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Exposure to Particulate Matter and Estimation of Volatile Organic Compounds across Wildland Firefighter Job Tasks

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ABSTRACT: Wildland firefighters are exposed to smoke-containing particulate matter (PM) and volatile organic compounds (VOCs) while suppressing wildfires. From 2015 to 2017, the U.S. Forest Service conducted a field study collecting breathing zone measurements of PM_4 (particulate matter with aerodynamic diameter ≤ 4 μm) on wildland firefighters from different crew types and while performing various fire suppression tasks on wildfires. Emission ratios of VOC (parts per billion; ppb): PM_1 (particulate matter with aerodynamic diameter ≤ 1 μm; mg/m^3) were calculated using data from a separate field study conducted in summer 2018, the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption, and Nitrogen (WE-CAN) Campaign. These emission ratios were used to estimate wildland firefighter exposure to acrolein, benzene, and formaldehyde. Results of this field sampling campaign reported that exposure to PM_4 and VOC varied across wildland firefighter crew type and job task. Type 1 crews had greater exposures to both PM_4 and VOCs than type 2 or type 2 initial attack crews, and wildland firefighters performing direct suppression had statistically higher exposures than those performing staging and other tasks (mean differences = 0.82 and 0.75 mg/m^3; 95% confidence intervals = 0.38−1.26 and 0.41−1.08 mg/m^3, respectively). Of the 81 personal exposure samples collected, 19% of measured PM_4 exposures exceeded the recommended National Wildland Fire Coordinating Group occupational exposure limit (0.7 mg/m^3). Wildland fire management should continue to find strategies to reduce smoke exposures for wildland firefighters.

KEYWORDS: *smoke, wildfire, hazardous air pollutants, occupational exposure, firefighter*

INTRODUCTION

Across the United States, large wildfires have occurred nearly 5 times more frequently on an annual basis compared to 50 years ago.[1,2] These wildfires are burning more acres of land and require longer fire suppression campaigns.[3] Wildfire smoke is a common workplace exposure for wildland firefighters, as they work long shifts under arduous conditions and do not have respiratory protection available.[4] Conducting exposure assessments on wildland firefighters can be difficult due to the highly variable conditions in the fire environment, arduous and emergency work conditions, and remote locations.

Past exposure assessments of wildland firefighters have measured acrolein, benzene, carbon dioxide, carbon monoxide (CO), formaldehyde, polycyclic aromatic hydrocarbons, and fine (aerodynamic diameters <2.5 μm) and respirable (aerodynamic diameters <4 μm) particulate matter (PM) from exposure to wildland fire smoke.[5] Additionally, firefighters can be exposed to mineral contaminants, such as crystalline silica, during soil-disturbing work activities.[6] Exposure to smoke can be influenced by different factors in the wildfire environment. In a previous assessment conducted by the U.S. Forest Service (USFS), job task, time spent performing the job task, wind speed and direction, and type of wildfire crew were determined to be important factors for predicting smoke exposure at wildfires.[7] Despite exposure to a complex mixture of health-relevant air contaminants including volatile organic compounds (VOCs) from smoke, previous smoke exposure assessments for wildland firefighters have mainly focused on measuring $PM_{2.5-4}$ and CO.[5,8] PM exposure from wildfires has been linked to adverse respiratory outcomes such as asthma symptoms and chronic obstructive pulmonary disease; however, PM in smoke typically exists in mixtures with VOCs, which have not been well studied.[5] The health-relevant VOCs commonly found in young smoke, such as acrolein, benzene, and formaldehyde, have been linked to irritation (eyes, skin, nose, mucous membrane, respiratory system), chronic respiratory illness, and cancer.[5,9−11] Thus, it is

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important to study the VOC content of wildfire smoke as this may exacerbate the respiratory impacts of other contaminants such as PM and CO.

The occupational exposure limit (OEL) for respirable fraction for particles not otherwise regulated (PNOR; "inert" dust that can include some PM_4, as well as larger particles) set by the Occupational Health and Safety Administration (OSHA) as the permissible exposure limit (PEL) for an 8 h work day is 5 mg/m^3.[12] To account for the longer work shift, arduous work demands, and the exposure to multiple chemicals in smoke, the National Wildfire Coordinating Group (NWCG): Smoke Exposure Task Group recommends a wildland firefighter OEL of 0.7 mg/m^3 for shift-average PM_4 exposure.[6,7] Smoke exposure assessments performed at wildfires and prescribed fires (fires intentionally set for resource benefit) over the last 10 years reported mean $PM_{2.5-4}$ concentrations up to 1.7 times the NWCG OEL (none above the OSHA PEL) and maximum concentrations up to 24.5 times the NWCG OEL and 3.2 times the OSHA PEL.[8] OSHA, the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH), also have established exposure limits for the three VOCs evaluated in this study: acrolein, benzene, and formaldehyde. The OSHA PELs for the VOCs are 100, 1000, and 750 ppb, respectively. The NIOSH recommended exposure limits (RELS) are 100 ppb for both acrolein and benzene and 16 ppb for formaldehyde. The ACGIH threshold limit values (TLVs) are 100 ppb for benzene and formaldehyde—no TLV exists for shift-average acrolein exposure.

