < METS ≤ 3.0). The composite data were used as the $ACCEL$ variable in the slope-adjusted equations to determine the estimated ventilation rates in real-time. To calculate an average ventilation rate, the sum of the estimated ventilation rates in real-time was divided by the number of time points measured. Potential inhaled dose of $PM_{2.5}$ (µg) was calculated by multiplying $PM_{2.5}$ exposure concentrations by the total volume of air inhaled which was obtained from the estimated ventilation rates. $PM_{2.5}$ dose was determined as inhaled $PM_{2.5}$ mass per unit body weight of subject (µg/kg body weight).

Statistical analyses

Gravimetric and filter-corrected real-time peak (average of the 95th percentile) $PM_{2.5}$, CO, absorption coefficient, ventilation rates and estimated inhaled exposure data were log-transformed, and mass absorption efficiencies (all were between 0 and 1) were arcsine-square-root-transformed to normalize these outcome variables (McDonald, 2009). Based on the residuals of fitted models, log- and arcsine-square-root-transformations did not normalize the LG concentrations, so their ranked values were used in the models.

After gravimetric $PM_{2.5}$ concentrations were blank corrected, ten sample filter weights were below or at zero. These were collected on nonburn work days, from a firefighter performing aerial ignition, or during the shortest burn of the summer season. Therefore, the instrument sensitivity (Cahn C-35 Microbalance) of 1.0 µg divided by the square root of two was used in such situations before $PM_{2.5}$ concentrations were calculated. Several integrated or shift average CO concentrations were zero, all of which were measured on nonburn days. These were replaced by one half of the smallest positive observed shift average value (0.00068 ppm) before log-transformations since the reading range for the CO instrument is between 1 and 2000 ppm. Two nonburn day absorption coefficients were below zero and were replaced with the LOD divided by the square root of two (LOD: 0.076×10^{-5}/m, assuming a 1 m^3 nominal sample volume). Filter LG weights in all samples collected on nonburn days and in 14 samples on burn days were below the LOD and were replaced by the LOD (0.0025 µg per filter) divided by the square root of two prior to calculating the LG concentrations.

Primary analyses consisted of using linear mixed-effects models (LMEM) to test the effect of work task on gravimetric $PM_{2.5}$, filter-corrected real-time peak (average of the 95th percentile) $PM_{2.5}$, CO, absorption coefficient, LG concentrations, ventilation rates, and estimated inhaled exposure/dose. Activities on nonburn days consisted of office work, patrolling, engine maintenance, and field prep work and were initially all categorized into one variable, 'Nonburn day work tasks'. However, in some instances, subjects' self-reported exposures during nonburn day work task, and patrolling on non-burn days could have resulted in smoke exposure from smoldering in portions of a previous burn. So, 'nonburn day work tasks' was recategorized into 'nonburn day exposure' and 'nonburn day office'. Apart from smoke from patrolling, 'nonburn day exposure' included exhaust from fire engines and dust during field prep work. 'Nonburn day office' tasks involved primarily work in the office and included one person-day when a firefighter did not report his primary work task on a nonburn day.

Subject and date of sample collection were treated as random effects in the models to account for longitudinal within-subject correlation and for possible heterogeneity from day to day in the data. Covariates including season (winter or summer), burn size, and sample/work-shift duration) were tested individually in the models, and then evaluated based on the forward elimination procedure with only significant covariates included in the final model. The effect of sample duration was not applied as a covariate when the dependent variable was ventilation rate or potential dose of $PM_{2.5}$ since sample duration is used to calculate both. Day type (burn and nonburn day) was not tested in the models since it is correlated with work task. LMEM and simple linear regression were fit to test the associations between absorption coefficients or LG weight/volume concentrations, and gravimetric $PM_{2.5}$ concentrations. All statistical analyses were conducted using SAS v.9.4 (SAS Institute, Cary, NC, USA). Statistical significance was set at P-value < 0.05 and adjusted using the Bonferroni method when doing multiple comparisons.

