*J Expo Sci Environ Epidemiol*. Author manuscript; available in PMC 2022 January 20.

Published in final edited form as:
*J Expo Sci Environ Epidemiol*. 2021 September ; 31(5): 923–929. doi:10.1038/s41370-021-00371-z.

# Carbon monoxide exposures in wildland firefighters in the United States and targets for exposure reduction

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## Abstract

**Background:** Every year thousands of wildland firefighters (WFFs) work to suppress wildfires to protect public safety, health, and property. Although much effort has been put toward mitigating air pollutant exposures for the public and WFFs, the current burden in this worker population is unclear as are the most effective exposure reduction strategies.

**Objective:** Quantify fireline carbon monoxide (CO) exposures in WFFs and identify predictors of exposures.

**Methods:** We collected one-minute breathing zone CO measurements on 246 WFFs assigned to fires between 2015 and 2017. We used generalized estimating equations to evaluate predictors of CO exposure.

**Results:** Approximately 5 percent of WFFs had fireline CO exposure means exceeding the National Wildfire Coordinating Group's (NWCG) occupational exposure limit of 16 ppm. Relative to operational breaks, direct suppression-related job tasks were associated with 56% (95% CI: 47%, 65%) higher geometric mean CO concentrations, adjusted for incident type, crew type, and fire location. WFF perception of smoke exposure was a strong predictor of measured CO exposure.

**Significance:** Specific job tasks related to direct suppression and WFF perceptions of smoke exposure are potential opportunities for targeted interventions aimed at minimizing exposure to smoke.



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Conflicts of Interest
The authors declare no conflicts of interest.

**Keywords**

wildland firefighter; carbon monoxide; prevention; occupational

## Introduction

Wildfires are growing in prevalence and intensity throughout the world (1) and occurring in areas that historically have been less impacted (2). The devastating consequences of wildfires in Australia, South America, southern Europe, and North America are well documented (3, 4). This global surge is a risk to public health (3) and places growing demands on wildland firefighters (WFFs).

The focus of the research described here is WFFs in the United States (US). In 2020, over 60,000 wildfires burned over 10 million acres of land in the US (5). This exceeds the ten-year annual average area burned by nearly 3.5 million acres. Climate change and readily-available fuel sources ensure the trend toward increased fire frequency and severity will persist (3, 6). Moreover, wildfires are not simply a short-term phenomenon; the duration of fire seasons has increased by nearly a month since 1979 in the western US (7).

Each year approximately 34,000 federally-employed men and women participate in wildland fire suppression activities and prescribed burns (8). In addition, an unknown number of state and local personnel also are engaged in these efforts. Wildland firefighter (WFF) shifts are long and often in rough terrain and remote locations. During these shifts, WFFs routinely and repeatedly encounter a range of inhalation hazards including particulate matter, carbon monoxide (CO), and polycyclic aromatic hydrocarbons (PAHs) (9–11). Exposures vary based on multiple factors including job task and incident and crew characteristics (12) and have both short and long-term consequences for health (10, 13, 14). CO exposure is the focus of this study both for its demonstrated acute and long-term health consequences and its correlation with other pollutants during wildfire events (9, 15, 16).

The Occupational Safety and Health Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) have promulgated occupational exposure limits (OELs) for CO, which are intended to protect worker safety and health under normal working conditions (Table 1). Specifically, they are designed for 8–10 hour days in 40-hour work weeks during mainly sedentary occupations. Wildland firefighting shifts can be 12 hours in duration or longer. Moreover, WFFs have higher levels of physical exertion resulting in higher respiratory rates and consequently higher exposures (14). Similar to structural firefighters, WFFs utilize a wide range of personal protective equipment (PPE); however, they typically utilize no respiratory protection (17). In recognition of the unique exposure conditions WFFs experience, the National Wildfire Coordinating Group (NWCG) in 2012 provided interim guidance recommending a lower OEL than OSHA, NIOSH, and the ACGIH (18).

Research from fires occurring between 2009–2012 found that WFFs exceeded OSHA’s 8-hour time-weighted average thresholds of 50 parts per million (ppm) 3.5 percent of the time at prescribed fires, which are started intentionally often to reduce fuels, and 5.6 percent of the time at project fires (14), which are prolonged, large incidents for which the goal is suppression (see Supplement). In spite of numerous recommendations over the past two decades aimed at reducing smoke exposures, previous work has indicated that exposures have not declined appreciably and, in some cases, have worsened (19). Our objectives for this study were to quantify the burden of CO exposures in WFFs assigned to fires between 2015 and 2017 in geographically diverse regions of the US, account for highly time-resolved WFF job tasks, and, as importantly, identify opportunities for intervention to reduce exposures.