Past wildland firefighter health studies have also measured acute health effects, such as lung function and biomarkers of effect, across work shifts or a whole fire season.[13−15] Across four work shifts, Gaughan et al. reported a significant decline in lung function in wildland firefighters, which was associated with exposure to wood smoke (levoglucosan was used as a tracer) for firefighters.[14] Among 60 wildland firefighters in California, Liu et al. reported significant declines in lung function (FVC, FEV_1, and FEF_{25-75}) and an increase in airway responsiveness, as measured by methacholine dose−response slopes.[15] To examine systemic inflammatory response, Main et al. measured a significant increase after a 12 h work shift for inflammatory markers (interleukin-6 and interleukin-8) among wildland firefighters working in Australia a week after a large wildfire outbreak.[16] To examine the long-term health risk from career exposures to $PM_{2.5}$, Navarro et al. estimated that wildland firefighters were at an increased risk of mortality from lung cancers (8−43%) and cardiovascular diseases (16−30%) across different exposure scenarios and career durations.[17]

To understand and estimate health risks for wildland firefighters, it is important to evaluate exposure to smoke on the fireline. The objective of our study was to measure wildland firefighter exposure to PM_4 on large wildfire incidents across the western United States and compare exposure concentrations across fire crew type and primary job tasks. This assessment of PM_4 exposure from smoke was conducted as a follow-up to a USFS study from 2009 to 2012.[6,7] Additionally, we used previously published ratios of VOC (parts per billion; ppb): PM (mg/m^3) to estimate health-relevant VOC exposures for wildland firefighters.[18]

MATERIALS AND METHODS

PM_4 Field Data Collection. This field study was conducted by the USFS National Technology and Development Program (NTDP) from 2015 to 2017. The research team collecting field samples were wildland firefighters who were trained by NTDP researchers to collect direct observations of the work environment and exposure data. As qualified wildland firefighters, the research team was able to simultaneously function within the highly complex wildland fire environment and directly observe firefighter participants throughout their respective work shifts, without compromising the safety or performance of fire personnel.

The NTDP research team chose wildfire locations for data collection based on seasonal patterns of fire activity and available information for current fire activity across various geographic regions of the United States. The research team traveled throughout the western United States based on the likelihood of a wildfire in a particular geographic region. After permission was given to proceed with data collection from each wildfire, recruitment for research participants was conducted from fire crews assigned to each wildfire. The research team recruited participants from various fire crew types. These types of crews range both in size and in function, such as engine crews, helitack crews, and handcrews. Engine crews work on engines to control fires using water and foam, while helitack crews use helicopters to travel to and fight wildfires. Handcrews generally suppress wildfires by constructing firelines (described below) on the ground with hand tools and fall into one of several types, such as type 1, type 2, and type 2—initial attack (IA).[19] The types of handcrews differ based on experience and supervisory capabilities—type 1 crews are required to hold higher qualifications for overhead staff, which means they have the most experience and can perform more complex tasks on the fireline. Type 2 and type 2IA crews may perform similar but less complex operations at a wildfire and do not have as rigorous of a qualification standard for their overhead positions as a type 1 crew.[20] Type 2IA crews and sometimes type 1 and engine crews will perform initial attack on a fire, which involves being an initial resource responding to the wildfire incident and trying to suppress and contain the fire quickly.

Methods used to collect PM_4 sample collection generally followed those presented by Reinhardt and Broyles.[7] PM_4 measurements were collected and analyzed following the NIOSH method 0600.[21] For this method, filters are equilibrated for 2 h and then weighed in an environmentally controlled area (e.g., 20 ± 1 °C and 50 ± 5% RH) using a balance with a sensitivity of 0.001 mg. Filters were then placed in a filter cassette with caps on each end to eliminate as much sample contamination as possible. This setup was used to transport the filters to and from the sampling locations and back to the laboratory for analysis. The preweighed, 37 mm diameter polyvinyl chloride (PVC) filters with a 1 μm pore size in three-piece cassettes with BGI SCC 1.062 Triplex cyclones were connected to a personal sampling pump. Air sampling pumps were calibrated with a BIOS DC-Lite frictionless piston dry calibrator before and after each sampling event by using a cyclone adapter. The samples were collected at a target flow rate of 1 L/min. Before the start of their work shift, participants were equipped with the sampling pump inside their gear pack. The cassette and cyclone were attached to the shoulder straps

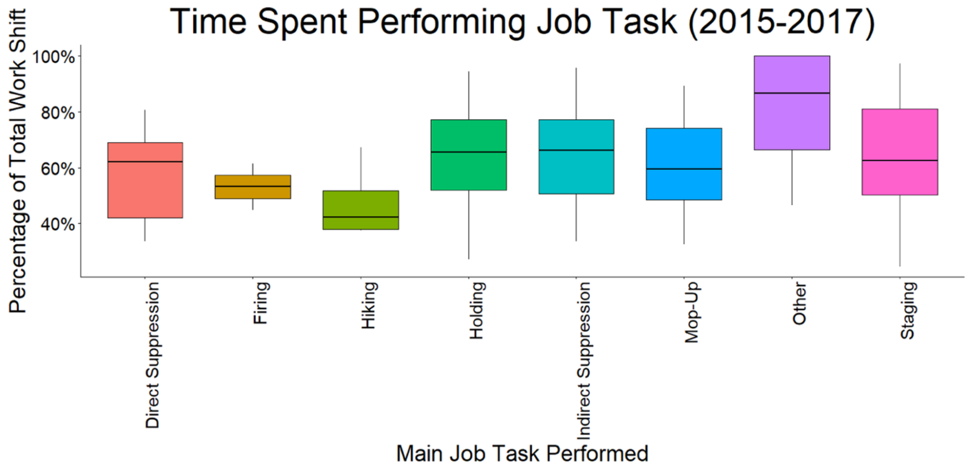

Figure 1. Percentage of the total work shift performing the main job task.

of the wildland firefighter gear pack, near the participant's breathing zone.