Results

Study population

The mean age of the subjects was 33 ± 5.4 years and 75% were male. None of the firefighters used any form of respiratory protection during the study, and none reported second-hand tobacco smoke exposure at home or work. Fifty-four person-day samples (35 in winter and 19 in summer) were collected from the 12 subjects working on 7 prescribed burn days (4 in winter and 3 in summer) during the study period. Twenty-one person-day samples (13 in winter and 8 in summer) were collected from 8 subjects during 3 nonburn days (2 in winter and 1 in summer). Information about size of the area that was burned (burn size), length of work-shift, and the means and/or the minimum and maximum concentrations for $PM_{2.5}$, its components and CO without controlling for any covariate are provided in Table 1. Corresponding exposure measurement results from prior SRS studies are also listed in the Table for comparison.

Five real-time and gravimetric $PM_{2.5}$ samples were excluded from statistical analyses due to random pump failures on three different burn days and one gravimetric $PM_{2.5}$ sample due to poor O-ring. One CO sample was not collected due to equipment loss in the field.

Covariates

There was no seasonal or burn size effect on geometric mean gravimetric $PM_{2.5}$ concentrations ($P = 0.84$ and $P = 0.26$, respectively). However, results indicated that sample duration was positively associated with gravimetric $PM_{2.5}$ ($P = 0.095$), and it was included in the final mixed model with the main effect of work task. The above finding of significance in relationship with duration held true for CO and mass absorption efficiency. Ranked LG concentration in weight/volume ($P = 0.004$ and 0.007, respectively) and LG per PM weight concentrations ($P = 0.007$ and 0.001) increased with sample

Table 1. Geometric means for exposure monitoring without controlling for covariates and a comparison between previous exposure assessment studies conducted at Savannah River Site.

Exposure	Geometric mean (95% confidence intervals)[a]	Minimum	Maximum	Number of person-days
2015 (Present Study)				
Samples from burn days				
Overall gravimetric $PM_{2.5}$ (μg/m³)	240 (179, 321)	11	1859	48
Winter	266 (185, 382)	11	1859	29
Summer	205 (122, 345)	48	1086	19
Overall integrated real time $PM_{2.5}$ (μg/m³)	175 (139, 221)	8	787	49
Winter	192 (140, 261)	8	787	30
Summer	153 (105, 222)	33	680	19
Overall carbon monoxide (ppm)	0.9 (0.6, 1.2)	0.02	9.0	53
Winter	1.2 (0.8, 1.7)	0.04	9.0	33
Summer	0.6 (0.3, 1.1)	0.02	6.8	20
Overall absorption coefficient (surrogate for BC) (10^{-5} m^{-1})	46.5 (33.0, 65.5)	1.6	339	48
Winter	41.0 (27.5, 61.0)	1.6	128	29
Summer	56.4 (29.2, 108.6)	4.5	339	19
Overall mass absorption efficiency (BC to $PM_{2.5}$) (10^{-5} m^{-2})	0.25 (0.19, 0.31)	0.03	0.87	48
Winter	0.18 (0.13, 0.23)	0.04	0.52	29
Summer	0.36 (0.23, 0.49)	0.03	0.87	19
Overall Levoglucosan/volume of air (μg/m³)	NC	0.03	166	48
Winter	NC	0.03	166	29
Summer	NC	0.07	83.1	19
Overall Levoglucosan/weight PM (μg/μg)	NC	0.0008	0.11	48
Winter	NC	0.0008	0.11	29
Summer	NC	0.002	0.08	19
Overall burn size (acres/’000 square meters)	280/1133	38/153	1000/4047	
Winter	350/1416	111/449	1000/4047	
Summer	161/651	38/153	392/1586	
Overall duration of work shift at fireline (h)	4.5	1.9	9.3	
Winter	5.3	3.2	9.3	
Summer	3.1	1.9	4.4	
Samples from Non Burn Days				
Gravimetric $PM_{2.5}$ (μg/m³)	42 (30, 60)	14	158	21
Integrated Real Time $PM_{2.5}$ (μg/m³)	13 (9, 17)	3	31	21
Carbon monoxide (ppm)	0.006 (0.002, 0.014)	0	0.8	21
Absorption coefficient (surrogate for BC) (10^{-5} m^{-1})	0.8 (0.5, 0.11)	0.1	3.3	21
Mass absorption efficiency (BC to $PM_{2.5}$) (10^{-5} m^{-2})	0.03 (0.01, 0.04)	0.002	0.15	21
Levoglucosan (μg/m³)	NC	ND	ND	21
Levoglucosan/weight PM (μg/μg)	NC	ND	ND	21
Duration of work shift (h)	6.2	3.9	7.8	21
2011 (Adetona 2011)				
Gravimetric $PM_{2.5}$ (μg/m³)	608 (481, 767)			41
Integrated real time $PM_{2.5}$ (μg/m³)	920 (779, 1088)			37
Carbon monoxide (ppm)	3.9 (3.2, 4.5)			58
Duration of work shift at fireline (h)	6.2	1.5	10.2	
2009–2008 (Adetona *et al.* 2013)				
Gravimetric $PM_{2.5}$ (μg/m³)	530 (476, 591)	64	2068	130
Carbon monoxide (ppm)	1.5 (1.3, 1.7)	0.02	8.2	140
Levoglucosan (μg/m³)	20 (16, 29)	0.04	291	122