## Materials and Methods

### Study population

The United States Forest Service National Technology and Development Program (NTDP) chose wildfire locations for data collection based on seasonal patterns of fire activity and available information for current fire activity across various regions of the United States. After arriving at each wildfire and obtaining permission to collect data from the Incident Management Team, researchers recruited fire crews to gain voluntary permission to collect full shift personal exposure measurements. Various crew types were eligible for participation, and crew selection occurred via multiple pathways (see Supplement for crew type definitions). In some cases, crew leads approached the research team regarding the study; in others, crews learned about the study at morning briefings, or Incident Management Teams often recommended crews to participate based on planned daily operations. Ultimately, the research team selected the crew. Once a crew was chosen, participants from the crew self-selected by volunteering for the research study. A maximum of four participants per day were monitored for their work shift, from the time the worker left fire camp, to when they returned to fire camp and the monitors were removed. This research was classified as exempt by the University of Montana Institutional Review Board.

### Exposure and covariate assessment

NTDP conducted an extensive field study between 2015 and 2017 that collected breathing zone measurements of occupational exposure to CO. The approach to measure CO was similar to that described in previous research in this population (12, 20) and is consistent with NIOSH methods (21). Breathing zone measurements were sampled for one full work shift using MSA Altair Pro Fire single gas CO dosimeters with electronic data logging (MSA Safety Inc, Cranberry Township, PA, USA). Calibration checks occurred daily before and after each shift. The data logger recorded average and maximum CO levels at one-minute intervals for the entire work shift. All analyses described here utilized the one-minute average data. The exposure period of interest for this analysis was “on fireline” exposure defined as the period after the shift start and after the initial “Driving Time” job task ended and the fire crew had arrived at their work site for the shift. The “on fireline” could include hiking to the fireline or to other parts of the fireline. Each participating WFF was sampled for only one shift. No stationary monitoring for CO was conducted at incident command posts (i.e., logistics coordination location) or spike camps (i.e., temporary remote camps close to fire; see Supplement).

An observer was assigned to each firefighter that was being sampled to record the job tasks performed for the sampled worker at one-minute intervals. To allow for safe and accurate capture of precise job tasks, observers were WFFs who were trained in study procedures. Job task was the predictor of primary interest and was a pre-defined categorical variable with 64 levels, which were grouped into eight distinct categories: hiking, lighting, holding, indirect suppression, direct suppression, mop-up, staging/operational or rest break, and other (see Supplement for full description of job tasks). In addition to job task, observers also ascertained information on incident type, which identifies what type of fire the crew was assigned to for that shift (i.e., station day, initial attack, managed fire, prescribed fire, and large incident, see Supplement), crew type, which identifies the personnel, equipment, and capabilities of the WFFs who make up the crew (i.e., Engine, Type I, or Type II/IA, see Supplement), and geographic area coordination center (GACC, see Figure S1). They also recorded WFF gender and tobacco use status on tablet devices. Observers also asked WFFs to rate their perceived level of wildfire smoke exposure over the shift (i.e., none, very little, low, moderate, high/very high). No participating WFFs wore respiratory protection during the sampling period.

## Statistical analysis

The overall objectives of the statistical analyses were to characterize the CO burden for WFFs while performing fireline activities and to quantify the contribution of grouped job tasks and other incident characteristics to CO exposure to inform targets for exposure reduction strategies. We first described the study population with respect to WFF and incident characteristics, overall and by year. By visual inspection of the data, we evaluated the variability in CO concentrations over time while on the fireline by job task, crew type, and WFF perception of smoke exposure. We then estimated means, medians, interquartile ranges, 95$^{th}$ percentiles, and maxima for WFFs across their entire “on fireline” time by year and for all years combined. In addition, we quantified the duration of the fireline shift above prespecified thresholds (Table 1) including the interim NWCG 13-hour OEL (16 ppm), the ACGIH 8-hour Threshold Limit Value (TLV; 25 ppm), the NIOSH 10-hour Recommended Exposure Limit (REL; 35 ppm), the OSHA 8-hour Permissible Exposure Limit (PEL; 50 ppm), and the NIOSH Ceiling Limit (200 ppm), which NIOSH recommends should not be exceeded at any time (22). Since “on fireline” duration often exceeds the standard eight-hour shift on which many of the thresholds above are based, we also adjusted “on fireline” averages to an eight-hour average equal to the “on fireline” mean multiplied by the “on fireline” duration divided by eight hours. We assigned one-minute average CO concentrations that were below the instrument’s manufacturer specified limit of detection (LOD) of 1 ppm a value of $\frac{1}{\sqrt{2}}$ ppm (23), as done in previous research in this occupational population (12).