Throughout the sampling campaign, we collected daily field blanks to correct for any contamination of PM_4 to our field samples. For every sample collected, one field blank was also collected (100% of total samples) by the NTDP research team by carrying one cassette in the field daily. Laboratory results indicated that there was no net blank mass above the limit of detection to subtract from the net sample mass. Additionally, any sample that had more than a 20% difference in the sampling rate between the pre- and postsampling event flow rate calibration was not included in the study results. A laboratory accredited by the American Industrial Hygiene Association (RJ Lee Group, Inc., Monroeville, PA) provided preweighed filters in cassettes and analyzed all field samples along with daily field blanks according to the NIOSH Method 0600. The PM_4 mass measured on each filter was divided by the sample volume (pump flow rate × sample duration) to calculate the PM_4 concentration for the entire work shift.

The NTDP field research team observed each participant throughout their entire work shift and recorded every job task performed and the duration of the job task. To collect these observations, the NTDP field research team closely followed and monitored each study participant during their work shift. These observations started when they were equipped with sampling equipment at the start of their work shift until the end of the work shift. The PM_4 sampling period included the entire work shift for each study participant. Generally, the day shift at a wildfire incident can start at 06:00 and end at 22:00. Each firefighter participant performed many different job tasks throughout a work shift; however, our PM_4 exposures were sampled across the work shift, and therefore the PM_4 exposure level could not be matched to each job task individually but rather represented a full-shift exposure.

To examine PM_4 exposure differences across different job tasks, the many cross-shift observations were used to assign each firefighter a "full-shift job task" for the sampling day. For each job task directly observed, a cumulative time spent (total duration in minutes) performing that task was calculated for each participant. Using the cumulative time for each job task performed, we determined the percentage of time spent performing that job task across the work shift (Figure 1). The job task that was performed for the highest percentage of the work shift was assigned as full-shift job task for each participant. The NTDP field research team used a list of 59 possible job tasks when collecting field observations. For this evaluation, we condensed those job tasks into nine main job categories: direct or indirect suppression, engine operator, hiking, holding, mop-up, firing, staging, and others. These main job categories are described below. Additionally, at the end of each shift, study participants were asked to provide a self-assessment of their perceived smoke exposure for that shift by choosing from none, very little, low, moderate, or high.

Direct suppression involves job tasks completed directly on the active fire edge to create a fuel break such as constructing fireline. Indirect suppression is a different tactic that can be made up of similar tasks completed away from the active fire edge. Engine operators work as a part of an engine crew (3−7 firefighters) and operate the diesel pumps on an engine that provides water to crews working near the fire. Firefighters regularly hike to reach their location of work. Firefighters engaged in holding ensure that the active fire has not crossed the fireline or fuel break. After the fire has been controlled, crews will mop up the area by extinguishing any burning or smoldering material by digging out the burning material or applying water to stop anything that may reignite a fire. Firing operations involve setting an intentional fire, typically with torches filled with a 3:2 diesel/unleaded gasoline mixture, to reduce the available flammable material for the wildfire to consume. Staging occurs when operations are paused, and firefighters are instructed to await further assignment while remaining immediately available. This includes situations such as waiting in a safety zone until fire behavior decreases, researching available, and safe access points to an area by vehicle, foot, or air, waiting to engage in an area of the fire until supervisors have properly scouted for hazards, or discontinuing a task until additional resources arrive. Job tasks classified as "other" included tasks that were not commonly performed such as helibase operations and gridding the green and gridding the black; both involve looking for hotspots in burned and unburned areas of the fire perimeter.

WE-CAN Hazardous Air Pollutant Data. Ratios of VOCs to PM_1 are taken from O'Dell et al.[18] Methods used to calculate these ratios are fully described in O'Dell et al. and are summarized here. VOC and PM_1 observations were collected during WE-CAN (Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption, and Nitrogen), an aircraft-based field campaign in summer 2018 (http://catalog.eol.ucar.edu/we-can). Over 16 research flights, the WE-CAN campaign focused on sampling fresh outflows from large western U.S.

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wildfires and opportunistically sampled more aged smoke during transits. The National Center for Atmospheric Research (NCAR) Trace Organic Gas Analyzer (TOGA) was used to measure VOC mixing rations.[22] PM_1 mass values were estimated by calculating the sum of the mass of black carbon as determined by a single particle soot photometer (SP2) and total nonrefractory mass measured by a high-resolution time-of-flight aerosol mass spectrometer (HR-ToF-AMS).[23−25] Ratios were calculated for three chemical smoke age categories by O'Dell et al.[18] In this study, we use PM_1 and VOC concentration ratios calculated for young smoke (smoke less than ~1 day old). The following VOC WE-CAN ratios were used: 5.4 ppb:mg/m^3, 9.2 ppb:mg/m^3, and 96.8 ppb:mg/m^3 for acrolein, benzene, and formaldehyde, respectively. These VOCs were selected as they have been previously measured on wildland firefighters and were found to be dominant contributors to gas-phase hazardous air pollutant risk in smoke plumes by O'Dell et al.[5,18,26] We used eq 1 to calculate each VOC concentration using our measured PM4 and the VOC WE-CAN ratios

$$\text{VOC (ppb)} = \text{PM}_4\left(\frac{\text{mg}}{\text{m}^3}\right) \times \text{VOC PM}_1\text{ ratio}\left(\frac{\text{ppb}}{\frac{\text{mg}}{\text{m}^3}}\right) \quad (1)$$