Table 1. Continued

Exposure	Geometric mean (95% confidence intervals)[a]	Minimum	Maximum	Number of person-days
Levoglucosan/weight PM (µg/µg)	0.07 (0.05, 0.09)	0.00008	0.61	122
Burn size (acres/'000 square meters)	910/3683	80/323	3300/13356	
Duration of work shift at fireline (h)	5.5	2	11	
Duration of Work Shift (h)	7.9	3	15	
2003–2005 (Adetona *et al.* 2011)				
Samples from Burn Day[i]				
Gravimetric $PM_{2.5}$ (µg/m³)	264 (221, 316)	5.9	2673	177
Carbon monoxide (ppm)	1.0 (0.09, 11.6)	<1	14	134
Burn size (acres/'000 square meters)	697/2821	1/4	2745/11109	
Duration of work shift (h)	10.3	6.8	19.4	
Samples from Non Burn Days				
Gravimetric $PM_{2.5}$ (µg/m³)	16 (12, 20)			35
Duration of work shift (h)	9.3	7	11.5	

[a]Arithmetic means for burn size and work shift duration. Arcsine-square root back-transformed values for mass absorption efficiency.
NC—not calculated—not enough samples with concentrations above detection to calculate a mean value.
ND—not detected—all sample with below detection limit concentrations.

duration and decreased with burn size, and both were included in the final mixed models for the main effect of work task on the LG concentrations.

Breathing zone exposure concentrations according to work task

Firefighters did not consistently perform the same dominant task across the burn day work shifts. Two firefighters performed ignition by helicopter on one of the burn days (two person-days) and these were included in the lighting category. Participants on four person-days self-reported spending 50% of the work-shift performing holding and 50% lighting. These samples were included in the lighting category since a significant amount of time was spent using the drip torch. Therefore, burn day work tasks performed by the subjects were categorized into holding and lighting.

Overall, the gravimetric $PM_{2.5}$ concentration depended on work task ($P = 0.0004$). Gravimetric $PM_{2.5}$ concentration was not significantly different between holding and lighting, but exposure during either of the burn day tasks was higher than that experienced during the nonburn day tasks (Fig. 1a). 'Nonburn Day exposure' gravimetric $PM_{2.5}$ concentration was significantly lower compared to 'nonburn day office' ($P = 0.02$).

Similar results were observed for filter-corrected real-time peak $PM_{2.5}$ concentration, which was calculated as the mean of the instantaneous concentrations in the 95th percentile (nonburn day office: 216 [78, 602] µg/m³; nonburn day exposure: 106 [41, 270] µg/m³; lighting: 2578 [1389, 4785] µg/m³; holding: 2295 [1115, 4727] µg/m³). Interestingly, we observed that the peak exposures covering 5% of the sample work-shift length for lighting resulted in an average of 63% (Range: 41–84%) of the total $PM_{2.5}$ exposure during a burn work-shift, while it accounted for 45% (Range: 20–77%) of the exposure for holding, 28% (Range: 13–89%) of the nonburn day exposure, and 21% (Range: 11–32%) of the nonburn day office exposure.