Potential predictors of CO concentrations including job task, incident type, crew type, and fire location were examined using linear regression with generalized estimating equations (GEE). This approach accounts for correlations between repeated measures of CO exposure on the same WFF (24). We applied an autoregressive with lag 1 structure to allow correlations to decrease for observations further apart in time. Logistic regression with GEE was used to evaluate associations between potential predictors and odds of exceeding CO concentrations of 16 ppm and 25 ppm, the NWCG and ACGIH thresholds, respectively. We performed analyses first with a single predictor and then included all predictors in the same model. Smoking status was included as an additional adjustment variable in sensitivity analyses. Lastly, we evaluated whether WFFs' perceptions of wildfire smoke exposure were associated with CO concentrations. Since experience level may differ by crew type, we adjusted for this variable in analyses examining the impact of WFF perception of smoke exposure on CO. CO concentrations were right-skewed and, as a result, were natural log-transformed in all GEE analyses. All analyses were performed using the R Project for Statistical Computing software or STATA/MP version 15.1.

## Results

Initially 192,079 minutes of observation on 279 unique WFFs were available. We excluded 35,186 observations occurring outside of fireline exposure periods and an additional 13,035 observations for which CO exposure was missing due to equipment malfunction. We also excluded three WFFs who were on either Helitack or Dozer crews due to the small sample size. A total of 246 WFFs with 142,109 minutes of observation were included in analyses. Table 2 provides descriptive information on the WFFs included in the analysis. Overall, 88% of WFFs were male. Smoking status was ascertained in 2016 and 2017, and 11% of WFFs reported being current smokers during that time. Smokeless tobacco use was assessed in 2017 only, and 41% reported being current smokeless tobacco users. A large majority of WFFs sampled (81%) were participating in large incidents and most frequently were members of Type II or Type II Initial Attack (IA) crews (37%) followed by Type I crews (35%). WFFs in this study were observed in one of eight geographic locations (i.e., GACCs) across the US. Thirty-seven percent of WFFs were assigned in the Southwest region of the U.S. Fifteen percent, 13%, and 11% were in the Northern California, Rocky Mountain, and Northern Rockies regions, respectively. The distribution of incident type, crew type, and fire location varied substantially from year to year.

Figure 1 shows examples of the variability in CO exposures throughout an "on fireline" shift by job task, crew type, and perceived smoke exposure level for twelve different WFFs. For all WFFs the mean "on fireline" duration was 9.6 (standard deviation, SD: 2.7) hours (Table 3). The mean CO of the shift averages ranged from 4.1 (3.9) ppm in 2015 to 4.8 (6.1) ppm in 2017. Overall, the 95$^{th}$ percentile of "on fireline" shift means was 15.6 ppm. The overall geometric mean and median were 2.5 ppm and 2.3 ppm, respectively. Maximum exposures during the "on fireline" period ranged from 566 ppm in 2017 to 600 ppm in 2016. Twelve WFFs (4.9%) had "on fireline" period means exceeding the NWCG thirteen-hour OEL of 16 ppm, and three (1.2%) had means exceeding the ACGIH 8-hour TLV of 25 ppm. Four WFFs (1.6%) exceeded the ACGIH 8-hour TLV when means were adjusted for an 8-hour shift.

Job task and incident type were associated with CO concentrations in adjusted analyses (Figure 2a). Relative to staging/operational/rest break, direct suppression job tasks were associated with 56% (95% CI: 47%, 65%) higher geometric mean CO concentrations. Lighting was associated with 27% (95% CI: 15%, 39%) higher geometric mean CO. Similarly, holding was associated with 27% (95% CI: 21%, 33%) higher CO concentrations.

