Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality

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ABSTRACT

Wildland firefighters are exposed to wood smoke, which contains hazardous air pollutants, by suppressing thousands of wildfires across the U. S. each year. We estimated the relative risk of lung cancer and cardiovascular disease mortality from existing $PM_{2.5}$ exposure-response relationships using measured PM_4 concentrations from smoke and breathing rates from wildland firefighter field studies across different exposure scenarios. To estimate the relative risk of lung cancer (LC) and cardiovascular disease (CVD) mortality from exposure to $PM_{2.5}$ from smoke, we used an existing exposure-response (ER) relationship. We estimated the daily dose of wildfire smoke $PM_{2.5}$ from measured concentrations of PM_4, estimated wildland firefighter breathing rates, daily shift duration (hours per day) and frequency of exposure (fire days per year and career duration). Firefighters who worked 49 days per year were exposed to a daily dose of PM_4 that ranged from 0.15 mg to 0.74 mg for a 5- and 25-year career, respectively. The daily dose for firefighters working 98 days per year of PM_4 ranged from 0.30 mg to 1.49 mg. Across all exposure scenarios (49 and 98 fire days per year) and career durations (5–25 years), we estimated that wildland firefighters were at an increased risk of LC (8 percent to 43 percent) and CVD (16 percent to 30 percent) mortality. This unique approach assessed long term health risks for wildland firefighters and demonstrated that wildland firefighters have an increased risk of lung cancer and cardiovascular disease mortality.

1. Introduction

Wildland firefighters suppress thousands of wildfires each year that burn across millions of acres in the U.S. (NIFC, 2017a). During 2017, more than 8.8 million acres burned and more than 26,000 wildland firefighters worked to suppress fire during the height of the summer wildfire season (NIFC, 2017a; NIFC, 2017b). Large forest fires in the western U.S. are nearly five times as frequent annually as they were in 1990 (NIFC, 2017a). These fires burn more land area and last much longer than in the past. The wildfire season is also much longer, as exemplified by the Thomas Fire near Santa Barbara, which became (on December 22, 2017) California's largest wildfire in modern history. The wildfire season in California typically ends in October, when the autumn rains begin (InciWeb the Incident Info, 2018).

Wildland firefighters are exposed to inhalation health hazards including hazardous air pollutants from the combustion of vegetative live and dead biomass (smoke) and the breathing of soil dust, while working long work shifts with no respiratory protection (Broyles, 2013; Naeher et al., 2007). Along with exposure to smoke on the fire line, wildland firefighters may be exposed to smoke at incident command posts (ICP) situated near the wildfire to support suppression operations (McNamara et al., 2012). Wildland firefighters conducting prescribed fires (intentionally ignited, low-intensity fires used for land management) are also exposed to smoke (Ryan et al., 2013). Wildfire smoke is a complex

mixture of gas and particle-phase air contaminants, including acrolein, benzene, carbon dioxide, carbon monoxide, formaldehyde, polycyclic aromatic hydrocarbons, and fine and respirable particulate matter (PM with aerodynamic diameters $\leq 2.5 \mu m$ or $\leq 4 \mu m$, respectively), which can contain amorphous carbon or soot (Naeher et al., 2007; Adetona et al., 2016). Soil disturbance from several work activities including fire line construction, mop-up, and open vehicle transportation, also exposes firefighters to mineral contaminants such as crystalline silica (Broyles, 2013).

Previous health studies of wildland firefighters examined acute health effects of smoke exposure across individual shifts and entire fire seasons. Liu et al., 1992, found that 63 wildland firefighters in California had significant declines of individual lung function (FVC, FEV_1, and FEF_{25-75}) and an increase in airway responsiveness post-season when compared with their pre-season baseline values (Liu et al., 1992). When examining cross-shift changes in lung function, Gaughan et al., 2014a, b, reported that wildland firefighters had a significant decline in lung function associated with high exposure to levoglucosan (a tracer for smoke from wood or vegetation combustion) (Gaughan et al., 2014a). Additionally, Adetona et al. (2017), Hejl et al. (2013), and Swiston et al. (2008), reported increased levels of biomarkers of systemic inflammation in firefighters after wildland fires and prescribed burns (Adetona et al., 2017; Hejl et al., 2013; Swiston et al., 2008). Booze et al. (2004), conducted a health risk assessment to characterize the risk of cancer and non-cancer health effects in wildland firefighters (Booze et al., 2004). The study concluded that there were elevated risks of developing cancer, primarily from exposure to benzene and formaldehyde, as well as non-cancer health effects from exposure to $PM_{3.5}$ and acrolein. Recently, Semmens et al. (2016), conducted the first long-term health survey of wildland firefighters that examined the association between the duration of wildland firefighters' careers and self-reported health outcomes (Semmens et al., 2016). The survey reported significant associations between the number of years worked as a wildland firefighter and history of ever diagnosis of two cardiovascular measures - hypertension and/or heart arrhythmia, as well as the need for knee surgery.