CO concentration was dependent upon work task ($P < 0.0001$) and was significantly higher for holding compared to lighting ($P = 0.03$) (Fig. 1b), and did not differ between nonburn day exposure and office work tasks ($P = 1.0$). Light absorption coefficient and mass absorption efficiency were also work task dependent ($P < 0.0001$) (Fig. 2). Contrary to $PM_{2.5}$ and CO concentrations, lighting had nearly a threefold and more than five times higher mean light absorption coefficient ($P = 0.003$) and mass absorption efficiency ($P < 0.0001$) compared to holding, respectively (Fig. 2). No significant difference was observed between nonburn day exposure and office work tasks for both BC-related measures, although, the mean mass absorption efficiency was 1.8 times higher for nonburn day exposure.

Contrary to the BC measures, ranks of weight/PM weight LG exposure concentrations were higher for holding compared to lighting ($P = 0.001$). Also, LG concentrations for either of the burn day task were significantly higher compared with the nonburn day exposure

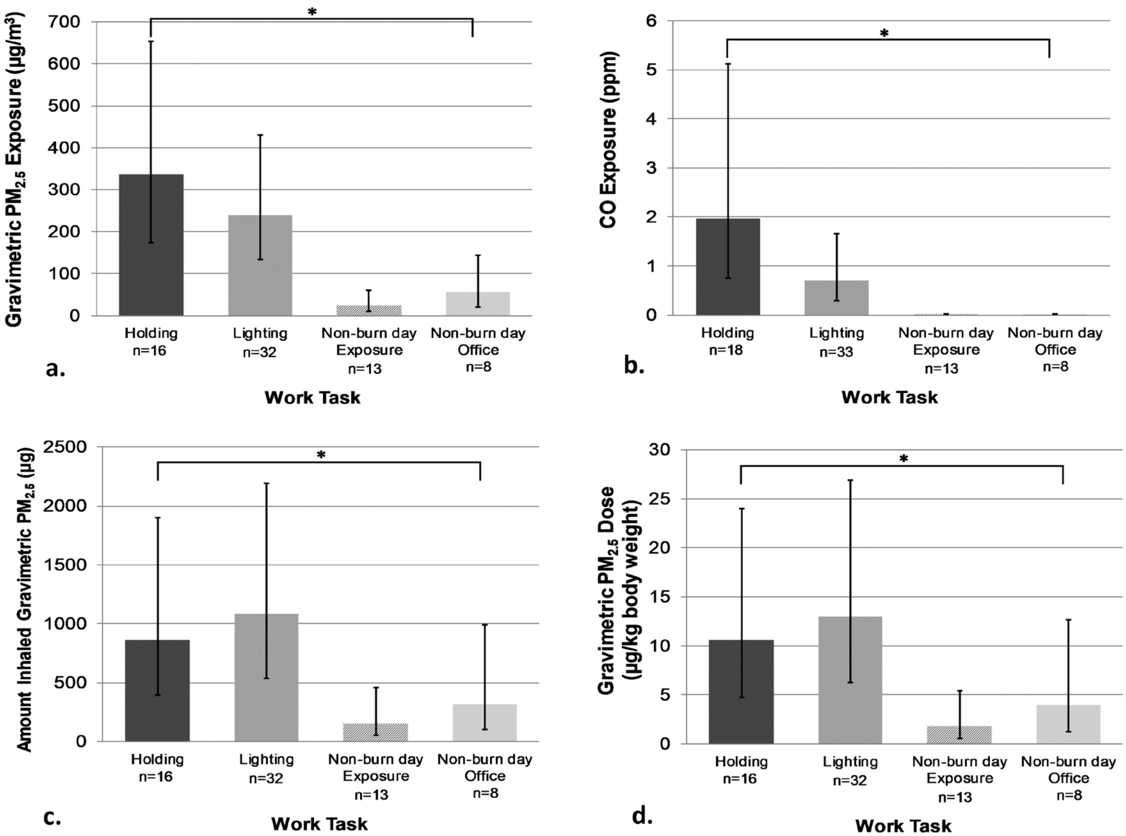

Figure 1. (a–d) Model derived geometric mean exposures concentrations of gravimetric $PM_{2.5}$ and integrated/shift average CO, estimated inhaled amount and dose concentrations of gravimetric $PM_{2.5}$ with control for covariates (a–d, respectively). Person-days are indicated as *n*. *Overall effect of work task is significant, $P < 0.05$.