Relative to station days, prescribed fires had significantly higher CO concentrations (233% higher CO; 95% CI: 175%, 305%). Large incidents and managed fires both were linked to higher CO concentrations compared to station days. Crew type and fire location both were associated with CO concentrations (Supplement, Table S1). Similar results were observed in analyses examining the contribution of job task and incident characteristics to odds of exceeding either the NWCG 13-hour OEL of 16 ppm (Figure 2b) or the ACGIH 8-hour TLV of 25 ppm (Figure 2c). Additional adjustment for smoking status in sensitivity analyses had little impact on overall findings in general (Supplement, Table S1).

A WFF's perception of wildfire smoke level was significantly associated with CO concentrations (Figure 3a). In addition, the odds of reaching or exceeding the NWCG OEL (16 ppm, Figure 3b) and the ACGIH TLV (25 ppm, Figure 3c) CO were significantly associated with WFF perception of wildfire smoke. Tests for linear trend between perceived smoke exposure categories and CO were highly significant ($p < 0.0001$).

## Discussion

Mean "on fireline" exposures across all WFFs included in this study did not exceed NWCG, ACGIH, OSHA, or NIOSH OELs. It is important to note that, with the exception of the NWCG OEL, these thresholds are based on sedentary activity, but WFFs may spend more than a quarter of their time in high physical activity job tasks (25). High exertion will result in higher respiratory rates and, as a consequence, underestimation of actual exposure to air pollutants (14). In addition, although average exposures did not exceed OELs, maximum shift means in 2016 and 2017 approached or exceeded these limits, even though exposures can vary dramatically and be very low for extended periods throughout a shift. Nearly 5% of WFFs had "on fireline" period means exceeding the NWCG thirteen-hour OEL of 16 ppm. This is important as CO exposure is associated with numerous health effects (26). Due in part to its stronger affinity than oxygen for hemoglobin, CO exposure can deprive tissues of oxygen. Short term impacts can include cognitive impairment and headache (10), and controlled exposure and epidemiologic studies indicate that those with underlying cardiovascular disease may be particularly sensitive (27). Acute CO exposure is associated with increased emergency department visits and hospital admissions especially during periods of physical activity (27) while persistent exposure to low levels of CO may also have long-term health consequences (28, 29). In addition, CO exposure is correlated with other exposures including particulate matter (9), which has well-documented adverse health effects (30, 31).

Numerous job tasks were associated with elevated CO exposures even after adjustment for incident type, crew type, and geographic location of the fire. Similar to prior work (12), direct suppression-related job activities were associated with the highest CO exposures followed by lighting and holding. Although exposures related to mop-up were elevated, they were significantly lower than those observed during direct suppression activities. Mop-up has long been targeted as a task associated with high exposures (19). Our findings may indicate that administrative recommendations aimed at reducing exposures while performing mop-up duties are having a beneficial impact. In contrast to an earlier study of CO exposure in WFFs assigned to fires between 2009 and 2012 (12), we observed higher exposures in

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Type I relative to Type II/IA crews. Notably, a WFF's perception of smoke levels was a strong indicator of measured CO concentrations.

Taken together, our findings highlight specific targets for intervention. They suggest that recommendations aimed at reducing CO exposure through administrative controls (i.e., workplace policies or guidance) might be most effective during particular activities and during times when WFFs perceive smoke exposures to be high. For example, in 2012 the NWCG endorsed guidance aimed at mitigating smoke exposure including rotating WFFs out of heavy smoke conditions and allowing contained areas of the fire to burn out (18). WFF tasks are demanding, and exertion levels are high (32). As a result, respiratory protection typically is not utilized during wildland firefighting and is not included in the list of required fireline PPE (17). There is no respirator currently available for WFFs; however, results presented here indicate that respiratory protection may not be needed during an entire shift but instead, its use could be targeted to those periods when WFFs perceive exposure to smoke to be high. However, feasibility concerns regarding the use of respiratory protection in WFFs may preclude this option. The NWCG requires that only respirators approved by the NIOSH will be used on the fireline (17). Although face filtering respirators like an N-95 may reduce particulate matter exposure from smoke, it will not provide any protection to CO or other volatile organic compounds (33). Only supplied air respirator would be able to provide protection against CO exposure, which is not feasible on the fireline given the physically demanding work and possibly extreme environmental conditions (22).