To use these VOC/PM enhancement ratios, we had to make two assumptions for our analysis. The first, wildfire smoke, generally consists of smaller-sized fractions of PM, which allows us to use PM_1 emission ratios with the measured PM_4 shift concentrations that were collected by NTDP. Data from past wood smoke studies demonstrated that the particle size of combustion-generated particles is on the order of 300 nm.[27,28] McMeeking et al. used an optical particle counter and a differential mobility analyzer to report that mass median aerodynamic particle diameter (MMAD) was about 300 nm. In addition, the study found that the volume geometric mean diameters ranged from about 200 nm during nonsmoke periods to between 300 and 400 nm during periods of highest fine aerosol mass concentrations associated with smoke-impacted times.[28] Kleeman et al. measured the particle sizes of smoke aerosol from several different types of wood (under laboratory conditions) and reported that particles ranged from about 90 to about 300 nm in MMAD. In addition, field studies of wildland fires have reported a majority of fine particles in wildfire smoke compared to particles in the coarse-sized range (aerodynamic diameters >2.5 μm). At a wildfire in Alaska, Leonard et al. collected aerodynamically size-selected aerosol samples and reported that ~78% of the total mass concentration was from collected particles with a mean diameter of 2.4 μm.[29] A recent study measuring personnel exposure to smoke aerosols at prescribed fires found that particles in the fine range (diameter 0.5−2.5 μm) dominated the particle number concentration (PNC) compared to coarse particles (diameter >2.5 μm). Nelson et al. measured the fine PNC to be 19,545 part/L, whereas the coarse PNC was 1411 part/L. Finally, larger particles measured in downwind wildfire smoke have been suggested to form secondarily, via coagulation or condensation, or mechanically generated and are not likely to have additional VOC emissions associated with them.[30]

Second, we assume that the VOC/PM ratios estimated within young, lofted smoke plumes from WE-CAN are representative of ground-level smoke to which firefighters are exposed. While the chemical age of the young WE-CAN plumes is likely similar to (or slightly older than) the chemical smoke age of the smoke to which firefighters are exposed, trace gas and particle abundance may differ between ground-level and lofted smoke plumes.[31] We discuss the implications of these assumptions on our study in the Results and Discussion section.

Statistical Analysis. Summary statistics are presented as geometric mean (GM), geometric standard deviation (GSD), and range by crew type, main job task, self-assessment of smoke, and geographic area. Limits of detection (LODs) for acrolein, benzene, and formaldehyde were defined as the TOGA instrument LOD from the WE-CAN campaign. In calculating the descriptive statistics, PM_4 and VOC concentrations below the LOD (0.1 mg for PM_4 and 1, 0.3, and 20 parts per trillion (ppt) for acrolein, benzene, and formaldehyde, respectively) were assigned values equal to one-half the LOD to prevent skewing the data.[32] All VOC minimum values calculated were above the LOD. Box-and-whisker plots with minimum, 25th percentile, median, 75th percentile, and maximum were generated for the PM_4 and VOC concentration levels. A dashed horizontal line for the recommended NWCG OEL of 0.7 mg/m^3 was included in each box-and-whisker plot in Figure 2 for comparison.

We conducted one-way analyses of variance (ANOVAs) to determine whether the log mean concentrations of PM_4 were significantly different across crew types, job tasks, self-assessments of smoke, or geographic areas. We also investigated significant differences in PM_4 concentrations among these categories through pairwise comparisons. Additionally, linear regression was performed to test for the linear trend of smoke self-assessment by examining whether the slope of the regression line was statistically different from zero. All tests were two-sided at a 0.05 significance level. Statistical analyses were conducted in SAS version 9.4 (SAS Institute, Cary, NC).

■ RESULTS AND DISCUSSION

PM_4 samples were collected from 81 wildland firefighters performing typical wildland firefighting job tasks on 22 wildfires across 9 states. On average, wildland firefighters were sampled for 667 min during their work shifts. The mean shift length and fireline time for the wildland firefighters sampled were 817 and 645 min, respectively. The amount of time spent performing the assigned main job task for each study participant ranged from 25 to 100% of their work shift. The median percentage of time spent performing the main job task ranged from 42 to 87% of the work shift. Most samples were collected in the Southwest region (N = 20; Arizona and New Mexico), followed by the Rocky Mountains (N = 14; Colorado and Wyoming), Pacific Northwest (N = 12; Oregon and Washington), Northern Rockies (N = 11; Montana and Northern Idaho), Northern California (N = 9), Southern California (N = 8), and the Great Basin (N = 7; Utah, Nevada, and Southern Idaho). Data from all 81 wildland firefighters who participated in the study were included in the statistical analysis. Participants ranged from ages 19 to 62 and 71 of the wildland firefighters whose shifts were sampled were male. Approximately 50% of the study participants worked on type 1 handcrews. The rest of the study population worked on engine, type 2, and type 2IA crews (12−13% each), while two study participants worked on a helitack crew. Wildland firefighters performed holding, indirect suppression, and mop-up for 25, 20, and 19% of the work shifts sampled, respectively. Fewer

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wildland firefighters performed direct suppression, firing, engine operation, hiking, and other for most of the work shift (Figure 1).

Table 1 summarizes the PM_4 concentrations measured on wildland firefighters, and Table 2 provides VOC concentrations of acrolein, benzene, and formaldehyde estimated from PM_4 exposures in wildland firefighters. The overall GM of PM_4 concentration measured from 2015 to 2017 was 0.32 mg/m^3, and the corresponding GMs for acrolein, benzene, and formaldehyde were 1.7, 3.0, and 31.2 ppb, respectively. Nineteen percent (15 of 81) of measured PM_4 exposures exceeded the recommended NWCG OEL of 0.7 mg/m^3. VOC and PM_4 concentrations were generally much higher for type 1 crews (GM = 0.4 mg/m^3 and 2.2, 3.7, and 38.9 ppb for acrolein, benzene, and formaldehyde, respectively). Mean PM_4 concentrations were similar for type 2 and type 2IA crews with reported GMs of 0.24 and 0.25 mg/m^3, respectively.