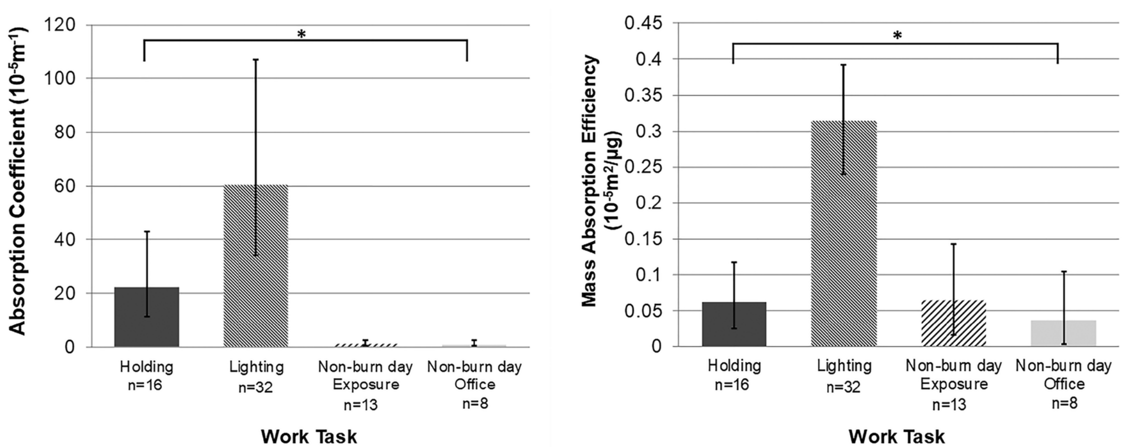

Figure 2. Model derived geometric mean light absorption coefficients (surrogate for black carbon) and backtransformed mean of arcsine-square-root-transformed mass absorption efficiencies (light absorption coefficient divided by gravimetric $PM_{2.5}$ concentration) by work task. Person days are indicated as *n*. *Overall effect of work task is significant, $P < 0.05$.

or office task ($P < 0.0001$ for all comparisons), while no difference was observed for both LG concentrations when the nonburn day tasks were compared.

There was a significant positive correlation between log-transformed light absorption coefficients and gravimetric $PM_{2.5}$ concentrations (Fig. 3) (LMEM results: $P < 0.0001$). The relationship appears to depend on work tasks with lighting having a higher slope compared to holding ($y = -0.7865 + 0.9229x$, $R^2 = 0.64$, and $y = -0.8810 + 0.7071x$, $R^2 = 0.81$, respectively) and an apparent clustering of data according to work task can be seen (Fig. 3). Ranked LG weight/volume and gravimetric $PM_{2.5}$ concentrations were also positively correlated (LMEM result: $P < 0.0001$).

Ventilation rates and potential inhaled dose estimations

As expected, the estimated ventilation rate depended on work task ($P < 0.0001$) (Fig. 4). Lighters, including the two subjects who lighted from the helicopter whose ventilation rates were calculated assuming low activity level tasks, had higher mean ventilation rate compared to holders or the nonburn day tasks ($P < 0.0001$) (Fig. 4), and there were no differences between the other tasks. Estimated inhaled mass and dose of $PM_{2.5}$ were also dependent on task ($P = 0.02$ and $P = 0.02$, respectively) (Fig. 1c and d). Though not different from holders, both inhaled mass and dose of $PM_{2.5}$ was highest for lighters.

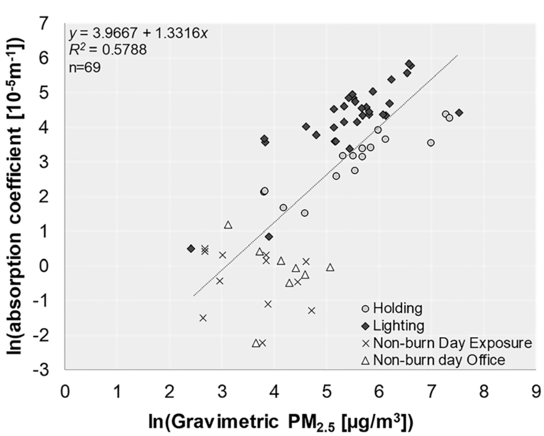

Figure 3. Correlation between log-transformed light absorption coefficients (surrogate for black carbon) and log-transformed gravimetric $PM_{2.5}$ concentrations. Linear regression result is provided on top left-hand corner of the graph. Linear mixed-effect model results was also statistically significant ($P < 0.0001$). Person days are indicated as *n*.

