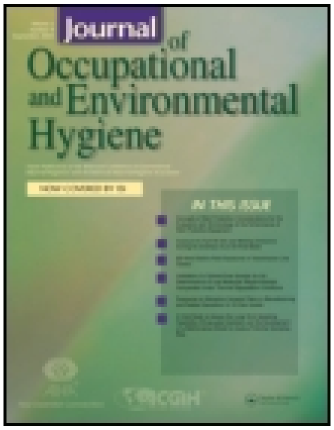

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Exposures and Cross-shift Lung Function Declines in Wildland Firefighters

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Respiratory problems are common among wildland firefighters. However, there are few studies directly linking occupational exposures to respiratory effects in this population. Our objective was to characterize wildland fire fighting occupational exposures and assess their associations with cross-shift changes in lung function. We studied 17 members of the Alpine Interagency Hotshot Crew with environmental sampling and pulmonary function testing during a large wildfire. We characterized particles by examining size distribution and mass concentration, and conducting elemental and morphological analyses. We examined associations between cross-shift lung function change and various analytes, including levoglucosan, an indicator of wood smoke from burning biomass. The levoglucosan component of the wildfire aerosol showed a predominantly bimodal size distribution: a coarse particle mode with a mass median aerodynamic diameter about 12 μm and a fine particle mode with a mass median aerodynamic diameter < 0.5 μm. Levoglucosan was found mainly in the respirable fraction and its concentration was higher for fire line construction operations than for mop-up operations. Larger cross-shift declines in forced expiratory volume in one second were associated with exposure to higher concentrations of respirable levoglucosan ($p < 0.05$). Paired analyses of real-time personal air sampling measurements indicated that higher carbon monoxide (CO) concentrations were correlated with higher particulate concentrations when examined by mean values, but not by individual data points. However, low CO concentrations did not provide reliable assurance of concomitantly low particulate concentrations. We conclude that inhalation of fine smoke particles is associated with acute lung function decline in some wildland firefighters. Based on short-term findings, it appears important to address possible long-term respiratory health issues for wildland firefighters. [Supplementary materials are available for this article. Go to the publisher's online edition of Journal of Occupational and Environmental Hygiene *for the following free supplemental resources: a file containing additional information on historical studies of wildland fire exposures, a file containing the daily-exposure-severity questionnaire completed by wildland firefighter participants at the end of each day, and a file containing additional details of the investigation of correlations between carbon monoxide concentrations and other measured exposure factors in the current study.]*

Keywords occupational lung disease, exposure assessment, levoglucosan

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INTRODUCTION

According to wildland fire statistics collected by the U.S. Government, the number and intensity of fires has grown over the past decades with approximately 6 million acres being destroyed in an average North American wildland fire season.[1] The year 2012 involved extremely arid conditions (i.e., the worst drought since 1934) and 9.3 million acres burned in wildfires (http://www.ncdc.noaa.gov/). The growing annual extent and intensity of these fires spurs increasing concern for the respiratory health of wildland firefighters, including the more than 34,000 who are seasonally or permanently employed by the federal government. Studies examining respiratory symptoms, pulmonary function, and inflammatory markers in wildland firefighters have found increases in upper and lower airways inflammation and symptoms, airways hyper-responsiveness, and declines in lung function across a work shift and a season.[2–8]

The chief inhalation hazards associated with wildland fire fighting have been identified as carbon monoxide (CO) and respirable particulate matter ($<10\ \mu$m).[5,8–13] Pyrolysis of organic components may increase the potency and or toxicity of particulate by producing radical and oxygenated species. Oxygen free radicals are highly reactive and have been implicated in lung injury, including asthma.[14] Measurement of levoglucosan (LG), a sugar anhydride byproduct of incomplete combustion of cellulose, may be used to indicate relative exposure to products of pyrolysis from burning biomass.[15]

While general observational information exists on adverse health effects and exposures associated with wildland fire fighting, studies directly linking respiratory function and exposure characteristics are lacking. Therefore, the objectives of our current study were to characterize exposures of wildland firefighters during a large wildfire, explore correlations between exposures and fire fighting activity, and examine the effects of these exposures on cross-shift lung function changes. Our secondary objective was to support improved selection of sampling methods for future studies.

METHODS

Study Population

The study population consisted of members of the Alpine Interagency Hotshot Crew (IHC) based in Rocky Mountain National Park, Colorado, who fought the Red Eagle Fire from August 7–10, 2006 (Table I). The Red Eagle Fire burned over 34,000 acres in Glacier National Park and on the adjoining Blackfeet Tribal Land in Montana. IHCs are elite crews that primarily conduct fire-line construction using hand tools during the most dangerous phases of wildfire suppression. Fire line construction involves clearing vegetation and exposing bare soil by cutting, scraping, or digging to create a break in fuel. IHCs also engage in mop-up operations, which involve extinguishing or removing burning material along or near a fire line after the fire has been controlled. Each crew comprises 20 members. Jobs include: "Lead workers" who oversee all crew operations; "Sawyers" who are the chainsaw operators who clear the way for fire line construction; "Swampers" who shadow the Sawyers, removing the fallen debris; and "Line workers" who construct the fire line.

TABLE I. Characteristics of Interagency Hotshot Crew (IHC) Study Participants

Variable	Study Participants n = 17
Median age, years	26 (23, 35)[A]
Median time spent as member of IHC, months	1 (1, 12)[A]
Male n,%	16, 94%
White, non-Hispanic n,%	16, 94%
Never smoker n,%	15, 88%
Former smoker n,%	2, 12%
Asthma, physician-diagnosed (current) n,%	1, 6%
Allergies (ever) n,%	9, 53%
Spirometry Results[B]	
• Median FEV_1% predicted	104 (86, 115)[A]
• Median FVC% predicted	104 (91, 125)[A]
• Median FEV_1/FVC	0.80 (0.73, 0.87)[A]

[A](10th, 90th percentiles).
[B]Spirometry values obtained at first pre-shift assessment.

The study protocol was approved by the NIOSH Human Subjects Review Board and informed consent was obtained from each research participant.

Medical Survey

Demographic and clinical variables for the crew members, as well as baseline spirometry measurements, were obtained during a preseason assessment conducted several months before the Red Eagle Fire; those results have been reported.[3]

Exhaled Breath Carbon Monoxide

Exhaled breath CO was measured twice daily—approximately one hour before the work shift began and one hour after the shift concluded—on each participant using a breath CO monitor according to the manufacturer's instructions (Micro 4 Smokerlyzer, Bedfont Scientific, Medford, N.J.). The elapsed time between the end of shift and the measurement of exhaled breath CO was recorded for each subject. The elapsed time provided for washout of residual inhaled CO from the lung volume. The medical monitoring location was situated at the base camp, at a location away from cooking, parking, and portable generator areas to avoid interference from local sources of CO. Ambient CO concentration was measured at the base camp where the pre-/post-shift exhaled breath measurements were obtained.

Spirometry

Spirometry was conducted twice daily, immediately following exhaled breath CO measurement, on each participant. Technicians who had completed a NIOSH-approved spirometry course followed American Thoracic Society (ATS) guidelines[16] using an ultrasonic flow spirometer (EasyOne

Diagnostic Spirometry System 2001, ndd Medical Technologies, Zurich, Switzerland).

We used equations for predicted values and lower limits of normal derived from the Third National Health and Nutrition Examination Survey (NHANES III) data.[17] We defined an individual cross-shift forced expiratory volume in 1 sec (FEV_1) decline of 10% or greater as significant;[18] we also examined declines of 5% or greater. We followed ATS procedure by inquiring about current medications, but we did not ask participants to abstain from using their medications, given safety concerns.