The U.S. Environmental Protection Agency regulates fine particulate matter ($PM_{2.5}$) because there is robust epidemiologic evidence of associations between short-term exposures to $PM_{2.5}$ and cardiopulmonary mortality, as well as increased risk of acute cardiovascular outcomes, including myocardial infarction, stroke, and arrhythmias (Atkinson et al., 2015). Along with the epidemiological evidence, experimental evidence from both animal and human studies supports the associations between exposure to $PM_{2.5}$ and cardiovascular outcomes (Brook et al., 2017). Risk of lung cancer is also associated with exposure to ambient $PM_{2.5}$ (Hamra et al., 2014). The recently reported results of a large U.S. cohort study of older individuals (nearly 19 million Medicare beneficiaries) showed increased risks of both cardiovascular mortality and lung cancer with increased $PM_{2.5}$ exposure (Pun et al., 2017).

In our study, we conducted an analysis to examine long-term health impacts for wildland firefighters. Our objective was to estimate relative risk of lung cancer and cardiovascular disease mortality from existing PM exposure-response relationships using a measured PM concentration from smoke and breathing rates from wildland firefighter field studies across different exposure scenarios.

2. Methods

Wildfire Smoke Exposure-Response Relationship. To estimate the relative risk of lung cancer (LC) and cardiovascular disease (CVD) mortality from exposure to $PM_{2.5}$ from smoke, we used the exposure-response (ER) relationships developed by Pope III et al. (2011); Pope et al., 2011. Briefly, they conducted a cohort study analysis from the American Cancer Society (ACS) Cancer Prevention Study II, which included 1.2 million adults, to examine the shape of the exposure-response relationships of $PM_{2.5}$ from ambient air pollution and cigarette smoke with lung cancer and cardiovascular (including ischemic heart disease and cardiopulmonary) mortality. They used the ACS data to estimate relative risks (RR) of LC and/or CVD mortality by increments of cigarette smoking and combined it with selected studies that reported RR from ambient air pollution and second-hand tobacco smoke exposure (estimated daily dose of $PM_{2.5}$) to quantify the exposure-response relationship using a power function with the form $[(RR = 1 + \alpha(dose)^\beta)]$. For lung cancer, the fitted function reported by Pope III et al. (2011), was $[RR = 1 + 0.3195 (dose)^{0.7433}]$ and for CVD the fitted function was $[RR = 1 + 0.2685 (dose)^{0.2730}]$. We used these equations with to calculate disease risk for wildland firefighters.

Estimation of Daily Dose of $PM_{2.5}$. We estimated the daily dose of wildfire smoke $PM_{2.5}$ from measured concentrations of PM_4 (particulate matter with a median diameter of $4 \mu m$), estimated wildland firefighter breathing rates, daily shift duration, and frequency of exposure. We estimated the daily dose across different frequency of exposure scenarios to examine varied days spent on wildfires each year and career length. We used equation (1) to estimate the lifetime daily dose of $PM_{2.5}$ from wildfire smoke for wildland firefighters. The occupational exposure data collected from wildland smoke was characterized based on an aerodynamic ratio of less than $4 \mu m$. However, since pulmonary transport increases with a reduction in particulate size, the use of a relation based on $PM_{2.5}$ should be a close approximation for data based on PM_4 and at the very least, be more conservative. This allowed us to use the Pope III et al. (2011), ER curves. Data from combustion studies have demonstrated that the particle size of combustion-generated particles are on the order of 300 nm (Kleeman et al., 1999; McMeeking et al., 2005). Thus, even though conventional occupational PM samples collect particles with an aerodynamic cut size of 3.5–4 μm, most PM from wildfire smoke exposure is composed of submicron particles, much smaller than $PM_{2.5}$. McMeeking et al. (2005), used an optical particle counter and a differential mobility analyzer to examine the size distribution of particles from wildfire smoke measured during an aerosol study in Yosemite National Park (McMeeking et al., 2005). That study concluded that mass median aerodynamic particle diameter (MMAD) was about 300 nm and volume geometric mean diameters ranged from about 200 nm during non-smoke periods to between 300 and 400 nm during periods of highest fine aerosol mass concentrations associated with smoke-impacted times. Kleeman et al. (1999), measured (under laboratory conditions) the particle sizes of smoke aerosol from several different types of wood and reported that particles ranged from about 90 to about 300 nm in MMAD and that smoke from conventional cigarettes ranged from 300 to 400 nm (Kleeman et al., 1999). Lastly, Leonard et al., 2007, collected aerodynamically size-selected aerosol samples at a wildfire in Alaska to examine particle size and reported that approximately 78 percent of the total mass concentration was from collected particles with a mean diameter of 2.4 μm (Leonard et al., 2007).