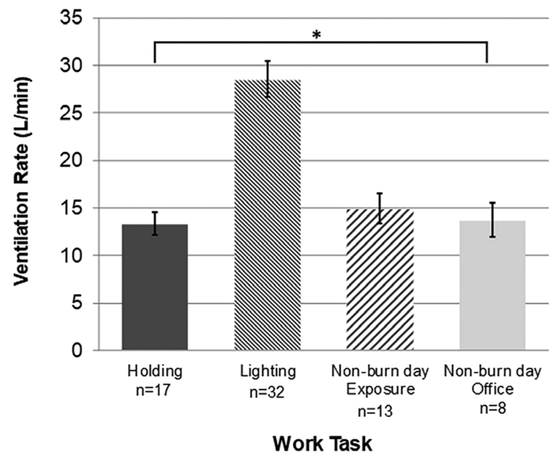

Figure 4. Model derived geometric mean estimated ventilation rates by work task. Person days are indicated as *n*. *Overall effect of work task is significant, $P < 0.05$.

Discussion

Combustion derived smoke including WFS consists of hundreds of chemicals with PM identified as its primary health hazard (Naeher *et al.*, 2007; Adetona *et al.*, 2016). Therefore, establishing methods to characterize PM exposure and its sources is relevant to the development of suitable occupational health standards. Results from past studies suggest that work tasks of WLFFs during prescribed burns may be associated with differences in the composition of the PM to which the WLFFs are exposed (Naeher *et al.*, 2007; Adetona *et al.*, 2013). Combustion phases and non-WFS sources, such as soot from drip torches, exhaust from fire engines, and mineral dust from suspended soil may significantly contribute to PM exposure (Reinhardt and Ottmar, 2004; Sandradewi, Prévôt, Szidat, et al., 2008; Du *et al.*, 2014; Reisen *et al.*, 2018). Increased efforts and novel approaches are required to identify and quantify components of PM and determine associated health effects with respect to the varying sources.

Micro-PEM was selected to use in this study for its light weight and dual capacity to concurrently measure gravimetric and real-time $PM_{2.5}$, and collect real-time accelerometer, humidity, and temperature data. However, these humidity and temperature data are not reported here since the measurements were collected within the breathing zone of the individual firefighter on-board the aerosol monitor and may be more reflective of micro-environment conditions and less representative of the general ambient environment. Till date, the Micro-PEM has been used in a variety of settings including household air pollution studies in low- and middle-income countries, as well as in high and low BC environments (Cho *et al.*, 2016; Lei *et al.*, 2016; Phillips *et al.*, 2016; Sloan *et al.*, 2016; Wang *et al.*, 2016; Wyss *et al.*, 2016; Chartier *et al.*, 2017; Olopade *et al.*, 2017; Sloan *et al.*, 2017; Wang *et al.*, 2017). For reference purposes, its performance as a personal exposure monitor has also been tested in previous validation studies by Chartier *et al.* and the USEPA (Williams *et al.*, 2014; Chartier *et al.*, 2017).

Overall higher exposures on burn days were reported in previous SRS studies compared to the current study (Adetona, 2011; Adetona *et al.*, 2013; Hejl *et al.*, 2013). The lower exposure concentrations that were observed in our current study could be due to shorter duration of work shift at the fireline, exclusive use of enclosed vehicles to conduct holding operations as opposed to mule trucks that firefighters had used in previous years, and the nonobservation of summer burns in previous studies. In addition, the average burn size during the current study was at least 2.5 times smaller than those performed during previous studies.

Although integrated CO concentrations were higher during holding, gravimetric and integrated real time $PM_{2.5}$ concentrations in our study were not significantly different between holding and lighting, as opposed to what had been observed in previous studies (Adetona *et al.*, 2013; Hejl *et al.*, 2013). These findings may be due to the exclusive use of fire truck engines to perform holding as opposed to the unenclosed mule utility vehicles that were used in previous years.