Exposure Questionnaire

Participants were asked daily, at the shift's conclusion, what job duties they had performed and to rate the severity (none, mild, moderate, or severe) and duration of his or her exposure to smoke and his or her exposure to dust during the preceding shift. Because use of the qualitative terms "none," "mild," "moderate," and "severe" is subjective, our instructions to the subjects were that they should base their responses on their individual perception of the smoke and dust conditions.

Exposure Assessment

Details on each environmental sampling method and associated instrumentation used in the assessment of exposure are provided in Table II. For each of the four days, each crew member agreed to wear a real-time (RT) personal breathing zone CO monitor (Industrial Scientific Corporation, Oakdale, Pa.) and one of the following samplers: a filter cassette with a 10-mm nylon respirable cyclone to measure respirable particulate concentration and either respirable LG concentration or respirable crystalline silica concentration; a personal cascade impactor to measure particle size distribution, total concentrations of particulates and LG, and respirable concentrations of particulates and LG; or a *personal*DataRAM (*p*DR) monitor (Thermo Scientific Corporation, Franklin, Mass.) to measure RT particulate in the size range of 0.1 to 10 μm.

The CO monitor was calibrated in the field using a certified canister of 100 ppm CO. The *personal*DataRAM was factory-calibrated annually, which provided an initial qualitative measure for use in side-by-side sampling with a filter/cyclone combination in the field. Because *personal*DataRAM response is dependent on the size distribution and refractive index of the particles sampled, sampling response to field aerosols are likely to be different from the response to calibration aerosols used at the factory. Samplers were worn for the duration of the work shift.

Arrays of the above-identified instrumentation, along with a closed-face cassette for total particulate sampling and a filter cassette with a 10-mm nylon respirable cyclone to collect samples for EC/OC analysis, were positioned 1.3 m above the ground in sampling "baskets" adjacent to the fire line and at the base camp (located approximately five miles from burn activity) to collect area samples for the duration of the work shift. Each basket also included an open-face cassette that was activated for a 1-hour period during the shift to collect particles for elemental analyses by energy dispersive x-ray analysis (EDX) and for morphological analyses by scanning electron microscopy (SEM). Closed-face versions of the filter cassettes were selected for collection of the total particulate samples to minimize unwanted collection of inertially dispersed debris such as chainsaw cuttings; open-face versions of the filter cassettes were selected for the shorter-term collection of a more uniformly distributed array of particles on the filter for microscopic examination.

Sample analyses for LG and for elemental particle composition and morphology were performed at the National Institute for Occupational Safety and Health (NIOSH); all other analyses were performed at a contract laboratory accredited by the American Industrial Hygiene Association (AIHA®).

Statistical Methods

Descriptive statistics were calculated for demographic and clinical variables, as well as for self-reported smoke exposures over the shift immediately preceding the medical assessment. Crew members' breathing zones were sampled, and their results were analyzed according to job (Lead worker, Line worker, Sawyer, or Swamper) and operation (fire line construction or mop-up).

The airborne concentration and aerodynamic size distribution of particulate mass were determined for each personal cascade impactor sample. Composite values of mass concentration as a function of particle size were calculated as averages for each stage across all samples. The concentration of the respirable fraction of particulate mass was calculated using standard cascade impactor correction factors.[19] The airborne concentration and aerodynamic size distribution of LG were determined from the personal cascade impactor samples. LG respirable concentrations were also determined from the respirable cyclone samples.

The geometric mean (GM) concentration and geometric standard deviation (GSD) of the concentration distribution were calculated for each analyte. Concentration values below the limit of detection (LOD) were treated using the maximum likelihood estimation method, consistent with conventional practice following a review of the data's distribution.[20] One-way and multifactor analysis of variance techniques were used to compare mean values of log-transformed analyte concentrations by job, operation, and location. Spearman correlation coefficients were calculated to examine associations between paired RT CO and RT particulate concentrations (for both time-weighted average (TWA) and individual 1-min interval values). Spearman correlations were also examined for associations between TWA CO and the following analytes: TWA total particulate concentrations, TWA respirable particulate concentrations (for both impactor and cyclone samples), LG (total and respirable), and organic carbon.

Mean cross-shift changes in FEV_1 (ΔFEV_1) and in exhaled breath CO (ΔCO) were investigated using paired difference

TABLE II. Environmental Sampling Methods

Analyte	Analytical Method	Sample Type: Area (A) and/or Personal (P)	Sampling Device and Media	Flow Rate (lpm)
Particle size distribution	Gravimetric analysis by NIOSH Method 0500	A, P	Marple 8-stage Personal Cascade Impactor, Model 298 (Thermo Scientific Corporation, Franklin, Mass.) with 34-mm diameter radial-cut polyvinyl chloride (PVC) substrates (first stage greased); stage cut points of 21.3, 14.8, 6.0, 3.5, 1.6, 0.93, and 0.52 μm; followed by a 5-μm-pore-size PVC final filter	2.0
Particle elemental and morphological analyses	Energy dispersive x-ray spectrometry (EDX) and scanning electron microscopy (SEM) for particle profiles; filter carbon tape-mounted on aluminum stub and sputter-coated with gold/palladium (SPI Supplies, West Chester, Pa.); EDX conducted with IMIX Microanalysis Imaging System (Princeton Gamma-Tech, Princeton, N.J.); SEM analyses conducted with model JEM6400 (JEOL, Tokyo, Japan)	A	Open-face cassette with 37-mm diameter, 0.8-μm pore size polycarbonate filter	2.0
Total particulate	Gravimetric analysis by NIOSH Method 0500	A	Closed-face cassette with 37-mm diameter, 5-μm pore size PVC filter	2.0
Respirable particulate	Gravimetric analysis by NIOSH Method 0600	A, P	10-mm nylon respirable dust cyclone followed by 37-mm diameter, 5-μm pore size PVC filter	1.7
Real-time particulate (0.1 to 10 μm)	Passive flow direct-reading instrument	A, P	*personal*DataRAM *p*DR-1000-AN monitor (Thermo Scientific Corporation, Franklin, Mass.) at 1-min averaging periods	N/A
Real-time carbon monoxide	Passive flow direct-reading instrument	A, P	T82™ Single-Gas Monitor (Industrial Scientific Corporation, Oakdale, PA) at 1-min averaging period	N/A
Levoglucosan	Levoglucosan extracted from filter using methanol and extract evaporated to dryness under nitrogen; each sample and standard derivatized using Tri-Sil reagent (Thermo Scientific, Rockford, Ill.), and then quantified by gas chromatography-mass spectrometry	P	Samples from personal cascade impactors were sent for this analysis after gravimetric analysis	2.0
		A, P	Subset of respirable dust cyclone samples were sent for this analysis after gravimetric analysis	1.7
Crystalline silica	X-ray diffraction by NIOSH Method 7500	A, P	Subset of respirable dust cyclone samples were sent for this analysis after gravimetric analysis	1.7
Elemental carbon/ organic carbon	Thermal-optical analysis and flame ionization detection by NIOSH Method 5040	A	10-mm nylon respirable dust cyclone followed by 37-mm diameter binder-free quartz fiber filter	1.7

Note: N/A indicates that an active flow rate value is not applicable to the passive flow devices.