$$Daily\ dose\ PM_4\ (mg) = Exposure\ Concentration \left(\frac{mg}{m^3}\right)$$
$$\times\ Daily\ Shift\ Duration \left(\frac{hrs}{shift}\right)$$
$$\times\ Breathing\ Rate \left(\frac{L}{min}\right) \times F \times CF$$

$CF - Conversion\ Factors \left(\frac{60\ min}{hr}\right) and \left(\frac{m^3}{1000\ liters}\right)$

$F - Frequency\ of\ exposure = \left(\frac{shift\ days\ per\ year}{365\ days\ per\ year} \times \frac{years\ of\ firefighting\ career}{45\ years}\right)$ (1)

From 2009 to 2012, the U. S. Department of Agriculture, Forest Service (USFS), National Technology and Development Program (NTDP), conducted an extensive field study that collected breathing zone measurements of occupational exposure to carbon monoxide, PM_4, and crystalline silica at wildfire incidents across the U.S., including Alaska (Broyles, 2013). From 2010 to 2011, a NTDP trained field research team measured wildland firefighter exposure to PM_4 across 80 wildland firefighters on different fire crew types performing various

suppression tasks on wildfires. The research team consisted of wildland firefighters trained by NTDP researchers to collect exposure data and perform direct observation methodologies. The ability of these trained individuals to function amid wildfire suppression activities enabled direct observation of research subjects throughout their respective work shifts without compromising safety or performance.

The research team directly observed each subject for the duration of the work shift, from the moment the subject was equipped with data recording devices before breakfast (typically at 6:00 a.m.) until the conclusion of the work shift. During sample collection, NTDP field observers also recorded information on work shift duration and used the average hours worked, which we used to calculate the daily dose of PM_4 Capturing the shift duration for wildland firefighters was important because individuals working on wildfires typically work more than an 8-h day.

The research team collected PM_4 through methods that are generally consistent with National Institute of Occupational Safety and Health (NIOSH) Method 0600, with analysis of crystalline silica content using NIOSH Method 7500 (NIOSH, 1998; NIOSH, 2003). The NTDP research team attached pre-weighed, 37-mm diameter polyvinyl chloride (PVC) filters with $1 \, \mu m$ pore size in 3-piece cassettes to BGI SCC 1.062 Triplex cyclone, constructed of aluminum to minimize wall losses from electrostatic effects. SKC AirChek pumps drew air through the cyclone and cassette at a target flow rate of just over 1 L per minute. A commercial laboratory accredited by the American Industrial Hygiene Association in their Industrial Hygiene Laboratory Accreditation Program (RJ Lee Group, Monroeville, PA) obtained and later analyzed the pre-weighed filters. After sampling, all filters were capped and transported under chain of custody to the laboratory, accompanied by field blanks prepared each day. Throughout the sampling campaign, we collected 20–100% frequency of field blanks of total samples collected each day. Lab results indicated that there was not net blank mass to subtract from the net sample mass. In addition, field replicates were collected to identify any potential equipment or data collection errors. Sampling pumps were calibrated on site with a primary standard frictionless piston dry calibrator (BIOS DC-Lite) before sampling, and checked again after sampling, using the cyclone calibration adapter provided by the manufacturer. Sampling pumps were placed inside each firefighter's gear pack and cassettes were placed on the shoulder straps of each firefighter's gear pack, as close to the breathing zone as possible. Additionally, the research team placed active sampling equipment at a central location at ICPs or spike camps (satellite camps closer to the wildfire) at most wildfire events to examine off-fire-line exposures.

Shift exposure concentrations were calculated for each firefighter as a time weighted average (TWA) that included exposure on the fire line and at the ICPs or spike camps, and while traveling to and from the wildfire. If ICP or spike camp data showed that the firefighters were exposed even when they were not on the fire line, this was included in the shift average. Summary statistics were calculated in the R System for Statistical Computing (Version 2.13.2), using the package *sand* Version 1.5 which allowed for nonparametric analyses for data with a large number of non-detect concentration values (Frome and Frome; Frome, 2005).

The data from personal PM_4 air samples collected on firefighters during typical firefighting activities would contain some contribution from soil sources that may include crystalline silica, such as dust from hiking on trails and constructed fire line. This could bias our estimates of PM_4 daily dose and could impact the calculated smoke-related health risks. To better estimate the amount of $PM_{2.5}$ from smoke, we subtracted out the respirable crystalline silica, which we used as a surrogate for the soil dust contribution to the measured PM_4 concentrations, yielding our best estimate of the exposure due only to smoke. Crystalline silica samples were analyzed using NIOSH 7500 method which uses x-ray powder diffraction).

We calculated wildland firefighter breathing rates (BR; L air inhaled per minute) from field-measured heart rates while firefighters performed wildland fire operations. A trained NTDP field research team following the protocols described above for smoke data collection collected heart rate measurements during the fire season (May through September) in the western U.S. from 2013 to 2015. The morning of each trial, two to three subjects from a fire crew were fitted with a Hidalgo Equivital™ Physiological Monitor (Equivital, UK) to record heart rate (HR). The NTDP field research team directly observed each subject for the duration of his or her work shift and collected minute-by-minute observations and information on each subject's job task and the physiologic response for each specific task performed. Breathing rate was calculated using HR across the main job tasks performed by wildland firefighters using regression equations developed by Valli et al., 2013) to estimate BR from HR. BR was first calculated for each individual job task and then averaged across all tasks generally performed by a firefighter each day (Valli et al., 2013).

The number of days spent on wildfire assignments per fire season can vary greatly from year to year, and we found no good data source for this information. Additionally, wildland firefighter career length is not well reported in the literature. For this reason, we developed a few different scenarios based on various frequencies of exposure to calculate daily dose of PM_4 using varied days spent on wildfire assignments and career duration. These scenarios were based on the expert opinion of the research team and conversations with wildland firefighters during field studies. According to the Interagency Standards for Fire and Fire Aviation Operations, the standard wildfire assignment is 14 days long; which we used as a guide to estimate days spent on fire assignments (NIFC, 2017c). Additionally, we used the common goal of working 1000 h of overtime for wildland firefighters per fire season to estimate the number of 14-day assignments completed. For wildland firefighters, we estimated a "firefighter long season" to be 98 days spent on fire assignments (equivalent to seven 14-day assignments) and a "firefighter short season" to be 49 days spent on fire assignments (equivalent to three and a half 14-day assignments). We calculated frequency of exposure using 5, 10, 15, 20, and 25 years for wildland firefighter career duration. Lastly, we adjusted career duration by 45 years, which is the average working career of an individual, according to the Occupational Safety and Health Administration (OSHA, 2016).

3. Results

Table 1 presents the parameters we used to calculate daily dose of PM_4 for the two exposure scenarios: (1) firefighter long season and (2) firefighter short season. Based on field study observations, firefighters worked an average of 13.6 h per shift. The mean concentrations of PM_4 and crystalline silica measured on wildland firefighters was $0.53 \, mg \, m^{-3}$ and $0.026 \, mg \, m^{-3}$, respectively. After adjusting the measured shift average concentration of PM_4 for dust exposure (crystalline silica), wildland firefighters were exposed to a mean concentration $0.51 \, mg \, m^{-3}$ of PM_4 due to smoke exposure, with the 95th percentile shift exposure of $0.64 \, mg \, m^{-3}$.

Based on measured HR, we calculated the firefighter breathing rate to be $24\text{-}L \, min^{-1}$ while conducting suppression operations on the fire line. For firefighters, we used measured HR data collected while they performed common work tasks during fire suppression operations, including: hiking, fire line construction, holding, mop-up, lighting, operating a pump, and standing by to receive work assignments (staging). Firefighters can perform fire line construction near the fire's edge (direct) or at a distance (indirect). Fire line construction involves clearing vegetation (often with a chain saw) and digging or scraping down to mineral soil with hand tools to create a break in fuels to stop the spread of a fire. Holding requires firefighters to walk along the active fire to ensure that it has not crossed the fire line. After the fire has burned through an area, firefighters will mop-up by digging out or applying water to extinguish any smoldering material. Another suppression tactic includes lighting, which involves using torches filled with a 3:2

Table 1
Parameters used to Calculate Daily Dose of PM$_4$ for Each Exposure Scenario and Relative Risk for Lung Cancer and Cardiovascular Disease.