Several studies have quantified BC using aethalometers (Weingartner *et al.*, 2003; Sandradewi, Prévôt, Weingartner, et al., 2008; Sandradewi, Prévôt, Szidat, et al., 2008; Kirchstetter, 2014); however, few studies have measured LAC contribution to $PM_{2.5}$ by reflectance (Kinney *et al.*, 2000; Kajbafzadeh *et al.*, 2015). Although there are limited comparisons, our study appears to have considerably higher (in some instances 25 times higher) LAC measurements from $PM_{2.5}$ at prescribed burns compared to $PM_{2.5}$ samples that were collected in highly polluted neighborhoods in New York City (Kinney *et al.*, 2000) and in traffic- and wood smoke-impacted cities in Vancouver, British Columbia, Canada (Kajbafzadeh *et al.*, 2015). To the best of our knowledge, our study is the first to differentiate PM LAC by work tasks conducted at wildland fires. While exposures to $PM_{2.5}$ and CO during lighting were respectively not statistically different or lower compared to holding, it was apparent that exposure to BC and its concentration in $PM_{2.5}$ (mass absorption efficiency) were higher for firefighters who performed lighting (Figs 2 and 3). Contrarily, holders had higher LG exposure concentration and LG content in $PM_{2.5}$ compared to lighters, which is similar to the results of a previous SRS study (Adetona *et al.*, 2013). These results are indicative of the different combustion sources at the fireline and the relative positioning of holders vs. lighters relative to a dominating combustion phase. Holding is mostly performed downwind of the prescribed burn where $PM_{2.5}$ exposure may be more likely to be dominated by smoldering, rather than flaming, combustion of vegetation. LG is a major pyrolysis product of burning vegetation and smoldering combustion more dominantly contributes to its emission (Mazzoleni *et al.*, 2007; Reisen *et al.*, 2018). On the other hand, emission from diesel combustion, such as with the drip torch used by the lighters, has a higher BC content compared to the burning of vegetation (Sandradewi, Prévôt, Szidat, et al., 2008; Du *et al.*, 2014). While particle morphology was not assessed in this study, visual differentiation of PM collected on personal air sample filters further confirmed our analytical results. PM on filters collected from firefighters conducting lighting appeared black, while PM from holding appeared brown in color. The observed differences in PM composition may have implication for the type and degree of toxicity elicited by exposure to the particles (Kocbach, Herseth, et al., 2008; Kocbach, Namork, et al., 2008). Furthermore, BC content was the only exposure measure correlated with acute cross-shift changes in urinary mutagenicity and inflammatory biomarker interleukin-8 in the study of acute responses to occupational firefighting exposure of the same cohort that has been reported elsewhere (Adetona *et al.*, 2017; Adetona *et al.*, 2019).

Physical exertion is expected to vary significantly across tasks performed by WLFFs at prescribed burns and wildfires. Therefore, we explored how differing pulmonary ventilation rate across tasks might impact exposure assessment in terms of the amount of $PM_{2.5}$ that is inhaled relative to its exposure concentration. Our estimated ventilation rates accounted for gender, age, activity levels relative to work tasks, and the effect of load burden. We estimated a mean ventilation rate of 29 ± 1.0 L/min for the lighters who carry a backpack weighing approximately 11–20 kg (25–45 lbs.) and a fuel torch (~6.8 kg when full [15 lbs.]) while hiking during the majority of their work-shift. Our method for estimating the ventilation rates in this study yielded conservative yet realistic estimates. The estimates are comparable to ventilation rates reported for subjects performing arduous activities in previous studies. A mean ventilation rate of 38 ± 2.1 L/min was calculated for healthy men carrying a 15 kg (33 lbs.) backpack who walked at a pace of 4.3 km/h (2.5 mph) on a treadmill that was inclined at 10% (Dominelli *et al.*, 2012). Furthermore, a mean ventilation rate of 41 ± 8 L/min (Range: 24–59 L/min) was calculated for WLFFs who built fire-lines with a rake hoe at a slow pace (Brotherhood *et al.*, 1997).

While the differences were not significant, we observed that the inhaled mass of gravimetric $PM_{2.5}$ of lighters was 1.3 times higher compared to the holders' but the breathing zone $PM_{2.5}$ exposure concentration of the lighters was 1.4 times less than that of the holders. The differences in inhaled amount of WFS and WFS dose may have even been further increased if firefighters had worked longer shifts at prescribed burns or had our approach of estimating ventilation rates not been as conservative. The disparity between the exposure concentration and the potential dose also demonstrates the limitation of the use of airborne concentrations to assess the occupational exposures of WLFFs and of the application of the current Occupational Safety and Health Administration standard for *Particulates Not Otherwise Regulated* to their exposure at the fireline. It also indicates there may be a need to determine appropriate respiratory protection for WLFFs who currently typically do not use any (Naeher *et al.*, 2007). Finally, a significant amount of the total exposure (63% and 45% for lighting and holding, respectively) was attributed to only 5% of a given work-shift on burn days. These results have implications for mitigation strategies, as reduction in exposure might be achieved through temporary avoidance of smoke or use of a mask coupled with alarm-activated sensors to alert firefighters of high exposures as suggested by Edwards *et al.* (2005).

Limitations

Additional weight-load while performing lighting and its effect on ventilation rate could not be directly captured in this study, therefore we had to account for it using an assumed effect. Furthermore, no physiological modeling was conducted in the calculation of dose. However, using slope-adjusted linear equations enabled us to estimate credible ventilation rates according to activity level, gender, and age. We believe these estimates to be realistic, albeit conservative, during prescribed burning. Substantial uncertainty may exist in individual-level accelerometry-based estimates of ventilation rates when subjects perform multiple fire operations resulting in alternating body burdens throughout a day. Rodes *et al.* noted that for high intensity tasks (METS >10), the relationship between accelerometry and ventilation rate can be nonlinear, although when and how nonlinearities become apparent is still unclear (Rodes *et al.*, 2012). Furthermore, reliance on the USEPA's Exposure Factor Handbook values does not necessarily account for the likely superior physical fitness of firefighters. Furthermore, the estimation approach assumes a 100% aerosol deposition efficiency for the inhaled PM, which is typically not the case (Koullapis *et al.*, 2020). Although, our estimation of potential dose has limitations as outlined above, we believe our approach to be a good starting point for future work on occupational exposures during high activity level tasks and their association with health effects. To better estimate ventilation rates, future studies may consider doing an actual in-field subject calibration of the accelerometer by having subjects, or a subset thereof, perform scripted activities while directly measuring ventilation rate. Furthermore, light absorption coefficients measured in the current work could not be converted into units of mass concentration since the conversion factors are source specific and no transformation was available for the PM filters used in our study. Also, the lack of real time documentation of the firefighter tasks at the fireline limited our ability to further explore the real time $PM_{2.5}$ and CO data beyond determining peak exposures. The statistical insignificance in the difference of $PM_{2.5}$ exposure between the two fireline tasks was probably because of the small sample size. We had detected differences between holding and lighting in a previous study with a sample size that was almost two times the one used for the current study (Adetona *et al.*, 2013). The lower level of granularity applied in categorizing the tasks could have also reduced the ability to detect a task difference. Nonetheless, the classification, which is based on post-shift self-report, was validated by the more objective accelerometer composite data.

Conclusion

Similar to previous studies, we observed that breathing zone exposure concentrations of CO, and gravimetric $PM_{2.5}$ and its components were dependent on the tasks performed by WLFFs at prescribed burns. These results suggest that emissions from nonwildland-fuel combustion sources, such as exhaust from fire engines and soot from drip torches, may significantly contribute to PM exposures of WLFFs at prescribed burns. Meanwhile, estimated inhaled amount of gravimetric $PM_{2.5}$ revealed that the use of breathing zone concentrations may underestimate actual exposure. Our study is the first to apply accelerometer data to estimate ventilation rates and inhaled $PM_{2.5}$ amount and dose of WLFFs. Even with some uncertainty, the ability to account for ventilation rate to estimate potential inhaled dose instead of the traditionally used air exposure concentration should result in more accurate assessment of the associations between exposures and biological responses. Future studies looking at PM exposure-health responses in the occupational setting may consider adopting ventilation estimation methods.

SUPPLEMENTARY DATA

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

There are no potential conflicts of interest and the authors have nothing to disclose.

Data availability

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

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