TABLE III. Personal Concentration Results by Job

Analyte[A]	Job	N	GM	GSD	MIN	MAX
Particulate, Total-Impactor (mg/m^3)	Lead	1	1.16	N/A[B]	N/A	N/A
	Line	9	1.99	1.51	0.92	3.12
	Sawyer	3	2.80	1.55	1.71	3.93
	Swamper	3	2.27	1.28	1.78	2.93
Particulate, Respirable-Impactor (mg/m^3)	Lead	1	0.88	N/A	N/A	N/A
	Line	9	0.35	1.58	0.20	0.72
	Sawyer	3	0.41	1.87	0.22	0.78
	Swamper	3	0.40	1.23	0.33	0.49
Particulate, Respirable-Cyclone (mg/m^3)	Lead	2	0.14	1.33	0.11	0.17
	Line	13	0.33	2.49	0.13	2.18
	Sawyer	7	0.52	1.96	0.27	2.07
	Swamper	7	0.69	1.59	0.27	1.03
Particulate-Real-time (mg/m^3)[C]	Line	10	0.60	1.60	0.29	1.49
	Sawyer	2	1.68	1.48	1.27	2.22
	Swamper	1	1.40	N/A	N/A	N/A
Carbon monoxide (ppm)	Lead	7	0.58	1.23	0.50	0.83
	Line	36	0.67	1.52	0.50	2.83
	Sawyer	12	8.19	1.64	4.15	16.5
	Swamper	12	6.24	1.71	2.51	14.6
Levoglucosan, Total-Impactor ($\mu g/m^3$)	Lead	1	0.65	N/A	N/A	N/A
	Line	8	3.04	2.41	1.43	20.4
	Sawyer	3	1.31	2.70	0.61	4.02
	Swamper	3	2.66	3.06	0.75	6.20
Levoglucosan, Respirable-Impactor ($\mu g/m^3$)	Lead	1	0.38	N/A	N/A	N/A
	Line	8	1.48	3.66	0.22	18.8
	Sawyer	3	0.50	3.48	0.22	2.12
	Swamper	3	0.92	2.83	0.30	2.42
Levoglucosan, Respirable-Cyclone ($\mu g/m^3$)	Lead	1	0.22	N/A	N/A	N/A
	Line	8	1.25	4.35	0.36	21.6
	Sawyer	2	0.21	1.01	0.21	0.21
	Swamper	3	3.24	3.73	0.71	7.08

Note: GM = geometric mean.
GSD = geometric standard deviation.
[A]Results for crystalline silica were below the minimum quantifiable concentration of 0.025 mg/m^3 and are not tabulated.
[B]N/A indicates not applicable for single value.
[C]No RT measurement obtained for lead worker.

Student t-tests. We used the MIXED procedure for repeated measures with a first-order autoregressive correlation structure (SAS software version 9.1, SAS Institute Inc., Cary, N.C.) to examine univariate and multivariate associations between individual ΔFEV_1 and several predictor variables, some of which were categorized by distributional tertiles (including total particulate concentration, respirable particulate concentration as measured by impactor, respirable particulate concentration as measured by cyclone, total LG concentration, respirable LG concentration as measured by impactor, and peak dust exposure). Similar univariate and multivariate associations were examined between exhaled breath ΔCO and the above-noted predictor variables.

Respirable LG concentration, as measured by filtration following a 10-mm respirable cyclone, and RT TWA particulate concentration each had distinct bimodal distributions and were categorized accordingly. Specifically, participants with values of respirable LG concentration exceeding 1 $\mu g/m^3$ were classified as having high LG exposure. Similarly, participants with values of RT TWA particulate concentration exceeding 1 mg/m^3 were classified as having high RT TWA particulate exposure. High peak RT particulate concentration (defined as one or more peaks greater than 10 mg/m^3) was also analyzed. We additionally examined age, a history of allergies, and pre-season FEV_1. Heterogeneities in the cohort were insufficient to support analyses of relationships involving race/ethnicity, gender, and smoking.

For individuals with more than one measurement for a specific analyte, categorization was based on the average of the measured values. For all analyses, we considered two-sided

TABLE IV. Personal Concentration Results by Crew Operation

	Crew Operation[A]	N	GM	GSD	MIN	MAX
Particulate, Total-Impactor (mg/m^3)	Fire line construction	8	2.28	1.43	1.16	3.93
	Mop-up	3	1.86	1.88	0.92	3.12
Particulate, Respirable-Impactor (mg/m^3)	Fire line construction	8	0.45	1.62	0.24	0.88
	Mop-up	3	0.38	1.92	0.20	0.72
Particulate, Respirable-Cyclone (mg/m^3)	Fire line construction	14	0.49	2.59	0.11	2.18
	Mop-up	8	0.51	1.96	0.17	1.14
Particulate-Real-time (mg/m^3)	Fire line construction	7	1.04	1.93	0.29	2.22
	Mop-up	5	0.51	1.21	0.42	0.68
Carbon monoxide (ppm)	Fire line construction	34	1.93	3.84	0.50	16.5
	Mop-up	16	1.24	3.06	0.50	6.64
Levoglucosan, Total-Impactor ($\mu g/m^3$)	Fire line construction	8	3.64	2.67	0.65	20.4
	Mop-up	2	1.13	1.79	0.75	1.70
Levoglucosan, Respirable-Impactor ($\mu g/m^3$)	Fire line construction	8	1.88	3.07	0.38	18.8
	Mop-up	2	0.26	1.25	0.22	0.31
Levoglucosan, Respirable-Cyclone ($\mu g/m^3$)	Fire line construction	7	2.59	5.20	0.36	21.6
	Mop-up	4	0.28	1.75	0.21	0.64

Note: GM = geometric mean; GSD = geometric standard deviation.
[A]Decreased sample numbers attributable to exclusion of day where crew split its time between fire line construction and mop-up.

$p < 0.05$ as indicating statistical significance and two-sided $p > 0.05$ but $p < 0.10$ as indicating borderline statistical significance.

RESULTS

Of the 20 members of the Alpine IHC, 18 were on active assignment with the crew during the time of the Red Eagle Fire. All 18 participated in the environmental measurement portion of the study and 17 of them (94%) participated in the medical portion of the study (Table I). Participants had a median age of 26 years, and were primarily Caucasian, non-Hispanic males (94%). Approximately 12% were former smokers and about 88% had never smoked. Nearly 53% reported having allergies and one participant reported current physician-diagnosed asthma. Median pulmonary function values obtained at the first pre-shift assessment were about 104% of predicted.

TABLE V. Area Concentration Results by Location

Analyte[A,B]	Location	N	GM	GSD	MIN	MAX
Particulate, Total-Impactor (mg/m^3)	Base camp	2	0.27	1.27	0.22	0.31
	Fire line	5	0.66	1.82	0.41	1.85
Particulate Total-Cassette (mg/m^3)	Base camp	2	0.14	1.01	0.14	0.14
	Fire line	5	0.53	2.16	0.19	1.48
Particulate, Respirable-Impactor (mg/m^3)	Base camp	2	0.13	1.15	0.12	0.14
	Fire line	5	0.35	2.23	0.16	1.29
Particulate, Respirable-Cyclone (mg/m^3)	Base camp	4	0.09	1.50	0.06	0.15
	Fire line	10	0.27	2.98	0.03	0.99
Particulate-Real-time (mg/m^3)	Base camp	2	0.38	1.10	0.35	0.41
	Fire line	3	0.59	2.77	0.19	1.31
Carbon monoxide (ppm)	Base camp	2	1.16	1.16	1.08	1.23
	Fire line	4	2.72	1.90	1.30	6.18
Levoglucosan, Respirable-Cyclone ($\mu g/m^3$)	Base camp	2	0.39	1.13	0.36	0.43
	Fire line	5	4.99	7.19	0.27	32.9
Organic Carbon, Respirable-Cyclone (mg/m^3)	Base camp	2	0.07	1.02	0.07	0.07
	Fire line	5	0.24	2.27	0.07	0.71

Note: GM = geometric mean; GSD = geometric standard deviation.
[A]Results for elemental carbon are not tabulated because only one value from a cyclone sample taken at the fire line was at the minimum detectable concentration (MDC) of 0.01 ug/m^3, and all other values were below that concentration.
[B]Results for crystalline silica were below the MDC of 0.005 mg/m^3 and are not tabulated.

Exposure Assessment

A total of 125 personal and 53 area air samples were collected during fire line construction (two full days and one half day) and mop-up operations (one full day and one half day). The average duration of the work shift was 12 hr. GM and GSD analyte concentrations from personal samplers are listed by job and crew operation in Tables III and IV, respectively. However, concentration means for the day when the crew split its time between fire line construction and mop-up operations are not reported in Table IV. GMs and GSD analyte concentrations from area samplers are reported by location in Table V.

Particle Size Distribution

Results of particle size distributions assessed using data from 13 personal impactor samples are illustrated in Figure 1. Figure 1A shows the mass-based distribution as a function of particle size. Wildfire smoke particles were present in all size ranges from smaller than 0.52 μm to greater than 21.3 μm. Note that airborne particle mass is mostly associated with larger particles, while the levoglucosan component of the wildfire smoke aerosol showed a primarily bimodal size distribution: a coarse particle mode with an MMAD greater than 15 μm and a fine particle mode with an MMAD less than 0.5 μm. When examined by percent mass, nearly half the particulate collected (44%) was found on the first stage of the impactor (in the very coarse range with effective cutoff diameter of 21.3 μm). The second largest percent mass collected (13%) was found on the backup filter of the impactor (in the ultrafine range with cutoff diameter < 0.52 μm). Figure 1B shows the distribution of airborne LG by particle size fractions. The largest mass fraction was found on the first stage of the impactor making up 27% of the total mass collected. However, nearly two-thirds of the levoglucosan collected (71%) was found in the respirable range.

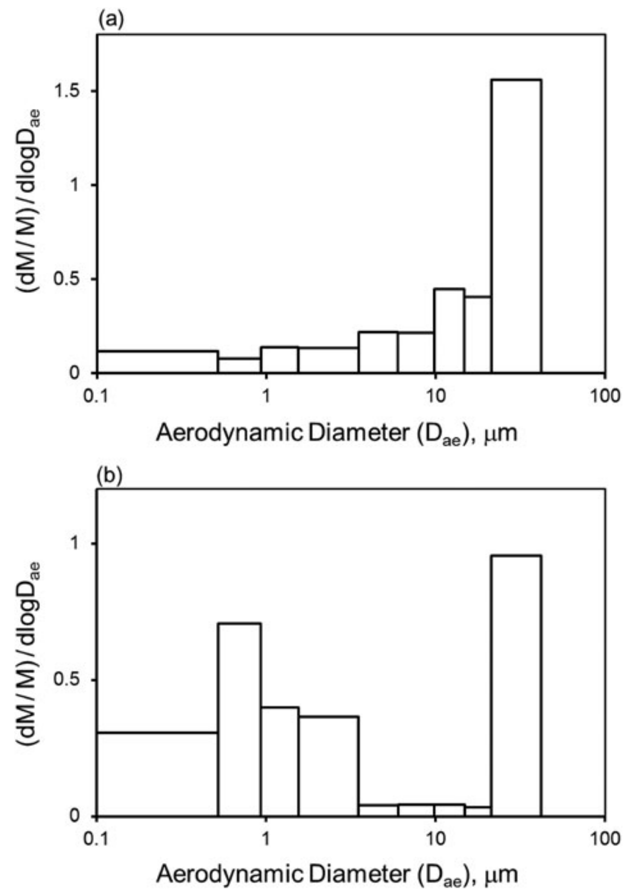

FIGURE 1. Normalized personal cascade impactor particle size distributions for (a) airborne particle mass and (b) airborne levoglucosan. Note that airborne particle mass is mostly associated with larger particles, while airborne levoglucosan is bimodally distributed.

Elemental and Morphological Analyses

The particulate profiles based on EDX and SEM techniques created from seven filter cassette samples obtained at the base camp and fire line revealed three distinctive types of particles: a crystal-like particle comprising mainly titanium, iron, and aluminum silicate (Figure 2A) (other similarly configured particles also showed lead, calcium, and/or magnesium); a spherical, tar-like particle containing mainly carbon (Figure 2B); and particles with an aggregate configuration of many tar-like particles (Figure 2C). There was no observed difference in the composition or type in the samples by location.

Total and Respirable Particulate Concentrations

Assessment of personal particulate concentration using data from 16 impactor samples and 29 cyclone samples showed that GMs for total particulate concentration did not vary significantly by job or crew operation. The GM for the respirable particulate portion of the impactors for all operations was 0.39 mg/m^3 (18% of total particulate). Although the only impactor measurement of total particulate exposure to Lead workers (who are responsible for supervision) appeared lower than exposures to the workers who are engaged in direct cutting, digging, and other fire line construction activities, the respirable fraction of that Lead worker's exposure measured by impactor was higher (0.88 mg/m^3) than those of the Line workers (0.35 mg/m^3), Sawyers (0.41 mg/m^3), and Swampers (0.40 mg/m^3), and, overall, the respirable particulate concentrations from the impactors did not vary significantly by job or crew operation.

Respirable particulates as measured by cyclone, however, were found to vary by job, ranging from a GM of 0.14 mg/m^3 for Lead workers, to a GM of 0.33 mg/m^3 for Line workers, to a GM of 0.69 mg/m^3 for Swampers. The influence of work type (e.g., Lead workers being involved in supervision versus other workers being directly involved in fire line construction) was reflected in the significantly higher respirable particulate concentrations that were observed for Swampers compared to Lead workers (GM = 0.14 mg/m^3) ($p < 0.05$) and Line workers (GM = 0.33 mg/m^3) ($p < 0.05$). Respirable particulate concentrations were also significantly higher for Sawyers (GM = 0.52 mg/m^3) than for Lead workers ($p < 0.05$).

Respirable particulate concentration as measured by cyclone did not vary significantly by crew operation.

Area respirable particulate concentration, as assessed using data from 14 cyclone samples, did not differ by location. The value of one sample obtained at a sampling rate of 1.7 L/min for 344 min during a digging operation was below the minimum detectable concentration (MDC) of 0.05 mg/m^3, based on an analytical LOD of 30 μg per sample. Total particulate concentration, as measured by cassette samples, was higher at the fire line (GM = 0.53 mg/m^3) than at base camp (GM = 0.14 mg/m^3). However, this difference was only marginally significant (p = 0.07).

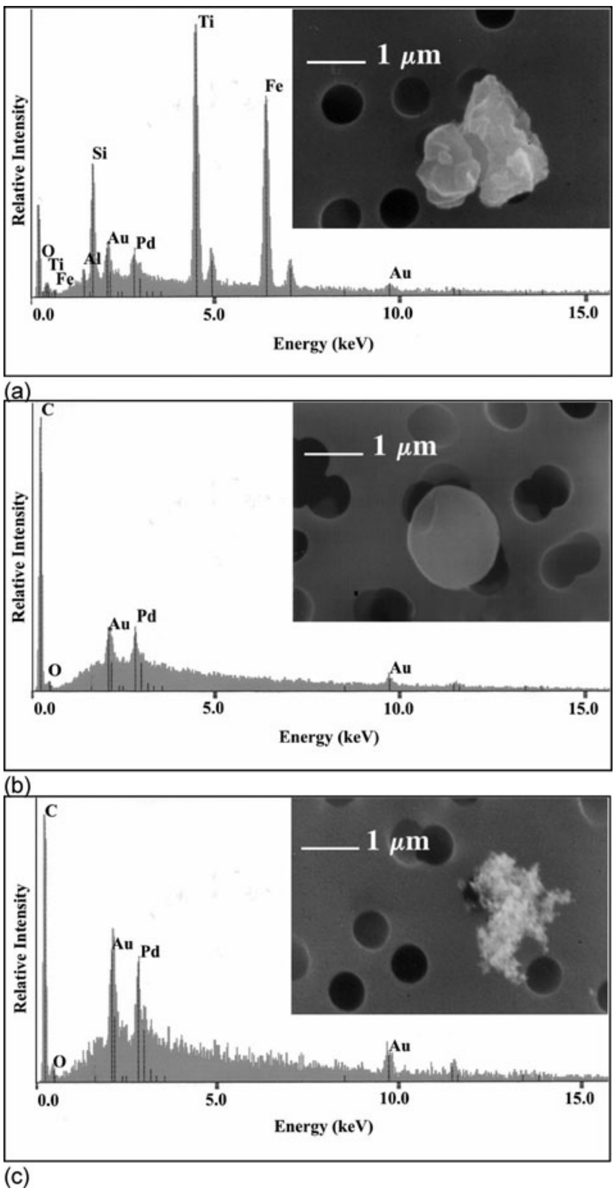

FIGURE 2. Elemental Particle Profile and Electron Micrograph of Particles: (a) samples obtained at base camp indicate a crystal-like particle comprised mostly of titanium, aluminum silicate, and iron; (b) samples obtained at the fire line revealed a spherical, tar-like particle containing mainly carbon; and (c) and other samples obtained at the fire line appear to have an aggregate configuration of many tar-like particles. The gold (Au) and palladium (Pd) peaks are from the sputter coating on the samples and are not constituents of the particles. The active diameter of EDX interrogation was approximately 1 μm and particle composition did not appear to vary with beam location on particle surface.

Real-time Particulate Concentrations

There were 7908 1-min interval data points from 13 personal RT particulate samplers. RT particulate concentration varied by crew operation. The TWA RT particulate concentration during fire line construction (GM = 1.04 mg/m^3) was significantly higher than during mop-up operations (GM = 0.51 mg/m^3) ($p < 0.05$). RT particulate concentration also differed by job, being significantly higher for Sawyers (GM = 1.7 mg/m^3) than for Line workers (GM = 0.60 mg/m^3) ($p < 0.05$). There were 2,431 1-min interval data points from five area RT particulate samplers. RT particulate concentration did not vary by location.

Personal particulate concentrations exceeded 1 mg/m^3 1707 times (i.e., during 21% of all measured intervals) (n = 10 participants); 5 mg/m^3 211 times (2.6%) (n = 10 participants), and 10 mg/m^3 62 times ($<$ 1%) (n = 6 participants). Area particulate concentrations exceeded 1 mg/m^3 434 times (25%) (5 samples), 5 mg/m^3 23 times (1.1%) (1 sample), and 10 mg/m^3 6 times ($<$ 1%) (1 sample).

Carbon Monoxide Concentrations

There were 45,035 1-min interval data points from 67 personal CO samples. Mean values differed by job. The CO concentrations for Swampers (GM = 6.24 parts per million (ppm)) and Sawyers (GM = 8.19 ppm) were significantly higher than those for Line workers (GM = 0.67 ppm) ($p < 0.001$) or Lead workers (GM = 0.58 ppm) ($p < 0.001$). Mean CO concentrations did not differ significantly by crew operation.

There were 3330 1-min interval data points from six area CO samplers. Mean values did not differ significantly by location. TWA CO values never exceeded the NIOSH recommended exposure limit (REL) of 35 ppm or the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) of 25 ppm. Nine personal samples, including eight Sawyers or Swampers, exceeded the NIOSH ceiling exposure limit of 200 ppm from one to four times during his or her shift.

Levoglucosan (LG) Concentrations

Results of LG concentration analyzed with data from 29 personal samples (15 samples by cascade impactor and 14 samples by cyclone) showed no differences by job or crew operation for personal total LG concentration. Respirable LG concentrations as measured by impactor differed by crew operation, being significantly higher for fire line construction (GM = 1.88 μg/m^3) than for mop-up (0.26 μg/m^3) ($p < 0.05$). Values from three cyclones were below the MDC of 0.4 μg/m^3

for 8-hr samples collected at 1.7 L/min based on an analytical LOD of 0.3 μg LG per sample.

The GM concentration of LG in the respirable particulate as measured by cyclones was 1.05 μg /m^3. Similar to the estimates from the respirable particulate portion of the impactor samples, concentrations obtained from the cyclone samples differed by crew operation; concentrations for fire line construction (GM = 2.59 μg/m^3) being significantly higher than those for mop-up (GM = 0.28 μg/m^3) ($p < 0.05$). Mean LG concentrations as measured by cyclone, also differed by job; concentrations for Swampers (GM = 3.24 μg/m^3) being significantly higher than for Sawyers (0.21 μg/m^3) ($p < 0.05$).

Analyses of respirable LG concentrations obtained from seven area cyclone samples showed that median respirable LG concentration appeared much higher in samples obtained from the fire line (GM = 4.99 μg/m^3, GSD = 7.19 μg/m^3) than base camp (GM = 0.39 μg/m^3, GSD = 1.13 μg/m^3). However, this difference was not statistically significant. The value of one cyclone sample obtained from the fire line area at a sampling rate of 1.7 L/min for 344 min was below the MDC of 0.54 μg/m^3 for LG, based on an analytical LOD of 0.3 μg per sample.

Crystalline Silica Concentrations

Analyses of concentrations of respirable crystalline silica obtained from 15 personal and 7 area samples showed that neither tridymite nor cristobalite was detected in any samples. None of the area samples and only three of the 15 personal samples (14%) were found to have quartz concentrations above the MDC of 0.005 mg/m^3 for an 8-hr sample collected at 1.7 L/min based on an analytical LOD of 4 μg per sample. None of the detected values exceeded the minimum quantifiable concentration of 0.025 mg/m^3 for an 8-hr sample. Thus, no concentrations exceeded either the American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value (TLV) of 0.025 mg/m^3 or the NIOSH REL of 0.05 mg/m^3 for crystalline silica.

Elemental Carbon/Organic Carbon Concentrations

GM concentration of organic carbon obtained from seven area samples was 0.17 mg/m^3. Although the geometric mean concentration of respirable airborne organic carbon measure at the fire line location (0.24 mg/m^3) was greater than the geometric mean concentration measured at the base camp (0.07 mg/m^3), the difference by location was not significant. All but one of the seven values for elemental carbon were below the minimal detectable concentration (MDC) of 0.01 mg/m^3 for an 8-hr sample collected at 1.7 L/min based on an analytical LOD of 6 μg elemental carbon per sample; the detectable sample value was at the MDC.

Investigation of Correlations Between CO Concentrations and Other Measured Exposure Factors

Paired analyses of RT personal air sampling measurements indicated that higher TWA CO concentrations were correlated with higher particulate concentrations when examined by mean values. However, this was not the case when values for each analyte were low (Figure 3). Moreover, we did not observe a similar relationship between CO and particulate concentrations when examined by individual data points. In multifactor analysis, TWA CO was associated with job ($p < 0.001$) and crew activity ($p < 0.01$). Specifically, Sawyers had the highest TWA CO (regression estimate: 9.0, 95% CI: 7.34–10.6 ppm), followed by Swampers (regression estimate: 5.90, 95% CI: 4.59–7.20 ppm), and Line workers (regression estimate: −0.00, 95% CI:–0.66, 0.65 ppm). Digging line produced the highest mean TWA CO concentrations (regression estimate: 6.09, 95% CI: 5.17, 7.00 ppm), followed by mop-up (regression estimate: 4.84, 95% CI: 3.57, 6.12). Additional information about investigated correlations is provided in the supplemental material section.

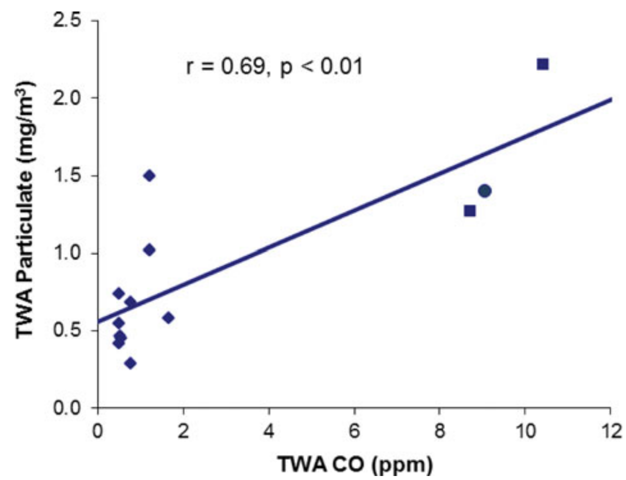

FIGURE 3. Correlation between paired real-time full-shift time-weighted average concentrations of CO and particulate (0.1 to 10 μm, as measured by personalDataRAM), stratified by job. Line worker (♦) (eight paired observations); Sawyer (■) (two paired observations); and Swamper (•) (one paired observation). (color figure available online)

Exposure Questionnaire Responses

A total of 68 questionnaire responses regarding the severity of smoke exposure and the severity of dust exposure during the preceding shift were obtained from the 17 participants over the course of four days. Regarding smoke exposure, day-one responses comprised two "no" smoke exposures, 14 "mild" exposures, and one "moderate" exposure; day-two responses comprised nine "no smoke" exposures, seven "mild" exposures, and one "moderate" exposure; day-three responses comprised three "no" smoke exposures and 14 "mild" exposures; and on day four, all 17 participants reported "no" smoke exposure. No "severe" smoke exposures were reported for any of the study days.

Regarding dust exposure, day-one responses comprised one "no" dust exposure, 10 "mild" exposures, and six "moderate" exposures; day-two responses comprised two "no" dust exposures, 10 "mild" exposures, and five "moderate" exposures;

day three responses comprised one "no" dust exposure, 12 "mild" exposures, and four "moderate" exposures; and on day four there were two responses of "no" dust exposure, five responses of "mild" dust exposure, and 10 responses of "moderate" dust exposure. No "severe" dust exposures were reported at any time.

Based on questionnaire responses, the median time spent in smoke during the preceding shift was 25 minutes min (range 0, 10 hr) and the median time spent in dust during the preceding shift was four hours (range 0, 10).

Medical Survey

Exhaled Breath Carbon Monoxide

The pre-shift exhaled breath CO level was 1.8 ppm and the mean post-shift level was significantly higher at 3.2 ppm ($p < 0.001$). Paired mean post-shift exhaled breath and personal TWA CO concentrations from the same shift and crew members were moderately correlated within firefighters ($r = 0.54$) ($p < 0.001$). In univariate analysis, exhaled breath ΔCO was significantly associated with TWA CO concentrations (regression estimate: 0.31, 95% CI: 0.10, 0.50). However, this association ceased to be significant after adjusting for job and crew activity ($p < 0.10$). No other analytes were found to be associated with exhaled breath CO.

Spirometry

A total of 67 sets of individually paired pre-shift and post-shift spirometry tests were available for analysis. One individual declined to participate in one post-shift session. The mean ΔFEV_1 was a 0.045 L decline ($p = 0.08$). Cross-shift spirometry results were previously reported.[3]

One participant experienced a 16% ΔFEV_1 decline over the first day of testing. His FEV_1 returned to his baseline value which was within the normal range on the evening of the second day of testing, but he experienced a greater than 9% ΔFEV_1 decline over the third day of testing. Five other participants, two of whom were Swampers, experienced a ΔFEV_1 decline between 5% and 10% at least once during the observation period. One participant experienced declines of this magnitude on three separate days, another on two separate days, and three on only one day during the study period. These six individuals ranged in age from 24 to 36 years (mean age 31), one had a history of asthma, and most (5/6) reported a history of allergies. They reported mild or no smoke exposure over the preceding shift on the days that they experienced the ΔFEV_1 declines. However, as we note in the Discussion section this subjective and qualitative description may underestimate the true exposure these individuals experienced.

The mean cross-shift ΔFEV_1 was a decline of 0.05 L ($p = 0.08$). However, univariate analysis by distributional tertiles of age revealed an age-related trend in this change ($p < 0.01$), with mean ΔFEV_1 values for participants ages 24 and younger, ages 25 to 29, and ages 30 and older, respectively, being an increase of 0.02 L, a decline of 0.08 L, and a decline of 0.10 L. Also in univariate analysis, ΔFEV_1 decline was associated with higher concentrations of respirable LG, as measured by cyclone. There were 14 spirometry measurements that had corresponding LG concentration measurements by cyclone. Participants in the high LG exposure group had a mean ΔFEV_1 decline of 0.23 L compared to a mean decline of 0.02 L in the low LG exposure group. Larger mean ΔFEV_1 values were also observed for Swampers (0.19 L decrease) compared to sawyers (0.03 L increase) and Line workers (0.03 L decrease). These associations remained significant in multifactor analyses for LG after adjusting for age, job, and crew operation ($p < 0.05$). Unadjusted and adjusted results can be found in Table VI. Finally, larger mean values of pre-shift exhaled breath CO were associated with larger declines in FEV_1. Specifically, for every 1 unit increase in pre-shift exhaled breath CO, ΔFEV_1 value increased by 0.03 L ($p < 0.05$). This association remained significant in multifactor analyses after adjusting for smoking status, job, and crew operation. No other analytes were significantly associated with change in FEV_1.

TABLE VI. Cross-shift Decline in FEV_1 (mean estimate in liters followed by 95% CI) Based on Univariate and Multivariate Analyses of Levoglucosan Exposure, Job, and Crew Operation

Variable	Unadjusted decline in FEV_1 (L)	Adjusted^A decline in FEV_1 (L)
Levoglucosan^B		
• High concentration	**0.23 (0.02, 0.44)**	**0.25 (0.02, 0.48)**
• Low concentration	0.02 (−0.10, 0.09)	0.05 (−0.05, 0.16)
Job		
• Line	0.03 (−0.04, 0.11)	0.06 (−0.03, 0.15)
• Sawyer	−0.03 (−0.22, 0.16)	0.03 (−0.17, 0.24)
• Swamper	**0.19 (0.04, 0.34)**	0.12 (−0.01, 0.30)
Crew operation		
• Fire line construction	0.00 (−0.09, 0.09)	0.01 (−0.10, 0.11)
• Mop-up	0.11 (−0.02, 0.23)	0.12 (−0.02, 0.26)
• Both^C	0.10 (−0.02, 0.21)	1.0 (−0.02, 0.21)

Notes: Positive values indicate a cross-shift decline in mean FEV_1 value; bold values indicate significance at $p < 0.05$; negative estimates indicate a cross-shift increase in mean FEV_1 value.
^{A}Age-adjusted estimates controlling for all other specified variables.
^{B}As measured by cyclone
^{C}Crew operations during the shift involved both fire line construction and mop-up.

Analyses of correlations with respirable dust are documented in the supplemental table. For total dust, the p-value was 0.77, and there were not enough observations to examine associations between peak dust and cross-shift lung function. Similarly, no other predictors, including exhaled breath ΔCO, TWA CO, time spent working on an IHC, or atopy, were significantly associated with change in FEV_1.

DISCUSSION

We found evidence that larger declines in ΔFEV_1 were significantly associated with exposure to higher concentrations of LG in the respirable range. Measurement of LG could serve as a valuable exposure assessment tool for fine and ultrafine smoke particles from biomass burning in the presence of other confounding factors including silicates and fossil fuel/gas engine exhaust. Additional work appears needed to confirm whether respirable exposure to LG is a robust indicator of acute pulmonary function changes resulting from inhalation of wildland fire smoke.

Because there were no periods during our field study when the crews were not fighting fires, our study is not able to indicate which firefighters might have cross-shift declines in the absence of smoke exposure, and whether individual firefighters with greater cross-shift declines during non-exposure periods are at greater risk for progressive declines in lung function. Future studies could benefit from inclusion of cross-shift information during periods when participants were unexposed to provide evidence of whether cross-shift FEV_1 declines such as those we observed were caused by fire-related exposures.

However, evidence from worker populations chronically exposed to other airborne occupational hazards suggests that individuals with greater cross-shift declines during exposure periods are at potentially greater risk for long-term declines in lung function.[21–23] In addition, we are not aware of any studies indicating a positive correlation between exercise and FEV_1, but it would be helpful to know whether exercise causes an increase in FEV_1 and whether this is an important consideration or not.

TWA CO concentrations differed by job and were not strongly correlated with total particulate, respirable particulate, organic carbon, and respirable LG. These findings differ from observations made by Reinhardt and Ottmar[9] who gathered area samples (specifically, TWAs of respiratory irritants including CO, acrolein, formaldehyde, and $PM_{3.5}$) at eight wildfires and 39 prescribed fires from 1991–1995. Those authors observed a high correlation between pollutants, supporting the use of CO as a surrogate for other pollutants.[9] Although in our study higher CO readings were associated with higher particulate concentrations, and measurement of lower CO concentrations were associated with a wide range of particulate concentrations. Thus, contrary to the observations of Reinhart and Ottmar, low CO readings may not provide reliable assurance that concomitant particulate exposures are, in fact, low. Nevertheless, a small, inexpensive CO monitor could still be used instead of a bulky, expensive particle monitor to screen for conditions of high average exposures.

When RT CO and particulate concentrations were examined as TWAs, the r-values for their correlation were high. However, when examined on the basis of 1-min interval data, the correlations remained statistically significant (likely due to the large amount of data), but the r-values decreased. For example, the highest correlation indicated that only 22% of the variation in minute-by-minute particulate concentration could be explained by variation in CO concentration ($r = 0.47$). Furthermore, the positive correlation based on TWAs was driven by job, specifically Sawyers and Swampers. It is possible that exhaust from the chainsaw is contributing to the elevated levels observed for these individuals.

We therefore conclude that although CO concentration may serve as a surrogate for particulate concentration when examined by mean values, CO concentration may be less instructive when predicting associations based on individual data points. This discrepancy would need to be considered during the design phase of protocol development when outcomes (e.g., peak exposures versus averages) and analytical methods are determined.

We found significant differences in exposures by crew operation. Specifically, concentrations of RT particulate and respirable LG (as measured by both cyclone and impactor) were higher with fire line construction than mop-up operations. Note that intercomparison of RT particulate concentration measurements alone is limited by possible task-related aerosol differences in light-scattering response. Job task differences in wildland firefighter exposures have been observed previously. Reinhardt and Ottmar reported that smoke exposure was highest in direct attack operations (where a fire line is dug adjacent to an active wildfire) compared with fire line construction farther from the active fire.[9]

Observed differences in organic carbon concentration were not significant between the base camp and the fire line locations, possibly due to the small number of samples taken ($n = 7$), but the general observation of higher organic carbon concentrations near the fire line was consistent with the generally higher concentrations of airborne particle mass. The loose agreements of respirable particulate and respirable LG concentrations measured by impactor and cyclone shown in Tables III–V are also consistent with the limited power of small-sample-number statistics.

It is of note that the estimated cross-shift ΔFEV_1 associated with exposure to higher concentrations of LG increased in magnitude from an unadjusted decline of 0.11 L to an adjusted decline of 0.18 L after controlling for job and crew operation. Specifically, job-related ΔFEV_1 declines were greatest for Swampers (compared to Lead workers, Line workers, and Sawyers) and operation-related declines were greater for fire line construction (compared to mop-up). As previously noted, Swampers were exposed to the highest concentrations of LG, CO, RT particulate, and respirable particulate. Moreover, both respirable particulate and LG mean concentrations were higher for fire line construction than for mop-up. Indeed, the second largest particle concentration percent mass collected (13%) was found in the ultrafine range and nearly two-thirds of the LG collected was found in the respirable range. In addition, in our previous analysis of wood smoke aerosol[24] we observed that highly reactive ·OH radical precursors were more prevalent (per unit mass) in the ultrafine particles, possibly explaining the mechanism for this association with greater cross-shift declines in lung function.

Sample collection is a challenge in wildland fire situations. Our analyses of wildfire aerosol particles by SEM and EDX revealed three distinct types of particles—a crystal-like particle comprised primarily of titanium, iron, and aluminum silicate; a spherical carbon particle, most likely tar; and aggregates of many tar-like particles—and is supportive of previous findings of Booze et al.[13] and Sandberg and Martin.[25] Use of impactors, although requiring greater labor for sampler preparation and greater cost for the analysis of multiple substrates, does yield useful information on particle size distribution, total concentration, and respirable concentration. Use of cyclones requires evaluation of only a single filter, but yields less information.

Confirmation of the equivalency of the impactor and cyclone methods for measurement of respirable concentrations was not quantitatively possible in the current study because it was not feasible to ask firefighters to wear more than a CO monitor plus one other sampler at a time. Perhaps future success in developing miniaturized samplers will overcome this limitation by enabling the collection of paired impactor and cyclone sample sets for job and crew activities. Area sampling in the current study was the only situation in which side-by-side impactor and cyclone samples were collected. When area values of respirable particulate concentration as measured by impactor were compared to the area values of respirable particulate concentration simultaneously measured by cyclone, they were not found to be significantly different ($p = 0.71$).

Limitations of Study

Interpretation and application of our findings involves a number of limitations. Our study involved only one fire and included a relatively small number of participants ($n = 17$) and sampling days ($n = 4$), which limited the statistical power of some of our analyses and may also restrict the generalizability of our findings. Our study also lacked cross-shift data during periods in which the crews were working but not fighting a fire. Such data could have strengthened our finding that the observed ΔFEV_1 declines were caused by exposure to wildland fire smoke particles. Note, however, that a recent study by Adetona et al. [26] did not find significant changes in cross-shift lung function on burn days compared to non-burn days.

We also recognize that use of the qualitative terms "mild," "moderate," and "severe" is subjective, and responses of the subjects to our instructions were based on their individual perception of the smoke conditions. Given the fact that smoke exposures perceived by the subjects as "none" or "mild" are associated with ΔFEV_1 declines, a more quantitative measure of self-reported smoke exposure should be found. We have considered training options (such as visible sight distance or smoke comparison to a printed gray-scale card) that might provide a more common basis for subject responses, but we have not taken that step.

The focus of our study was on health concerns related to firefighter exposures to aerosols in the respirable size range. As shown in Figure 1, the mode of the airborne particle size distribution was above the respirable size range, indicating that a complete characterization of the airborne particle size distribution would require use of instrumentation capable of providing size-fractionated samples in the range greater than 30 μm and possibly as large as several hundred μm. Characterization of the larger particle range could be done, but would need to be justified on the basis of concerns for health effects in the head airways and conducting airways.

CONCLUSION

Despite limitations, results from the current study inform considerations and decision-making for improving the protection of respiratory health. Respiratory protection is not normally worn by wildland firefighters, but NIOSH announced in July 2012 that in collaboration with the Safety Equipment Institute, they will begin issuing certificates of approval for respirators for use during wildland fire-fighting operations.[27] Certification will be in compliance with NFPA 1984-2011.[28]

We conclude that wildland firefighter smoke exposures are characterized by a wide range of particle sizes and that inhalation of fine smoke particles, including associated airborne concentrations of respirable LG, is associated with acute lung function declines in some wildland firefighters. Based on these short-term findings, it appears important to address possible long-term respiratory health issues for workers involved in wildland fire fighting.

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We dedicate this article to the memory of the 19 wildland firefighters from the Granite Mountain IHC of Prescott, Arizona, who perished battling the Yarnell Hill Fire, 80 miles northwest of Phoenix, Arizona, on June 30, 2013.

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

1. **National Interagency Fire Center:** "Total Wildland Fires and Acres (1960–2009)." Available at http://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html (accessed June 14, 2013).
2. **Betchley, C., J.Q. Koenig, G. VanBelle, H. Checkoway, and T. Reinhardt**: Pulmonary function and respiratory symptoms in forest firefighters. *Am. J. Ind. Med. 31*:503–509 (1997).
3. **Gaughan, D.M., J.M. Cox-Ganser, P.L. Enright, et al.:** Acute upper and lower respiratory effects in wildland firefighters. *J. Occup. Environ. Med. 50*:1019–1028 (2008).
4. **Liu, D., I.B. Tager, J.R. Balmes**, and **R.J. Harrison:** The effect of smoke inhalation on lung function and airway responsiveness in wildland firefighters. *Am. Rev. Respir. Dis. 146*:1469–1473 (1992).
5. **Materna, B.L., J.R. Jones, P.M. Sutton, N. Rothman, and R.J. Harrison**: Occupational exposures in California wildland fire fighting. *Am. Ind. Hyg. Assoc. J. 53*:69–76 (1992).
6. **Rothman, N., D.P. Ford, Baser, M.E., et al.:** Pulmonary function and respiratory symptoms in wildland firefighters. *J. Occup. Med. 33*:1163–1167 (1991).
7. **Swiston, J.R., W. Davidson, S. Attridge, G.T. Li, M. Brauer, and van S.F. Eeden:** Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. *Eur. Respir. J. 32*:129–138 (2008).
8. **Hejl, A.M., O. Adetona, D. Diaz-Sanchez, et al.**: Inflammatory effects of woodsmoke exposure among wildland firefighters working at prescribed burns at the Savannah River Site, SC. *J. Occup. Environ. Hyg. 10*:173–180 (2013).
9. **Reinhardt, T.E., and R.D. Ottmar:** Baseline measurements of smoke exposure among wildland firefighters. *J. Occup. Environ. Hyg. 1*:593–606 (2004).
10. **Slaughter, J.C., J.Q. Koenig, and T.E. Reinhardt:** Association between lung function and exposure to smoke among firefighters at prescribed burns. *J. Occup. Environ. Hyg. 1*:45–49 (2004).
11. **Edwards, R., M. Johnson, K.H. Dunn, and L.P. Naeher:** Application of real-time particle sensors to help mitigate exposures of wildland firefighters. *Arch. Environ. Occup. Health 60*:40–43 (2005).
12. **Lee, S., K. Baumann, J.J. Schauer, et al.:** Gaseous and particulate emissions from prescribed burning in Georgia. *Environ. Sci. Technol. 39*:9049–9056 (2005).
13. **Booze, T.F., T.E. Reinhardt, S.J. Quiring, and R.D. Ottmar:** A screening-level assessment of the health risks of chronic smoke exposure for wildland firefighters. *J. Occup. Environ. Hyg. 1*:296–305 (2004).
14. **Jarjour N.N., and W.J. Calhoun:** Enhanced production of oxygen radicals in asthma. *J. Lab. Clin. Med. 123*:131–136 (1994).
15. **Simoneit, B.R.T., J. J. Schauer, C.G. Nolte, et al.:** Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles. *Atmos. Environ. 33*:173–182 (1999).
16. **Miller, M.R., J. Hankinson, V. Brusasco, et al.:** Standardisation of spirometry. *Eur. Respir. J. 26*(*2*):319–338 (2005).
17. **Hankinson J.L., J.R. Odencrantz, and K.B. Fedan:** Spirometric reference values from a sample of the general U.S. population. *Am. J. Respir. Crit. Care. Med. 159*:179–187 (1999).
18. **Ghio, A.J., R.M. Castellan, K.B. Kinsley, and J.L. Hankinson:** Changes in forced expiratory volume in one second and peak expiratory flow rates across a work shift among unexposed blue collar workers. *Am. Rev. Respir. Dis. 143*:1231–1234 (1991).
19. **Rubow, K.L., V.A. Marple, J. Olin, and M.A. McCawley:** A personal cascade impactor: Design, evaluation and calibration. *Am. Ind. Hyg. Assoc. J. 48*:532–538 (1987).
20. **Finkelstein, M.M., and D.K. Verma:** Exposure estimation in the presence of nondetectable values: Another look. *Am. Ind. Hyg. Assoc. J. 62*(*2*):195–198 (2001).
21. **Wang, X., H.X. Zhang, B.X. Sun, et al.:** Cross-shift airway responses and long-term decline in FEV_1 in cotton textile workers. *Am. J. Respir. Crit. Care. Med. 177*(*3*):316–320 (2008).
22. **Becklake, M.R.**: Relationship of acute obstructive airway change to chronic (fixed) obstruction. *Thorax 50*(*Suppl 1*):S16–21 (1995).
23. **Glindmeyer, H.W., J.J. Lefant, R.N. Jones, R.J. Rando, and H. Weill:** Cotton dust and across-shift change in FEV_1 as predictors of annual change in FEV_1. *Am. J. Respir. Crit. Care Med. 149*:584–590 (1994).
24. **Leonard, S.S., V. Castranova, B.T. Chen, et al.:** Particle size-dependent radical generation from wildland fire smoke. *Toxicology 236*(*1–2*):103–113 (2007).
25. **Sandberg, D.V., and R.E. Martin:** Particle Size in Slash Fire Smoke. USDA Forest Service research paper. PNW-199. Pacific Northwest Forest and Range Experiment Station, Portland Ore., 1975.
26. **Adetona O., D.B. Hall, and L.P. Naeher:** Lung function changes in wildland firefighters working at prescribed burns. *Inhal. Toxicol. 23*(*13*):835–841 (2011).
27. **Ahlers, H.:** "NIOSH Initiation of Respirator Certification of Respirators with Protections for Wildland Fire-Fighting Operations," 2012. Available at http://www.cdc.gov/niosh/npptl/resources/pressrel/letters/Manufacturers/lttr-07102012.html?s_cid=3ni7d2TW1207171200 (accessed June 14, 2013).
28. **National Fire Protection Agency:** "NFPA 1984: Standard on Respirators for Wildland Fire Fighting Operations 2011 Edition." Available at: http://www.nfpa.org/catalog/product.asp?pid=198411 (accessed June 14, 2013).