Exposure Scenario	Shift Duration (hours)	Shift Exposure (mg/m^3)		Breathing Rate (LPM)	Fire Days (Days/Year)	Career Duration	PM$_4$ Daily Dose (mg)	Lung Cancer	CVD
		Mean	95th Percentile				Mean[a] (95th PCTL)	RR[b]	RR[b]
Firefighter Short Season	13.6	0.51	0.64	24	49	5	0.15 (0.19)	1.08 (1.09)	1.16 (1.17)
						10	0.30 (0.37)	1.13 (1.15)	1.19 (1.21)
						15	0.45 (0.56)	1.18 (1.21)	1.22 (1.23)
						20	0.60 (0.75)	1.22 (1.26)	1.23 (1.25)
						25	0.74 (0.93)	1.26 (1.30)	1.25 (1.26)
Firefighter Long Season					98	5	0.30 (0.37)	1.13 (1.15)	1.19 (1.21)
						10	0.60 (0.75)	1.22 (1.26)	1.23 (1.25)
						15	0.89 (1.12)	1.29 (1.35)	1.26 (1.28)
						20	1.19 (1.50)	1.36 (1.43)	1.28 (1.30)
						25	1.49 (1.87)	1.43 (1.51)	1.30 (1.32)

[a] Daily dose was calculated using the mean and 95th percentile shift exposure concentration.
[b] Relative Risk was calculated using the mean and 95th percentile PM$_4$ Daily Dose.

diesel/unleaded gasoline mixture to burn any unburned fuel to create a fuel break. Pump operators manage gas or diesel pumps that provide water to firefighters.

For wildland firefighters, as frequency of exposure, career duration and days on fire assignment each year (fire days), increased, the daily dose of PM$_4$ also increased (Table 1). Even though exposure concentration, shift duration, and breathing rate remained static for each exposure scenario, the frequency of exposure increased which resulted in an increase of daily dose of PM4 across exposure scenarios. Firefighters who worked a short fire season (49 days) were exposed to a daily dose of PM$_4$ that ranged from 0.15 mg for a 5-year career to 0.74 mg for a 25-year career, respectively. Daily dose of PM$_4$ ranged from 0.30 mg to 1.49 mg for firefighters who worked 5–25 years, respectively, for a long fire season (98 days).

Across all exposure scenarios and career durations, the calculated relative risk for LC and CVD was greater than 1, indicating an increased risk of mortality from LC and CVD from smoke exposure (Fig. 1). Risk of LC ranged from 1.08 to 1.26 for short-season firefighters and 1.13 to 1.43 for long-season firefighters across 5- to 25-year careers. Risk of CVD ranged from 1.16 to 1.25 for short-season firefighters and 1.19 to 1.30 for long-season firefighters across careers that spanned 5–25 years. For both firefighter exposure scenarios, the risk of LC steadily rose as career length increased, while the risk of CVD increased sharply for firefighters with 5- to 15-year careers and increased slightly over 20-

and 25-year careers.

4. Discussion

Our study objectives were to estimate lifetime risk of lung cancer and cardiovascular mortality from exposure to PM$_4$ from smoke. Our analysis used measured PM$_4$ concentration from smoke and estimated breathing rates that we collected as part of extensive field studies of wildland firefighters in the U.S. Using the PM$_{2.5}$ exposure-response relationships developed by Pope III et al. (2011), we estimated that wildland firefighters had an increased risk of LC and CVD mortality, with RRs greater than 1 across all exposure scenarios and career durations.