Table 1. PM_4 Concentration across All Study Participants, Crew Type, Job Task, Firefighter Assessment of Smoke, and Geographic Area[a]

	PM_4 concentration (mg/m^3)				
	N	GM	GSD	min	max
all study participants	81	0.32	2.06	0.11	2.56
Crew Type					
engine	13	0.31	1.88	0.13	0.77
helitack	2	0.15	1.05	0.14	0.15
Type 1	41	0.40	2.2	0.11	2.56
Type 2	13	0.24	1.88	0.12	0.81
Type 2IA	12	0.25	1.62	0.12	0.49
Job Task					
engine operator	1	0.30		0.30	0.30
firing	2	0.43	1.93	0.27	0.68
hiking	4	0.26	1.74	0.15	0.45
direct suppression	7	0.65	2.94	0.11	2.56
holding	20	0.37	1.94	0.12	1.08
indirect suppression	15	0.34	1.97	0.12	0.97
mop-up	16	0.34	1.92	0.12	1.22
other	4	0.15	1.22	0.12	0.20
staging	12	0.20	1.68	0.12	0.60
Firefighter Assessment of Smoke					
none	14	0.26	1.84	0.12	0.60
very little	27	0.26	1.8	0.12	0.97
low	20	0.36	2.13	0.12	1.22
moderate	18	0.43	2.35	0.11	2.56
high	2	0.72	1.04	0.70	0.74
Geographic Area					
Great Basin	7	0.31	1.57	0.15	0.60
Northern CA	9	0.42	1.79	0.20	1.08
Northern Rockies	11	0.28	2.09	0.11	1.22
Pacific Northwest	12	0.60	2.33	0.14	2.56
Rocky Mountains	14	0.25	2.05	0.12	1.07
Southern CA	8	0.27	1.62	0.15	0.70
Southwest	20	0.28	2.01	0.12	1.03

[a]*N*, number of samples that were collected; GM, geometric mean; GSD, geometric standard deviation.

Wildland firefighters performing direct suppression as their main job task for the day had the highest mean PM_4 concentration (GM = 0.65 mg/m^3). Although only two wildland firefighters performed firing for a majority of the work shift, they had the second-highest mean concentration of PM_4 (GM = 0.43 mg/m^3). Wildland firefighters performing holding, mop-up, and indirect suppression had similar GMs, ranging from 0.34 to 0.37 mg/m^3. The highest maximum PM_4 concentrations were measured on wildland firefighters performing direct suppression, mop-up, and holding (2.56, 1.22, and 1.08 mg/m^3, respectively). In addition, wildland firefighters conducting direct suppression strategies had statistically significantly higher exposures to VOCs (3.5, 6.0, and 63.1 ppb for acrolein, benzene, and formaldehyde, respectively) compared to those performing staging and other tasks (Tables 1 and 2).

Wildland firefighters that reported a high daily assessment of smoke were exposed to the highest mean concentrations of PM_4 (GM = 0.72 mg/m^3). Wildland firefighters who reported moderate and low assessments of smoke had GM concentrations of 0.43 and 0.36 mg/m^3, respectively. Although the highest daily maxima were reported for wildland firefighters in the moderate and low categories, the linear trend testing result indicated that measured PM_4 exposures tracked well with the self-reported assessment of daily smoke exposures (p-value = 0.004) (Table 1 and Figure 2).

Wildland firefighters' exposures to PM_4 while working in the Pacific Northwest (Oregon and Washington) (GM = 0.6 mg/m^3) were significantly higher than PM_4 exposures measured in both the Southwest (Arizona and New Mexico) (GM = 0.28 mg/m^3) and Rocky Mountains (GM = 0.25 mg/m^3). Wildland firefighters suppressing wildfires in Northern California had the second-highest measured mean PM_4 concentrations (GM = 0.42 mg/m^3), followed by wildland firefighters in the Great Basin (Nevada, Utah, and Southern Idaho) (GM = 0.31 mg/m^3).

The objective of this study was to measure personal exposures to PM_4 from wildfire smoke among wildland firefighters at wildfires and examine the relationship to job task, crew type, self-assessment of smoke, and geographic region. In addition, we used enhancement ratios for PM to VOCs (acrolein, benzene, and formaldehyde) to estimate exposures to other contaminants found in wildfire smoke. Among the wildland firefighters that participated in this study, wildland firefighters performing direct suppression and those on type 1 crews consistently had higher mean concentrations of both PM_4 and estimated VOCs. We also found that exposure varied based on the geographic region. Average PM_4 exposure was significantly higher for wildland firefighters in Pacific Northwest than for other areas of the United States. This may be due to the higher density of organic matter from the fuels present and biomass burned in this region compared to those of other areas. Between 1988 and 2004, 23% of the biomass burned in the United States was in the Pacific Northwest, compared to 4% in the Rocky Mountains and 2% in the Southwest; in both regions, we found significantly lower PM_4 exposures than in the Northwest.[33] However, this difference observed could have also been influenced by burning conditions including the fuel type and moisture at each wildfire, which was not measured or observed for this study.

As a follow-up to the large smoke exposure assessment conducted by the USFS from 2009 to 2012 and reported by Reinhardt and Broyles,[26] concentrations of PM_4 measured in this study were generally consistent with the previous smoke assessment. The previous smoke assessment reported a GM concentration of 0.35 mg/m^3 for PM_4 on large wildfire incidents (called "project fires" in their study), compared to

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Table 2. Estimated Volatile Organic Compound Concentrations across All Study Participants, Crew Type, and Job Task[a]

		acrolein (ppb)				benzene (ppb)				formaldehyde (ppb)			
	N	GM	GSD	min	max	GM	GSD	min	max	GM	GSD	min	max
all study participants	81	1.7	2.1	0.6	13.8	3.0	2.1	1.0	23.6	31.2	2.1	10.7	247.9
Crew Type													
engine	13	1.7	1.9	0.7	4.2	2.8	1.9	1.2	7.1	29.7	1.9	12.2	74.9
helitack	2	0.8	1.0	0.8	0.8	1.4	1.0	1.3	1.4	14.4	1.0	13.9	14.9
Type 1	41	2.2	2.2	0.6	13.8	3.7	2.2	1.0	23.6	38.9	2.2	10.7	247.9
Type 2	13	1.4	1.6	0.6	2.7	2.3	1.6	1.1	4.5	24.6	1.6	11.5	47.8
Type 2IA	12	1.3	1.9	0.7	4.4	2.2	1.9	1.1	7.4	23.1	1.9	11.8	78.2
Job Task													
engine operator	1	1.6				2.7				28.8			
firing	2	2.3	1.9	1.4	3.7	3.9	1.9	2.5	6.2	41.3	1.9	25.9	65.6
hiking	4	1.4	1.7	0.8	2.4	2.4	1.7	1.4	4.2	25.2	1.7	14.9	43.8
direct suppression	7	3.5	2.9	0.6	13.8	6.0	2.9	1.0	23.6	63.1	2.9	10.7	247.9
holding	20	2.0	1.9	0.7	5.8	3.4	1.9	1.1	9.9	36.1	1.9	11.9	104.6
indirect suppression	15	1.8	2.0	0.6	5.2	3.1	2.0	1.1	8.9	32.5	2.0	11.5	93.5
mop-up	16	1.8	1.9	0.6	6.6	3.1	1.9	1.1	11.2	32.8	1.9	11.5	117.8
other	4	0.8	1.2	0.7	1.1	1.4	1.2	1.1	1.8	14.7	1.2	11.8	19.1
staging	12	1.1	1.7	0.7	3.2	1.8	1.7	1.1	5.5	19.4	1.7	11.9	57.9

[a]*N*, number of samples that were collected; GM, geometric mean; GSD, geometric standard deviation.

the GM of 0.32 mg/m^3 found by this study. Earlier work conducted by Reinhardt and Ottmar reported the overall shift concentration of respirable PM to be 0.50 mg/m^3 on wildland firefighters in the early 1990s throughout Washington, Idaho, Montana, and Colorado.[26] The 2009−2012 smoke study found that type 2 crews followed by type 1 crews were exposed to higher levels of PM_4 than engine and other types of crews. The current study found this to be true for type 1 crews. These differences may occur because the previous study included prescribed burns, which can involve different types of work and tasks than large wildfires, the focus of our study. Thus, it is difficult to compare means of different groupings of firefighters across different types of fire and job tasks.

No wildland firefighter sampled for this study was above the OSHA PEL of 5 mg/m^3 for PNOR. The percent of samples collected for this assessment that were above the recommended NWCG OEL of 0.7 mg/m^3 was 19% compared to that of 22% reported by the previous assessment, which is a slight reduction.[7] The median PM_4 concentration (0.79 mg/m^3) for wildland firefighters performing direct suppression exceeded the recommended NWCG OEL of 0.7 mg/m^3 (Figure 2). In our assessment, wildland firefighters performing holding, mop-up, or indirect suppression as their main job task also experienced exposures to PM_4 above the recommended NWCG OEL. Although the recommended NWCG OEL is not approved by any occupational health organization that sets exposure standards, it provides a better comparison as it takes into account the longer work shifts faced by firefighters. There is no standard that considers the multiple air contaminants in smoke. Previously, Adetona et al. stated that wildfire smoke is more comparable to diesel particulate matter than it is to the inert dust on which the OSHA regulation is based.[5]

Wildland firefighters perform a variety of job tasks while suppressing wildfires and some similar tasks while conducting prescribed burns. Past exposure assessments have reported that some jobs will have higher exposures to air contaminants due to exposure to smoke or ash.[7,34] Measured job tasks for this study performed by wildland firefighters include direct and indirect suppression, operating a fire engine, hiking, holding, mop-up, firing operations, and staging. In our study, wildland firefighters performing direct suppression had higher exposure to PM_4 compared to those performing staging and other ancillary tasks. In the 2009−2012 assessment, wildland firefighter performing mop-up had significantly higher exposures compared to nonarduous ancillary tasks such as operational breaks or staging. In 2014, Gaughan et al. measured wildland firefighters performing mop-up (0.51 mg/m^3) and constructing the fireline (0.49 mg/m^3) at a large wildfire incident.[14] The concentrations reported by Gaughan et al. for mop-up were slightly higher than our measured PM_4 concentrations, but wildland firefighters in our study performing direct suppression tasks (including constructing fireline) had elevated concentrations of PM_4 compared to those constructing fireline in the 2014 study. However, we were able to sample at many different wildfire events compared to just one event, and this may have led to slightly different average exposure concentrations.

We selected acrolein, benzene, and formaldehyde as the VOCs to estimate for our analysis because they are defined by the EPA as hazardous air pollutants (HAPs) and have been identified as the main gas-phase contributors to health risk in wildfire smoke.[18] Further, these HAPs have been previously measured on wildfire firefighters. Finally, the selected VOCs had high Spearman correlations with PM ($r_s > 0.93$), indicating a strong relationship between VOC and PM concentrations. Our study estimated GMs for the three hazardous air pollutants to be 1.7, 3.0, and 31.2 ppb, respectively. A 2004 study by Reinhardt and Ottmar measured wildland firefighter exposures to these VOCs at project fires and found averages of 1, 4, and 13 ppb for acrolein, benzene, and formaldehyde, respectively, which is consistent with our findings for acrolein and benzene but lower for formaldehyde.[26] Formaldehyde can be formed as a secondary compound from atmospheric degradation, and the WE-CAN VOC ratios may include smoke that is slightly older, which could have led to higher concentrations of formaldehyde.[18] Additionally, formaldehyde can be difficult to measure, and this measurement difference could have led to concentration differences as well. All estimated concentrations of acrolein and benzene were well below the OSHA PELs (acrolein = 100 ppb and benzene =