Our study benefitted from a number of strengths. Through trained observers, who were WFFs themselves, we obtained temporally resolved information on job task throughout long shifts. The sample of WFFs was large, and there was substantial diversity with respect to geographic areas, incident types, and crew types included. However, we acknowledge several limitations. We did not have information on potentially important predictors of CO exposure such as altitude and wind direction (9). We also did not have information on the duration of time between establishment of the fire and the arrival of the research team. It is possible that the tactics applied during a particular job task could vary during the early stages of a fire compared to a prolonged incident, which could have affected job task-associated CO concentrations. Adjustment for both incident and crew type in analyses minimizes this concern, but we acknowledge that timing of recruitment in relation to the start of the fire could have had an impact on job task-associated CO exposure. WFFs who participated in the research study were not selected at random, and it is possible that exposures observed were not representative of exposures in other, non-sampled WFFs. Moreover, we do not have reliable information on CO exposure outside of the "on fireline" sampling period. This likely resulted in an underestimate of total exposure as multiple studies have demonstrated elevated exposure to air pollutants at base camps from diesel exhaust and generators or during transport to the fireline (11, 12, 34). Lastly, we included a single "on fireline" shift for each WFF in the study. It is possible the repeated CO exposures during a season and over multiple seasons is equally important to examine as sustained exposure even at low concentrations may have important implications for WFF health.

In summary, we found that while mean exposure during the "on fireline" period generally was low, there was marked variability in exposure throughout a shift. Specific job tasks related to direct suppression and WFF perceptions of smoke exposure both emerged as potential opportunities for targeted interventions aimed at minimizing exposures. Since wildfires are increasing in frequency, duration, and severity, future work should aim to assess the longer-term health impacts of repeated exposures of this magnitude over the career of a WFF.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.


## Acknowledgments

We are grateful to the WFFs who volunteered to participate in this study.

### Funding

This work was supported by the US Forest Service National Technology and Development Program (18-CR-11138100-023), the National Institute for Occupational Safety and Health (R21OH011385), and the National Institute of General Medical Sciences (P20GM130418). The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company name or product does not constitute endorsement by NIOSH/CDC. The findings and conclusions in this report are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.


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**Figure 1.**

CO exposure by job task, crew type, and perceived smoke exposure for selected WFFs during a single shift. CO concentrations exceeding 250 ppm are not shown in the plots but occurred for 16 minutes during the Whittier fire, and for 1 minute for during the Superior, Cedar (Type II), and Modoc July Complex fires.