The measured mean shift TWA PM$_4$ exposures (after correcting for soil-derived respirable particulate contribution using the measured concentrations of quartz) from the NTDP field study used for this analysis were similar (Mean: 0.51 mg m^{-3}; 95th percentile 0.64 mg m^{-3}) to previous firefighter PM2.5 exposure concentrations measured at prescribed burns and similar to or within the range of concentrations reported by others for wildfire incidents (Adetona et al., 2011; Materna et al., 1992; Reinhardt and Ottmar, 2004). After excluding soil dust contribution using the measured concentrations of quartz (averaging 4% of the mass), the remaining PM$_4$ that we measured is expected to be mostly of smal aerodynamic size (averaging
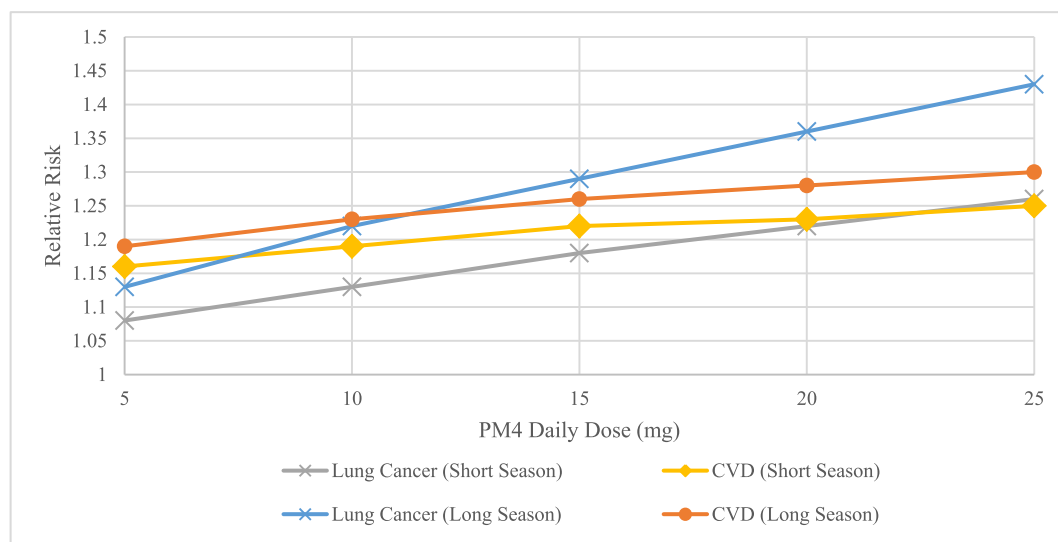

Fig. 1. Relative risk of lung cancer and cardiovascular disease across career length.

approximately 300 nm in diameter), as reported by others (McMeeking et al., 2005; Chakrabarty et al., 2006). Leonard et al. (2007) reported 36% of their mass concentration had an MMAD at 4.2 μm or above, and 64% of the total mass concentration was from collected particles with a mean diameter of 2.4 μm or below (Leonard et al., 2007). Those authors did not grease their collection substrates and noted that their long sampling times may bias their results due to particle bounce. McMahon and Bush reported that operating a Dorr-Oliver nylon cyclone at $4 \, \text{L min}^{-1}$ to measure an MMAD of PM2.3 only captured 88% of the weight concentration of PM3.5 in open burning experiments with forest biomass in a greenhouse, but it is not clear that these tests would be representative of actual exposures in ambient conditions affecting particle removal and agglomeration rates at an actual wildfire (McMahon and Bush, 1992). Reh et al., 1994, measured respirable particulate matter on six firefighters over 2 days in Yosemite National Park and reported concentrations ranging from 0.60 to $1.7 \, \text{mg m}^{-3}$ (Reh et al., 1994). Although occupational health studies generally report personal concentrations as geometric means, we were able to use the geometric mean and geometric standard deviation to calculate arithmetic mean values to compare with our mean shift concentrations. Booze et al. (2004), used $PM_{3.5}$ concentrations measured on the firefighters by Reinhardt and Ottmar (2000) at western wildfires to calculate non-cancer hazard indices (Booze et al., 2004; Reinhardt and Ottmar, 2000). Reinhardt and Ottmar reported mean concentrations of $PM_{3.5}$ of $0.79 \, \text{mg m}^{-3}$ over the entire work shift and $1.13 \, \text{mg m}^{-3}$ for fire line only exposure. Gaughan et al. (2014a,b), reported mean concentration of respirable particles collected by cyclones to be 0.77 and $0.80 \, \text{mg m}^{-3}$ for firefighters performing fire line construction and mop-up, respectively (Gaughan et al., 2014a). Our lower measured mean shift TWA exposures could have resulted in an underestimation of risk, however, our estimate is based on a larger sample size of 80 samples at project wildfires.

Our measured heart rates and estimated breathing rate were lower than one would expect for most individuals presumably performing reasonably heavy labor and were also lower than previous studies measuring breathing rate of wildland firefighters in the field and laboratory over shorter periods of time. However, firefighters are expected to work at consistent exertion levels for the duration of a shift and they are conditioned to be able to perform under the conditions of the job. Cuddy et al. (2015), reported that, based on measured heart rate, wildland firefighters do not experience high levels of cardiovascular strain (Cuddy et al., 2015). By comparison, our estimated breathing rate was comparable to those measured for trained athletes performing exercise at a relatively mild level (e.g., walking on a treadmill at $10.8 \, \text{km h}^{-1}$) (Sracic, 2016). Brotherhood et al. (1997), measured breathing rates of four crews constructing fire line for 7-min periods at various work rates and reported mean breathing rates from 41 to $100 \, \text{l min}^{-1}$ (Brotherhood et al., 1997). In the laboratory, eight male wildland firefighters had a mean breathing rate of $48.4 \, \text{l min}^{-1}$ while performing endurance exercises (45–60 min) three times per week to test for physiological differences from various types of personal protective clothing (Carballo-Leyenda et al., 2017). Past estimates of inhalation doses during wildland firefighting used breathing rates that ranged from 21.6 to $60 \, \text{l min}^{-1}$. Booze et al. (2004), used breathing rates of 40 and $60 \, \text{l min}^{-1}$ to calculate inhalation doses for their screening-level health risk assessment. When calculating inhalation doses for exposure to radionuclides, Viner et al. (2018), used a breathing rate of $21.6 \, \text{l min}^{-1}$ for industrial workers to estimate firefighter cumulative dose. The estimated breathing rate we used was lower than previously reported measurements, it led to underestimation for daily dose and our overall risk calculation.