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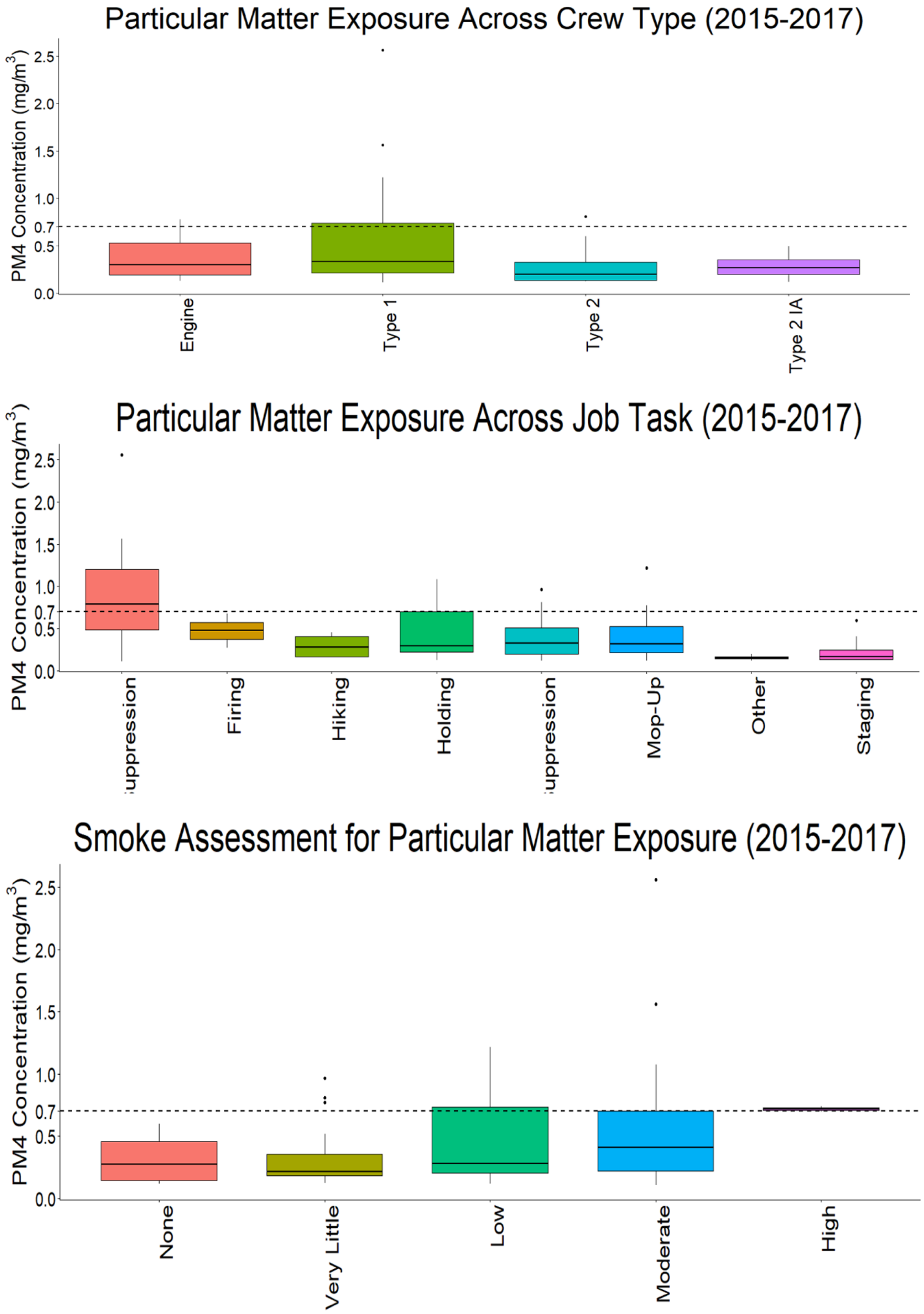

Figure 2. PM_4 exposure across crew type, job task, and firefighter smoke assessment.

1000 ppb), NIOSH recommended exposure limits (RELs; acrolein and benzene = 100 ppb), and ACGIH threshold limit values (TLVs; benzene = 500 ppb).[11] Sixty-seven wildland firefighter estimates for formaldehyde were above the NIOSH REL and five were above the ACGIH TLV (16 and 100 ppb, respectively), but all participants had estimated concentrations below the OSHA PEL (750 ppb). Of the wildland firefighters above the formaldehyde REL, many performed holding (N = 19), mop-up (N = 14), and indirect suppression (N = 12) job tasks for most of their work shift.

Although we were able to collect a robust data set of PM_4 concentration measurements on wildland firefighters throughout the western United States, there are limitations when interpreting our results. Some limitations of the findings of this study include the variability inherent to measuring exposure to smoke at wildfires. Wildfire incidents by definition are large and complex; thus, it is difficult to characterize an "average" wildfire exposure. Despite this, smoke concentration quantities found by this study were comparable to similar studies done on VOC and particulate exposure at wildfires. Another limitation was the representation of certain crew types and job tasks performed. Although the study cohort included 81 participants, only two of them were on a helitack crew, so the mean exposure found by this study may not truly represent exposures faced by wildland firefighters on helitack crews. This is also true of job tasks such as engine operator and firing, which had one and two participants, respectively. Although many firefighters performed these tasks and others throughout the

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work shift, it was not for the majority of the work shift and thus was not classified through our assessment of assigning a main job task performed each shift. Our classification of the main job task for this analysis did sacrifice the details provided by the research team of the many different job tasks performed and may have led to some job task and exposure misclassification. For some assigned main job tasks, they were only performed for ∼30% of the work shift (Figure 2). This indicates that there were many other tasks performed throughout the shift by study participants that may have contributed to the total PM_4 exposure for the work shift.

This analysis used data from two separate field campaigns, which provided an innovative approach but did introduce limitations to our final estimated concentrations. The occupational exposure data collected by NTDP was measured based on respirable particles as defined by the OSHA PEL for PM, and an aerodynamic diameter of less than 4 μm. However, wildfire smoke has been measured to be a majority fine PM (≤aerodynamic ratio of less than 2.5 μm), making it reasonable to use a ratio based on PM_1. Although we do not know how PM_1 compromised our PM4 concentration, we assumed that the mass contribution of smoke particulate matter with diameters between 1 and 4 μm was negligible. Consequently, the use of PM_4 in this analysis may lead to an overestimation of VOC concentration. The ratios from the WE-CAN campaign applied here were derived from observations of lofted smoke plumes, whereas we are interested in ground-level exposures for wildland firefighters. However, trace gas abundances may differ between lofted and ground-level plumes. Burling et al. observed slightly higher formaldehyde in ground-level compared to lofted prescribed fire plumes (acrolein and benzene were not included in the study). In addition, the WE-CAN "young" smoke age category may include smoke older than that to which firefighters are exposed. This may have led to the higher exposure estimates than previous works, especially for formaldehyde. Although our method may have led to an overestimation of formaldehyde, it is classified by the International Agency for Research on Cancer as carcinogenic and we believe that it should be measured further in wildland firefighters.[35] Finally, this assessment focused on exposure to PM_4 and could have included exposure to fine dust and crystalline silica that can occur during soil-disturbing events such as mop-up and constructing handline.[7] For this reason, the estimation of VOCs using PM_4 may be overestimated where there were elevated exposures to fine dust and silica.

Exposure to PM from smoke is one of many hazardous air contaminants inhaled by wildland firefighters.[5] In addition to PM_4, the NTDP field research team collected 1-min breathing zone carbon monoxide measurements through real-time dosimeters on wildland firefighter study participants during this field study.[36] CO mean concentrations exceeded the National Wildfire Coordinating Group's occupational exposure limit of 16 ppm on ∼5% of samples collected. This study also found that WFF perception of smoke exposure was a strong predictor of measured CO exposure.

Smoke exposure is one of many hazards faced by wildland firefighters in the wildfire environment.[37] As the wildfire environment is complex and highly variable, smoke mitigation strategies should aim to be flexible and adaptable to changing fire behavior, available resources and personnel, and fire management objectives. Initial recommendations from the 2009 to 2012 smoke exposure assessment included minimizing mop-up where feasible, developing a medical surveillance program and fire-specific OELs, training firefighters on the hazards of smoke, and reducing exposure by limiting shift length and rotating crews out of heavy smoke areas.[6]

Although the objective of this study was to compare smoke exposure after these recommendations were made to fire personnel and managers, this study did not evaluate if or how any of these recommendations were being implemented on the fireline. Smoke exposure was not the highest task for wildland firefighters performing mop-up in this assessment; however, it was still a task that saw higher exposures to PM_4. Mitigations proposed for the 2020 fire season by incident management planning teams continue to be similar and included rotating fire personnel in areas of high unavoidable smoke exposure, using air resource advisors to monitor and address smoke issues, and locating incident command posts (ICPs) and remote camps in areas with the least smoke exposure practicable.[38] As ICPs and remote camps are used to support fire personnel and provide an off-duty rest area, they should not be locations in areas with strong nighttime inversions, which can trap smoke and lead to higher exposures.[39,40]

Wildland firefighters' self-reported assessment of daily smoke exposure was associated with measured concentrations of PM_4. This indicates that wildland firefighters may be good at qualitatively assessing their own exposure to smoke. As a mitigation tool, this qualitative assessment could be used by wildfire incident management personnel to track cumulative exposure throughout individual fire assignments or across the fire season. If crews are experiencing high cumulative exposures to smoke, fire managers could redirect or reassign crews to performing suppression tasks that have been reported to have lower exposure to smoke or work in areas of the wildfire incident that are not experiencing heavy smoke concentrations. In addition, researchers may be able to use this to qualitatively assess exposure to smoke when it may be difficult to conduct a large-scale exposure assessment.

Wildland firefighters typically have long work shifts across multiweek fire assignments that can result in higher cumulative exposures and increased risk of adverse health outcomes. Past health studies have demonstrated that exposure to wildfire smoke may increase wildland firefighters' risk for declines in lung function, increases in inflammation, and lung cancer and cardiovascular diseases in the long term.[13−15] Currently, there is no respirator that can both provide protection to particles and gases from wildfire smoke and perform in the extreme and complex environment of wildfire.[7] It is important to continue to measure and understand multipollutant exposure in smoke to better understand the associations with adverse health outcomes for wildland firefighters. Exposure to additional health-relevant pollutants in smoke can be estimated by applying smoke emission or enhancement ratios of these pollutants to measured PM exposure and could be used for future exposure assessments. However, we also recommend that future field studies directly measure more health-relevant pollutants in smoke to continue to validate emission or enhancement ratios and explore real-world exposure concentrations. Both the estimation and measurement of health-relevant pollutants can be used to better understand the concentrations of these pollutants for wildland firefighters. Overall, smoke exposures for wildland firefighters have not significantly reduced over time, and fire management should continue to find and implement strategies to change work practices that will reduce exposure to smoke and protect the wildland firefighter's health.

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Notes

The authors declare no competing financial interest.

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