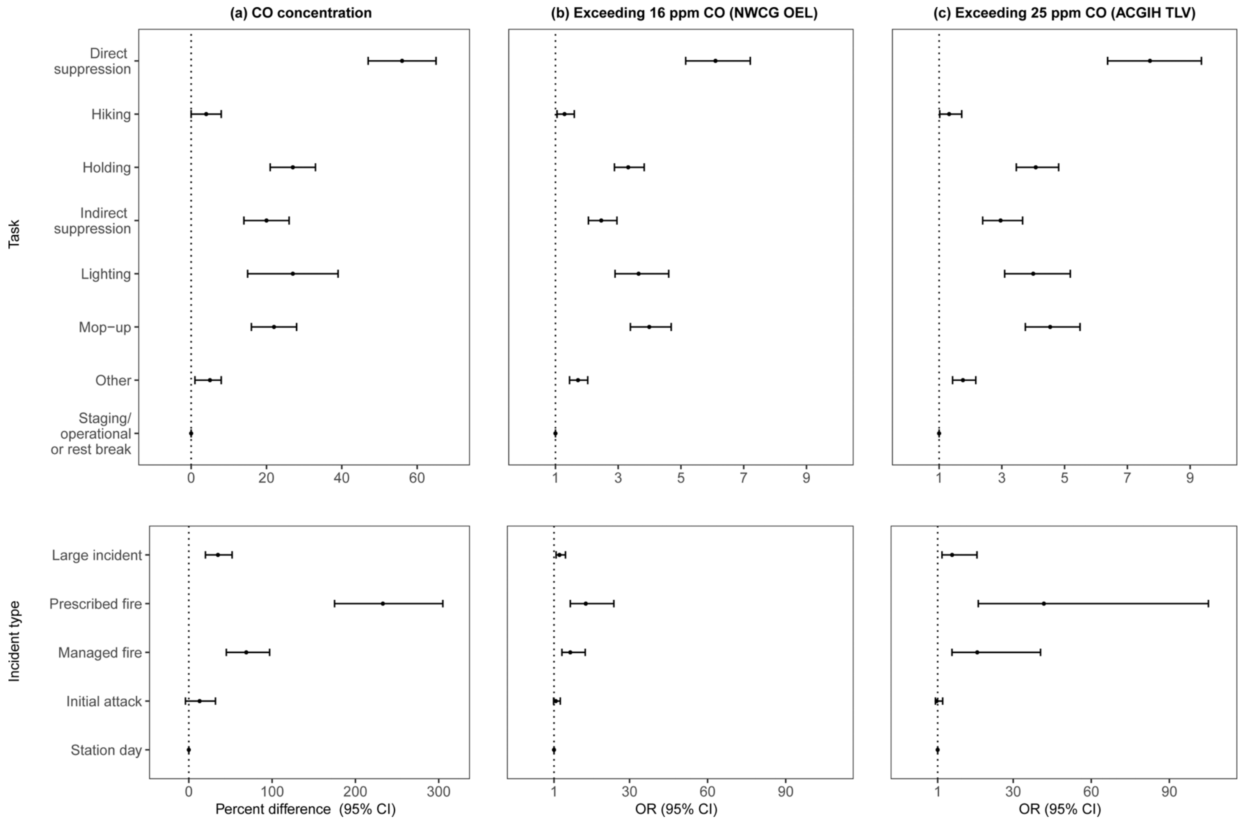


**Figure 2.**

Job task and incident type as predictors of percent difference in geometric mean CO (a) and 16 ppm (b) and 25 ppm (c) threshold exceedances (N=246 WFFs).

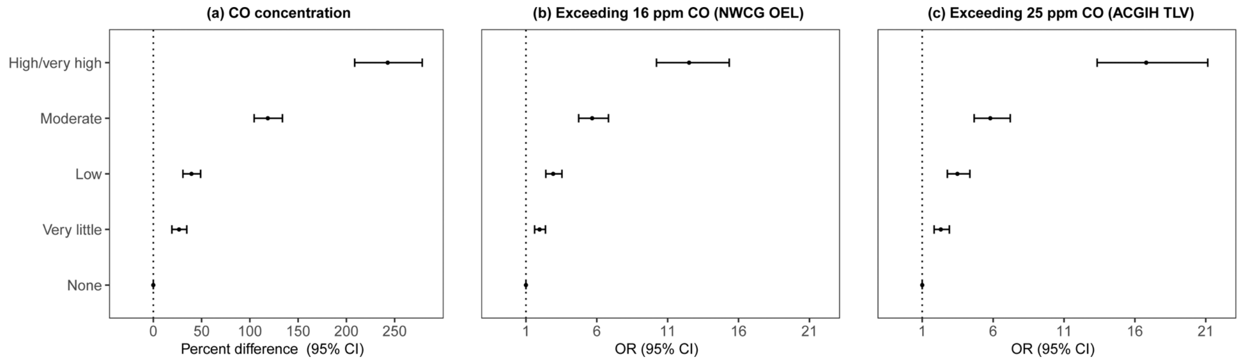


**Figure 3.**

Wildland firefighter perceptions of smoke exposure as a predictor of percent difference in geometric mean CO (a) and 16 ppm (b) and 25 ppm (c) threshold exceedances (N=246 WFFs).

**Table 1.**

CO Occupational Exposure Limits (OEL)

| | OEL (ppm) | averaging period (hours) |
|---|---|---|
| OSHA | 50 | 8 |
| NIOSH | 35 | 10 |
| NIOSH ceiling | 200 | —[a] |
| ACGIH | 25 | 8 |
| NWCG | 16 | 13 |

Abbreviations: CO, carbon monoxide; ppm, parts per million; OSHA, Occupational Safety and Health Administration; NIOSH, National Institute for Occupational Safety and Health; ACGIH, American Conference of Governmental Industrial Hygienists; NWCG, National Wildfire Coordinating Group

[a]NIOSH recommends this concentration not be exceeded at any point during the shift.