For this analysis, we developed wildland firefighter exposure scenarios that accounted for days spent working on wildfires and career duration. Although we based these scenarios on the expert opinion of the research team and conversations with wildland firefighters during field studies, they are similar to past wildland firefighter studies.

Semmens et al. (2016), surveyed 545 wildland firefighters (499 completed surveys) about occupational history and self-reported health outcomes and reported that 35 percent of survey respondents had careers that lasted less than 10 years, 33 percent had careers of 10–19 years, and 32 percent had careers of more than 20 years and a mean career duration of 17 years (Semmens et al., 2016). The number of days spent firefighting that we selected for our analysis were within the range of days used by Booze et al. (2004), for Type I wildland fire crews (67 days). However, they were much higher than Type II crews (10 days). The Type I data came from the Northwest Regional Coordinating Center for 1990 to 1994, and the Type II data came from a database from the Okanogan National Forest, which may not have been representative of wildland firefighters across the U.S. The shift durations that NTDP recorded and used to calculate daily dose were similar to past exposure assessments of wildland firefighters. Gaughan et al. (2014a,b), reported a mean shift duration of 12 h and Reinhardt and Ottmar (2000) reported a mean shift duration of 10.4 h (range: 0–24 h) (Gaughan et al., 2014a; Reinhardt and Ottmar, 2000). The varying career durations that we used for our risk calculations seemed reasonable and representative of a wildland firefighter's career and were comparable to previous studies of wildland firefighters.

In the context of the $PM_{2.5}$ exposure-response (ER) curves of Pope III et al. (2011), the daily dose of PM_4 that we calculated for wildland firefighters was in the range of the daily dose of $PM_{2.5}$ from exposure to ambient air pollution and secondhand cigarette smoke. Even after we adjusted the daily dose of PM for firefighters with the frequency of exposure to account for fire days and career length. Through the use of the Pope III et al. (2011) ER curves, we observed that the risk for lung cancer mortality increased nearly linearly with exposures over time and is more strongly influenced by exposure duration than is the risk of death from CVD. However, the risk of cardiovascular mortality rises steeply for doses in the range we estimated for firefighter exposures but flattens out at higher doses. Short-season firefighters that had 5- to 10-year careers and long-season firefighters with a 5-year career had daily doses of PM_4 in the ambient air pollution range. Short-season firefighters with a 15- to 25-year career and long-season firefighters with a 15-year career had daily doses of PM_4 in the secondhand cigarette smoke range; while long-season firefighters with 20- to 25-year careers had higher doses, these doses were still lower than daily doses of $PM_{2.5}$ for active cigarette smokers. Additionally, our calculated range of daily dose of PM_4 for wildland firefighters was similar to the mass intake (equivalent metric to daily dose) of $PM_{2.5}$ from the 2013 Rim Fire in California (Navarro et al., 2016). In Tuolumne County (where the Rim Fire occurred), which was most impacted by smoke, mass intake of $PM_{2.5}$ averaged 0.49 mg per day with a maximum of 1.31 mg per day across the most active 10-day fire period. This comparison demonstrates that a wildland firefighter's inhalation dose of smoke can be similar to communities that are highly impacted by wildfires. However, a wildland firefighter is exposed to these concentrations of smoke for longer periods and not just for a span of a few days or weeks during a single wildfire event.

Although mortality has not been well studied in wildland firefighters, there is evidence of excess mortality among structural firefighters. Baris et al., 2001, observed statistically significant excess risks of ischemic heart disease (SMR = 1.09) among a retrospective cohort of 7789 Philadelphia firefighters (Baris et al., 2001). Daniels et al. (2014, 2015), observed statistically significant positive associations between fire-hours and both leukemia and lung cancer mortality; the relationship between lung cancer and cumulative exposure was nearly linear (Daniels et al., 2014, 2015). Lastly, female firefighters in Florida had increased risk of death from atherosclerotic heart disease when compared with the general Florida population (SMR = 3.85; 95% CI: 1.66 to 7.58) (Ma et al., 2005).

Previous health assessments of wildland firefighters found evidence of arterial stiffness and inflammation after exposure to smoke, which are important to the development of cardiovascular disease (Adetona

et al., 2017; Navarro et al., 2016). Gaughan et al. (2014b), reported that arterial stiffness (measured as mean augmentation index percent) was higher for firefighters from a Type 1 interagency hotshot crew (IHC) exposed to wildfire smoke 4 days before testing when compared with a different Type 1 IHC crew that was not exposed to smoke (Gaughan et al., 2014b). Additionally, the researchers stated that mean augmentation index percent was higher in firefighters with a higher oxidative stress score, which was positively associated with higher levoglucosan concentrations (an indicator of wood smoke). A recent study of wildland firefighters performing holding and lighting at prescribed burns reported that firefighters performing lighting had significantly higher increases in three pro-inflammatory mediators (interleukin-8, C-reactive protein, and serum amyloid A) across their work shifts when compared with firefighters performing holding (Adetona et al., 2017). The researchers did not find an association between estimated $PM_{2.5}$ dose and biomarkers and noted that the biomarker difference in lighters and holders could have been due to exposure to the combustion of the diesel/gasoline mixture used by lighters to ignite prescribed fires. Although we based our analysis on exposure to PM_4 from smoke, the firefighters measured for the NTDP field study did perform lighting duties on wildfires and were also exposed to the combustion of the diesel/gasoline mixture.

Past health assessments of wildland firefighters recommended the need to conduct long-term studies. However, given the seasonal employment and relatively short-term tenures of many wildland firefighters, such studies are difficult to conduct. Semmens et al., 2016, examined long-term health impacts, but only surveyed currently employed wildland firefighters (Semmens et al., 2016). Future long-term health assessments should also target retired wildland firefighters to examine health status later in life. Our analysis provided a unique approach to assess long-term mortality risks for two specific diseases using calculated inhalation doses of PM_4 from smoke that we estimated from measurements collected during extensive field studies. However, there are some limitations to consider when interpreting our results. First, because we used the Pope III et al. (2011), curves to estimate RR for specific disease outcomes, we were unable to provide any confidence values in the calculated RR values. Additionally, because the ER curves have a steep relationship at lower exposures, this approach did not lend itself to back-calculating a threshold exposure for an elevated RR. Second, we assumed PM_4 from most fires (after correcting for coarse-mode contribution using the measured concentrations of quartz) to be equivalent in size, toxicity, and carcinogenicity to $PM_{2.5}$ from tobacco smoke and ambient air pollution, so that we could use the ER curves from Pope III et al. (2011), to estimate RR. Next, we based the long-term risks associated with exposures over a working life on assumptions about exposure concentration, exposure frequency and duration to determine a daily dose. Over an individual firefighter's career, he or she will serve in many tasks and activities that may influence these assumptions. Thus, a weighted average of exposures over the course of a career, possibly by job title, could potentially provide a more realistic measure of exposure for a wildland firefighter. Additionally, our current data did not account for any smoke exposure from prescribed fires and we were unable to use our current data sources to estimate risk for individuals working in ICPs as part of an incident management team. In future analyses, one should adjust the daily doses by the demographics and other characteristics that may impact exposure or any underlying disease risk. Also, our analysis only considered the size and concentration of PM across exposures to wood smoke, ambient air pollution, and cigarette smoke, and we did not address any of the differences in chemical composition of the PM from these sources. In future analyses, characterizing the toxicity and health risk of the different chemical components of wildfire smoke would be ideal.

Our study demonstrated that wildland firefighters are at an increased risk for the development of lung cancer and cardiovascular disease. This risk increases with an increase in career duration and days spent on wildfire incidents each fire season. Over the last 25 years,

there have been recommendations to reduce exposure to smoke by minimizing mop-up where appropriate on a fire line and rotating firefighters in and out of heavy smoke situations throughout a work shift, develop a medical surveillance program and occupational exposure limits specific to wildfires, and increase wildland firefighter training on the hazards of smoke. Currently, it is unclear if these recommendations would reduce exposure to smoke enough to reduce health risks. We believe that firefighters should reduce exposure to smoke in any way possible. Exposure to wildland smoke underlies virtually every aspect of risk management and must be addressed effectively in order to assure risk management decisions are sound and safe. It is essential that sound smoke exposure mitigation strategies be developed, implemented, and enforced.

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