**Table 2.**

Selected characteristics of sampled wildland firefighters (WFFs) and assigned incidents, overall and by year (N = 246)

| | All years n(%) | 2015 n(%) | 2016 n(%) | 2017 n(%) |
|---|---|---|---|---|
| **WFF characteristic** | | | | |
| Male | 217(88) | 29(83) | 112(93) | 76(84) |
| Current smoker[a] | 23(11) | - | 7(6) | 16(18) |
| Current smokeless tobacco user[a] | 37(41) | - | - | 37(41) |
| **Incident type** | | | | |
| Station day | 16(7) | - | - | 16(18) |
| Initial attack | 12(5) | - | 3(3) | 9(10) |
| Managed fire | 12(5) | - | 12(10) | - |
| Prescribed fire | 6(2) | - | 5(4) | 1(1) |
| Large incident | 200(81) | 35(100) | 100(83) | 65(71) |
| **Crew type** | | | | |
| Engine | 69(28) | - | 38(32) | 31(34) |
| Type I | 86(35) | 27(77) | 30(25) | 29(32) |
| Type II / IA | 91(37) | 8(23) | 52(43) | 31(34) |
| **Fire location** | | | | |
| Great Basin (ID, UT) | 21(9) | - | 7(6) | 14(15) |
| Northern CA (CA) | 38(15) | 5(14) | 14(12) | 19(21) |
| Northern Rockies (MT, WY) | 28(11) | 12(34) | 9(8) | 7(8) |
| Northwest (OR, WA) | 16(7) | 16(46) | - | - |
| Rocky Mountains (CO, UT, WY) | 32(13) | - | 31(26) | 1(1) |
| Southern (GA, FL, OK) | 1(<1) | - | - | 1(1) |
| Southern CA (AZ, CA) | 20(8) | 2(6) | 13(11) | 5(5) |
| Southwest (AZ, NM) | 90(37) | - | 46(38) | 44(48) |

Abbreviations: ID, Idaho; UT, Utah; CA, California; MT, Montana; WY, Wyoming; OR, Oregon; WA, Washington; CO, Colorado; GA, Georgia; FL, Florida; OK, Oklahoma; AZ, Arizona; NM, New Mexico

[a]Thirty-five and 155 WFFs were missing information on smoking status and smokeless tobacco, respectively.

**Table 3.**

"On Fireline" one-minute mean CO exposures (ppm) of sampled WFFs, overall and by year (N=246)

| | **All years** | **2015** | **2016** | **2017** |
|---|---|---|---|---|
| Number of WFFs | 246 | 35 | 120 | 91 |
| Fireline duration (hrs), mean (sd) | 9.6 (2.7) | 10.6 (2.0) | 9.6 (2.6) | 9.3 (2.9) |
| **Fireline CO exposure** | | | | |
| Mean (sd) | 4.6 (6.4) | 4.1 (3.9) | 4.7 (7.3) | 4.8 (6.1) |
| Mean (sd) adjusted to 8-hr shift | 5.6 (7.9) | 5.6 (5.4) | 5.4 (8.6) | 5.8 (7.8) |
| Geometric mean | 2.5 | 2.7 | 2.5 | 2.4 |
| Median | 2.3 | 2 | 2.2 | 2.3 |
| IQR (Q1, Q3) | 4.8 (0.9, 5.7) | 5.5 (1.2, 6.7) | 4.3 (1.0, 5.3) | 5.2 (0.7, 5.9) |
| $95^{th}$ percentile | 15.6 | 12.6 | 14 | 16.7 |
| Maximum | 52.9 | 13.8 | 52.9 | 34.5 |
| **Maximum one-minute mean within "on fireline" period** | 600 | 597 | 600 | 566 |
| **Mean (sd) number of 1-minute averages per WFF above CO OELs** | | | | |
| 16 ppm (NWCG) | 41.1 (64.0) | 42.3 (54.6) | 36.2 (61.1) | 47.1 (70.8) |
| 25 ppm (ACGIH) | 26.6 (47.5) | 26.3 (32.8) | 25.1 (51.3) | 28.7 (47.6) |
| 35 ppm (NIOSH) | 16.4 (35.5) | 15.6 (20.5) | 16.2 (41.6) | 17.0 (31.5) |
| 50 ppm (OSHA) | 9.6 (25.9) | 8.3 (12.0) | 10.0 (32.1) | 9.5 (20.5) |
| 200 ppm (NIOSH ceiling) | 0.4 (2.0) | 0.2 (0.7) | 0.4 (1.7) | 0.4 (2.5) |

Abbreviations: CO, carbon monoxide; ppm, parts per million; sd, standard deviation; IQR, interquartile range; Q1, $25^{th}$ percentile; Q3, $75^{th}$ percentile; OEL, occupational exposure limit; NWCG, National Wildfire Coordinating Group; ACGIH, American Conference of Governmental Industrial Hygienists; NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration