



Review

Wildland firefighter exposure to smoke and COVID-19: A new risk on the fire line



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HIGHLIGHTS

- Wildland firefighters are exposed to smoke while performing regular job tasks.
- Wildfire exposure smoke leads to increased susceptibility to respiratory infections.
- Exposure to wildfire smoke may provide an additional risk for SARS-CoV-2 infection.
- Immune responses from smoke can increase risk for severity of COVID-19 outcomes.

GRAPHICAL ABSTRACT



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ABSTRACT

Throughout the United States, wildland firefighters respond to wildfires, performing arduous work in remote locations. Wildfire incidents can be an ideal environment for the transmission of infectious diseases, particularly for wildland firefighters who congregate in work and living settings. In this review, we examine how exposure to wildfire smoke can contribute to an increased likelihood of SARS-CoV-2 infection and severity of coronavirus disease (COVID-19). Human exposure to particulate matter (PM), a component of wildfire smoke, has been associated with oxidative stress and inflammatory responses; increasing the likelihood for adverse respiratory symptomatology and pathology. In multiple epidemiological studies, wildfire smoke exposure has been associated with acute lower respiratory infections, such as bronchitis and pneumonia. Co-occurrence of SARS-CoV-2 infection and wildfire smoke inhalation may present an increased risk for COVID-19 illness in wildland firefighters due to PM based transport of SARS CoV-2 virus and up-regulation of angiotensin-converting enzyme II (ACE-2) (i.e.

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ACE-2 functions as a trans-membrane receptor, allowing the SARS-CoV-2 virus to gain entry into the epithelial cell). Wildfire smoke exposure may also increase risk for more severe COVID-19 illness such as cytokine release syndrome, hypotension, and acute respiratory distress syndrome (ARDS). Current infection control measures, including social distancing, wearing cloth masks, frequent cleaning and disinfecting of surfaces, frequent hand washing, and daily screening for COVID-19 symptoms are very important measures to reduce infections and severe health outcomes. Exposure to wildfire smoke may introduce additive or even multiplicative risk for SARS-CoV-2 infection and severity of disease in wildland firefighters. Thus, additional mitigative measures may be needed to prevent the co-occurrence of wildfire smoke exposure and SARS-CoV-2 infection.

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1. Introduction

Over the past decade, an average of approximately 6.8 million acres has burned annually due to wildfires across the United States (NIFC, 2020). During the peak of the 2015 and 2017 fire seasons, on average, over 27,000 fire personnel were deployed to wildfire incidents each day in the western US (NICC, 2017; NICC, 2020). Wildland firefighters perform arduous work under difficult conditions in remote locations for shifts often longer than 24 h, and for up to 14–21 days. Hence, wildfire incidents can be an ideal environment for the transmission of infectious diseases, including SARS-CoV-2, due to close living and working conditions, limited access to hygiene supplies, and a workforce that responds to incidents all over the country on short notice. Furthermore, occupational factors that increase stress on the body such as arduous work, long work shifts, and environmental exposures (including wildfire smoke) may contribute to an increased susceptibility for SARS-CoV-2 infection.

Smoke from wildland fires contains a variety of air pollutants including particulate matter (PM), which is a heterogeneous mixture of particles and liquid droplets consisting of organic compounds including metals, acids, soil, or dusts suspended in the atmosphere. PM is a commonly measured air pollutant and classified by the particle's aerodynamic diameter: coarse (aerodynamic diameter between 2.5 and 10 μm), fine (<2.5 μm), and ultrafine (<0.1 μm) (Adetona et al., 2016; Ciencewicz and Jaspers, 2007). Previous studies that attempt to quantify wildland firefighter toxic smoke exposure have measured fine PM ($\leq 2.5 \mu\text{m}$), and respirable PM ($\leq 4 \mu\text{m}$), acrolein, benzene, carbon dioxide, carbon monoxide, formaldehyde, and polycyclic aromatic hydrocarbons (PAH) (Adetona et al., 2016). Between 2009 and 2012, the United States Department of Agriculture Forest Service (USFS) reported that 22% of wildfire and 20% of prescribed burn (fires intentionally set for resource benefit) work shifts exceeded the recommended PM₄ daily occupational exposure limit (0.7 mg/m³) that was specifically recommended for wildland firefighters (Reinhardt and Broyles, 2019). Respiratory health effects reported for wildland firefighters include decreases in lung function, increases in airway responsiveness, and increases in respiratory symptoms across work shifts and single fire seasons (Gaughan et al., 2008; Gaughan et al., 2014; Liu et al., 1992).

In March 2020, the World Health Organization declared the coronavirus disease 2019 (COVID-19), caused by the novel SARS-CoV-2 virus

(a beta coronavirus), a global pandemic (CDC, 2020a). Although some individuals with SARS-CoV-2 infection are asymptomatic, many experience the cardinal symptoms of dry cough, fever, and/or shortness of breath (Wang et al., 2020). In April 2020, the Centers for Disease Control and Prevention (CDC) reported a 6.7% COVID-19 case fatality rate (CFR). By September, a cumulative 1.9% COVID-19 CFR was being reported (Brady et al., 2020). Brady et al., 2020, suggested that this reduction was due to a combination of many factors, such as new treatments, more experienced healthcare workers, community awareness and intervention, the use of cloth masks, and social distancing measures.

Moderate cases of SARS-CoV-2 respiratory infection can precipitously progress to pneumonia with hypoxemia, acute lung injury, respiratory failure, and ARDS. Severe COVID-19 can have multiple extrapulmonary manifestations including acute cardiac injury, acute kidney failure, stroke, and multiple organ failure (Wang et al., 2020). Severe COVID-19 is age-related, with up to 20% of COVID-19 patients ≥ 65 years of age, developing ARDS (Moore and June, 2020). Past research suggests associations between ambient air pollution (mostly measured by PM concentrations) and CFR in both the 2003 SARS-CoV-1 outbreak and COVID-19 pandemic. Cui et al., 2003 conducted an ecological study and found positive associations between 2003 SARS-CoV-1 CFR and ambient air pollution levels (including PM₁₀). A recently published Chinese study assessed the risk of SARS-CoV-2 infection from short-term air pollutant exposure levels and found significant associations for several pollutants, including PM_{2.5} (Zhu et al., 2020). There are also early reports from Italy that suggest that areas with high rates of mortality from severe COVID-19 also have relatively high levels of PM (Accarino et al., 2021). In the United States, an ecological study conducted by Wu and colleagues analyzed county level data and reported an 11% increase in COVID-19 CFR for every 1 $\mu\text{g}/\text{m}^3$ increase in annual PM_{2.5} exposure (Wu et al., 2020).

In this review article, we examined how smoke in the wildland fire environment may influence the risk of SARS-CoV-2 infection and severity of COVID-19 illness. First, we reviewed evidence that may explain the association between increased COVID-19 infection and elevated PM exposure. Next, we evaluated the epidemiological literature on exposure to wildfire smoke and respiratory infections. We briefly reviewed how exposure to PM can adversely affect the immune system, through inflammatory responses and oxidative stress; and how existent inflammation from exposure to wildfire smoke could lead to the

development of more severe COVID-19 illness in wildland firefighters. We also highlighted current best practices for prevention of COVID-19 and possible mitigative strategies to reduce both smoke and SARS-CoV-2 exposure for wildland firefighters during wildfire operations.

2. PM exposure and risk of lower respiratory and SARS-CoV-2 infections

Considerable evidence has been reported to suggest significant associations between exposure to air pollution and an increased risk for lower respiratory infections. Studies involving size-specific PM associations are less common, and typically do not differentiate between viral or bacterial lower respiratory infections (Horne et al., 2018). One study in Beijing showed that ambient PM_{2.5} concentrations were significantly associated with flu-like illness risk, in adults more than in children (Feng et al., 2016). A second study from China involving over 4.2 million hospital admissions for pneumonia in 184 cities showed that short-term elevations in PM_{2.5} concentrations were associated with increased pneumonia admissions (Tian et al., 2019). Controlled exposure studies to NO₂, O₃, and/or PM_{2.5} in both animals and humans showed enhanced viral proliferation and severity of infection of several viruses, including influenza, rhinovirus, and respiratory syncytial virus (RSV) (Ciencewicz and Jaspers, 2007).

PM lung deposition is determined by several biological and physical properties, but particle size is a chief determinant for regional deposition along the respiratory tract (Ciencewicz and Jaspers, 2007). Although past exposure assessments of wildland firefighters have measured exposure to PM_{2.5-4}, data from wood and wildfire combustion studies have demonstrated that most PM from wildfire smoke is composed of submicron particles (about 300 nm), much smaller than 2.5 μm (Kleeman et al., 1999; McMeeking et al., 2005). Upon inspiration, smaller particles are transported into more distal regions of the respiratory tract and become independent of gravitational forces. These respirable particles penetrate beyond the terminal bronchioles into the alveolar region. Ultrafine particles (PM_{0.1}) readily cross alveolar surface membranes where they are translocated into epithelial tissue, interstitium, pulmonary endothelium, or to secondary organs (Schraufnagel, 2020). Translocation of particles is usually rapid (one to two days) and dose-dependent, meaning that when there are more particles, more will be translocated across surface membranes (Moller et al., 2009). During arduous work or strenuous exercise, dominant nose breathers will switch to nasal-oral breathing. This nasal-oral switch allows for less efficient filtering of inspired air, and a greater proportion of larger particles will be deposited into more distal airways and the alveolar region (Brown et al., 2013; Wu et al., 2018).

The respiratory system utilizes a number of innate defense mechanisms to trap and remove PM. Upper airway filtering efficiently prevents most inhaled particles ≥10 μm from penetrating into the lower airway (Sturm, 2011). Within the tracheobronchial region, the mucociliary escalator transports distally deposited particles superiorly, for elimination through the cough reflex. However, if this mechanism gets overwhelmed or damaged, particles will accumulate. Alveolar macrophages readily phagocytize particles in the deep lung and can migrate to terminal bronchioles for mucociliary clearance, migrate into the interstitium for lymphatic clearance, or simply remain particle-laden within the alveolar region (Beachey, 2012; Costanzo, 2009). Migliaccio et al., 2013 demonstrated that post-wood smoke exposure, pulmonary macrophages showed decreased ability to defend against infection in mice.

A unifying mechanism by which ambient PM deposited in the lower airways and alveoli is thought to increase risk of infection is through oxidative stress and production of free radicals, causing local damage to epithelial cells (Gowdy et al., 2010). PM generated through wildfires has the potential to promote local oxidative stress and inflammation (Adetona et al., 2017; Adetona et al., 2019; Chen et al., 2017; Kim et al., 2018). Following PM-induced epithelial injury, pattern receptors

located on resident macrophages recognize and bind to endogenous DAMP (damage-associated molecular patterns) molecules. Once activated, these macrophages release pro-inflammatory cytokines, tumor necrosis factor alpha and interleukin-1 (TNF-α and IL1), that cause endothelial selectins to recruit leucocytes (neutrophils and monocytes) to the injured area. Macrophages and leucocytes then phagocytize dead or damaged epithelial cells and further release profibrotic cytokines and growth factors for tissue repair (Kim et al., 2018; Wu et al., 2018). Epithelial reactive oxygen species (ROS) can also induce inflammatory cytokines to be released through the activation of the nucleotide-binding oligomerization domain-like receptor related protein 3 inflammasome (NLRP3), activator protein 1 (AP-1), and mitogen-activated protein kinase (MAPK) signaling (Setti et al., 2020b; Wu et al., 2018). In addition, immunoglobulin E (IgE)-dependent adaptive immune response occurs when susceptible wildland firefighters inhale PM containing adsorbed allergens. Exacerbation of pre-existing asthma can be caused by both early-phase and late-phase responses to inhaled allergen and sensitization to a new allergen can lead to new-onset asthma (Abbas et al., 2011).

Two hypotheses may explain the apparent association between increased cases of COVID-19 and elevated PM exposure. The first hypothesis suggests that the SARS-CoV-2 viral clusters are adsorbed to respirable PM to promote SARS-CoV-2 airborne transmission (Setti et al., 2020a). This PM-facilitated airborne transmission has been identified in experimental studies for other viruses such as RSV, the *Morbivirus paromyxovirus*, and the H5N1 virus (avian influenza) with corresponding increases in infection rates (Chen et al., 2017; Peng et al., 2020; Setti et al., 2020a; Setti et al., 2020b; Ye et al., 2016). Studies have demonstrated that atmospheric PM is a substantial factor affecting the spread of SARS-CoV-2 within outdoor environments (Coccia, 2020; Comunian et al., 2020; Frontera et al., 2020; Martelletti and Martelletti, 2020). Wildfire smoke consists of fine soot particles coated with organic materials that may enable them to adsorb droplets and droplet nuclei which contain lipid viruses such as SARS-CoV-2 (Ciencewicz and Jaspers, 2007). These hydrophobic soot particles have median aerodynamic diameters ranging between 0.4 μm and 0.7 μm, which are small enough to reach the terminal alveoli (Balmes, 2018; Deng et al., 2019). The hydrophobic nature of smoke particles limits their growth potential as condensation nuclei in the atmosphere, or as respired particles traveling through the high humidity of a human respiratory system, allowing these fine particles to remain within the respirable airstream (Marr et al., 2019). A recent study purported that viruses bound to PM mimic the action of drugs delivered by dry powder inhalers (DPI), which use organic particles to stabilize, protect, and inertially transport biologically active molecules to the lower airways. In similar mechanisms, virus "hitchhikers" may be released from PM after inertial impact against the upper airways, allowing the virions to settle to lower airways via sedimentation (Farhangrazi et al., 2020). Atmospheric studies have demonstrated that virus deposition distances within outdoor environments are positively correlated with organic aerosols smaller than 0.7 μm (Aller et al., 2005; Cao et al., 2014; Ferrari et al., 2008; Reche et al., 2018). These studies show that viruses have much longer persistence and a greater deposition range in the atmosphere when provided with an organic platform that can protect and stabilize the virus by absorbing ultraviolet radiation and slowing dehydration, while also adding inertial momentum to help the virus more effectively travel with wind (Feng et al., 2020). Although there are still knowledge gaps that exist to support this hypothesis, such as how far these viral particles on organic materials may be able to travel in the environment. This research suggests that Backspace wildland firefighters may be at a greater risk for SARS-CoV-2 infection due to the expanded range and potential increased efficiency of respirable transmission.

Another hypothesis regarding the association of COVID-19 severity and mortality with elevated PM exposure involves gene expression changes observed within pulmonary capillary endothelial and alveolar epithelial cells. Following PM exposure or smoke inhalation, epithelial

cells upregulate angiotensin-converting enzyme II (ACE-2), a trans-membrane protein receptor for the virus, to reduce cytokine-induced lung injury and inhibit ARDS (Imai et al., 2005). Rats exposed to wood smoke have demonstrated significant increases in ACE-2 expression within alveolar cells (Yilin et al., 2015). Similar increases in expression of ACE-2 have been found in cigarette smokers compared to non-smokers (Leung et al., 2020). Recently published studies have determined that SARS-CoV-2 virus depends on the ACE-2 protein embedded on epithelial cell membranes to gain access into cells. This offers one explanation for why smokers have higher COVID-19 illness rates and more severe outcomes than non-smokers (16.9% versus 5.2%) (Guan et al., 2020; Hoffmann et al., 2020). Consequently, wildland firefighters who have had high exposure to wildfire smoke may have an additional risk for contracting SARS-CoV-2 as a result of increased expression of alveolar ACE-2 from exposure to wildland fire smoke.

3. Wildfire smoke exposure and risk of lower respiratory infection

Wildfire smoke exposure has been associated with lower respiratory infections such as acute bronchitis and pneumonia in many epidemiological studies (Delfino et al., 2009; Morgan et al., 2010; Rappold et al., 2011). Several systematic reviews have found associations between wildfire smoke and emergency department visits and hospitalizations for acute bronchitis and pneumonia (Adetona et al., 2016; Cascio, 2018; Liu et al., 2015; Reid et al., 2016; Reid and Maestas, 2019). Yao et al., 2013 reported a significant association between PM_{2.5} on extreme fire days with physician visits for individuals with lower respiratory tract infections in British Columbia over 10 fire seasons. In San Diego and Colorado, Alman et al., 2016 and Hutchinson et al., 2018 reported significantly elevated risks of ED visits and hospital admissions for individuals diagnosed with respiratory infections during wildfires.

Wildfire smoke exposure may also be associated with risk for respiratory infection during the winter months after an intense, prolonged wildfire season. Landguth et al., 2020 examined seasonal influenza infection rates between 2010 and 2018 and reported a 22% increase in seasonal influenza incidence associated with elevated daily average PM_{2.5} concentrations during the previous summer wildfire season. Though not studied specifically in wildland firefighters, the published epidemiological literature provides considerable evidence for an association between exposure to wildfire smoke and respiratory infections.

4. Wildfire smoke exposure and risk of severe COVID-19 outcomes

As previously noted, exposure to PM from wildfire smoke can affect lung health through oxidative stress which subsequently leads to cell toxicity and an inflammatory response (Adetona et al., 2019). Kim et al., 2018 examined lung toxicity in mice and mutagenicity in *Salmonella* from exposure to PM in both the flaming and smoldering phases of combustion from multiple biomass fuel types. After adjusting for mass of fuel burned, the researchers reported that PM from smoldering eucalyptus had the highest lung toxicity, as measured by increases in neutrophil count measured in bronchoalveolar lavage fluid per mass of fuel burned, and mutagenicity, measured by a *Salmonella* plate incorporation assay, for eucalyptus and pine and pine needles, respectively. Gaughan et al., 2008 found an association between post-fire respiratory symptom scores with inflammatory biomarkers (eosinophilic cationic protein and myeloperoxidase) measured in sputum and nasal lavage fluid of wildland firefighters. This provides evidence that wildland firefighters may be at increased risk for severe respiratory outcomes through activation of inflammatory pathways.

Other recent studies measured inflammatory markers in wildland firefighters conducting prescribed fires, intentionally ignited low-intensity fires conducted for resource benefit, and during a large wildfire event (Adetona et al., 2017; Main et al., 2020). Adetona et al., 2017 found that wildland firefighters who ignited prescribed fires using torches filled with diesel and gasoline had elevated inflammatory markers for serum

amyloid, interleukin (IL)-8, and C-reactive protein (CRP), compared to firefighters tasked with holding (ensuring the fire did not escape). The additional exposure to combustion of diesel and gasoline could have led to an increase in inflammatory markers. Lastly, Main et al., 2020 reported a significant increase in the inflammatory biomarkers, IL-6 and IL-8, after a 12-h work shift compared to before the shift among wildland firefighters during a large wildfire event in Australia in 2009.

COVID-19 disease severity is also associated with cytokine release syndrome (resulting in "cytokine storm") induced by SARS-CoV-2 virus (Moore and June, 2020; Pedersen and Ho, 2020). Chen et al., 2020 reported that severe cases of COVID-19 had more frequently elevated levels of CRP and cytokines (IL-6, IL-10 and TNF- α) than less severe cases. Ruan et al., 2020 examined predictors of fatality in 150 cases of COVID-19 and found that mortality may be due to viral-caused hyperinflammation as measured by elevated IL-6 and CRP in non-survivors compared to survivors ($p < 0.0001$). An excessive inflammatory response to SARS-CoV-2 infection may be related to risk of hypotension and ARDS (Moore and June, 2020). Hypotension may also result from increased expression of ACE-2 in vascular cells resulting from increased cytokine release. ACE-2 lowers blood pressure by converting angiotensin II (a vasoconstrictor) into angiotensin (1-7) (Wang et al., 2016). Because the airway inflammation that wildland firefighters experience from exposure to smoke involves the same inflammation pathways that have been reported in severe COVID-19 cases, firefighters could have more severe COVID-19 outcomes.

Overall, wildland firefighters are at a greater risk for developing adverse respiratory health effects from wildfire smoke exposure due to a number of unique factors inherent to the wildfire environment. First, combustion of wildland biomass can produce PM containing adsorbed antigens that can elicit acute airway inflammatory responses or exacerbate chronic inflammation in sensitized individuals with asthma (Abbas et al., 2011; Liu et al., 2015). Wildfire PM also has a higher proportion of ultrafine particles that are readily translocated across the alveolar-capillary membrane and cause alveolar, pulmonary interstitial, and secondary systemic cell damage. Furthermore, the long workday and job demands of wildland firefighters can profoundly increase PM exposure (Reinhardt and Broyles, 2019).

In addition, sex-related differences in inflammatory responses have been measured in males after exposure to wood smoke. Both innate and adaptive immune responses are also modified by the sex of an individual (Klein and Flanagan, 2016). In a small pilot study, Rebuli et al., 2019 exposed both male and female adult participants to wood smoke and nasally inoculated live attenuated influenza virus following smoke exposure. After 2 days, males had increases in inflammation-related gene expression, whereas female inflammatory gene-expression was down-regulated. These sex-related differences in gene expression suggest that firefighters, the vast majority of whom are males, would be at higher risk of increased inflammatory reaction compared to female wildland firefighters.

Sex-specific immune response differences have also been noted in COVID-19 patients. Yale-New Haven researchers examined SARS-CoV-2 serum RNA concentrations, anti-SARS-CoV-2 antibody titers, and plasma cytokine/chemokine levels in 39 patients admitted to their acute care facility ($n = 17$ male and $n = 22$ female) (Takahashi et al., 2020). They found that males displayed greater innate immune IL-8 and IL-18 cytokine serum levels, whereas, females produced a more robust T cell-mediated response. Only in males, were poor COVID-19 outcomes negatively associated with poor a T cell-mediated response (Takahashi et al., 2020). Thus, they suggested that different sex-specific treatment regimens may benefit COVID-19 patients and help mitigate the severity of disease outcomes.

5. Wildland firefighter exposure to smoke

When performing common job tasks on wildfires and prescribed fires, wildland firefighters can be exposed to elevated concentrations of air pollutants found in smoke. Table 1 provides a description of

Table 1
Definitions for common job tasks performed by wildland firefighters.

Job task	Definition
Direct suppression	Use tactics (such as constructing fireline) next to the fire's edge to stop forward progression of the main fire. Firefighters are likely to be exposed to smoke when working close to this active fire edge.
Fireline construction	Clear vegetation (often first with chainsaws) and dig or scrape down to bare mineral soil to create a fuel break and stop forward progression of the fire.
Firing	Ignition of burnable materials (fuels) drip torches filled with a diesel/unleaded gasoline mixture, fuses, flare launchers, or other incendiary devices. How the burn is ignited (through firing patterns) may produce different amounts of PM in the smoke.
Holding	Monitor and patrol a section of the fireline (on wildfires and prescribed fires) and ensure that fire does not cross the fireline. Firefighters performing holding can be instructed to stand along a fireline and watch for the fire escaping control lines which can involve being in areas of high smoke and low visibility.
Indirect suppression	Use tactics (such as constructing fireline) away from the fire's edge to stop forward progression of the main fire. Often these indirect suppression firelines will be used to implement a firing operations.
Mop-up	Extinguish any burning or smoldering material by digging out the burning material or applying water to prevent rekindling and improve the chances the fireline will hold the fire.
Patrolling	Inspect and monitor a fire perimeter
Staging	Crews or resources waiting for operational assignments
Structure protection	Use tactics to protect a structure from active wildfire in the immediate area or prepare the structure for the threat of wildfire

common job tasks performed by wildland firefighters and how they can be exposed to smoke while performing those tasks. Mean PM concentrations from smoke measured across most prescribed fires and wildfires over the past 10 years did not exceed the occupational exposure limits for PM₄ (Navarro, 2020).

Reinhardt and Broyles, 2019 reported that job task, type of wildfire crew, and wind position were important factors for predicting exposure to PM₄. Exposure to PM₄ was significantly lower for firefighters completing non-arduous ancillary tasks such as operational breaks or waiting for assignments compared to mop-up (extinguishing a fire). In a 2015–2017 USFS follow-up study, wildland firefighters had significantly higher exposures of PM₄ when completing direct fire suppression (0.65 mg/m³), including fireline construction, compared to those firefighters who performed other job tasks. This study also found that firing (0.43 mg/m³) and holding (0.37 mg/m³) tasks resulted in elevated mean concentrations of PM₄ (Navarro KM, Butler C, O'Dell K, et al. *Exposure to Particulate Matter and Estimation of Volatile Organic Compound Across Wildland Firefighter Job Tasks. In Preparation 2020*). Gaughan et al., 2014 reported that wildland firefighters performing mop-up (0.51 mg/m³) had higher PM exposures compared to those constructing the fire line (0.49 mg/m³) at a large wildfire incident. This study also found that during fire line construction, an arduous task, wildland firefighters operating a chainsaw and clearing brush for the chainsaw operator had higher PM exposures (1.40–1.68 mg/m³) compared to fire line construction (0.60 mg/m³) as measured by real-time particulate matter samplers.

When compared to laboratory and field studies that found increased respiratory inflammatory responses, wildland firefighters experience similar or higher exposures to PM on wildfires. Rebuli et al., 2019 exposed study participants to 0.5 mg/m³ of wood smoke for 2 h. Adetona et al., 2017 reported the PM_{2.5} time-weighted average concentrations at 0.24 mg/m³ (range: 0.01–0.61 mg/m³) for firefighters that performed firing. Exposure assessment studies reported mean exposure PM_{2.5–4} from 0.32 to 0.51 mg/m³ across work shifts and maximum exposures that ranged from 0.68 to 2.56 mg/m³ for wildland firefighters at wildfires (Gaughan et al., 2014; Reinhardt and Broyles, 2019). Wildland firefighters working on the fire line typically have long work shifts and multi-week fire assignments that can result in higher cumulative exposures which may increase risk of adverse health outcomes.

In addition, wildland firefighters, incident management personnel, and camp support crew can be exposed to smoke at incident command posts (ICPs) that support thousands of individuals while off the fire line, which can contribute to a higher cumulative work exposure (McNamara et al., 2012; Navarro et al., 2019). Although wildland firefighters perform arduous tasks and are in great physical condition, fire personnel supporting fire operations at ICPs can be older, not as physically active, and have underlying health conditions. In 2006 and 2007, incident management personnel were surveyed to examine health status, activity levels, and cardiovascular risk factors. These surveys found that incident management personnel had an average of 2.6 coronary artery disease risk factors and indicated a need for improved physical activity, nutrition, and a reduction in stress (Lieberg et al., 2008). The National Wildfire Coordinating Group recommended that personnel at ICPs follow exposure limits to PM from the US Environmental Protection Agency (35.5–80.4 µg/m³ over 24 h), because they may be demographically similar to the general population and can have underlying health conditions or behaviors that put them at increased risks for adverse health outcomes from exposure to smoke including cigarette smoking, cardiovascular disease, high blood pressure, and obesity (NWCG, 2012). Older adults (≥ 65 years of age) or any-aged adults with underlying medical conditions or behaviors such as: chronic lung disease; cardiovascular disease; hypertension; Type 2 diabetes; chronic kidney disease; smoking; and obesity are also at increased risk for severe COVID-19 illness (Ahrenfeldt et al., 2020; CDC, 2020b; Wolff et al., 2020). At present, there is no empirical information that indicates whether incident management personnel who are regularly exposed to wildfire smoke are at greater risk for SARS-CoV-2 infection when compared to frontline wildland firefighters. However, incident management personnel may be at greater risk for severe COVID-19 outcomes due to the co-occurrence of wildfire smoke exposure and underlying comorbidities.

6. Prevention and mitigation strategies for wildland firefighters

The best way for wildland fire personnel to prevent COVID-19 illness is to avoid being exposed to SARS-CoV-2. As of August 2020, current guidance and recommendations from the Centers for Disease Control and Prevention and the Fire Management Board's Interagency Wildland Fire Medical and Public Health Advisory Team (MPHAT) to prevent or minimize the transmission of SARS-CoV-2 include social and physical distancing of wildland fire personnel, wearing cloth masks (especially when social distancing is not possible), frequent cleaning and disinfecting of surfaces and equipment, and daily screening for COVID-19 symptoms and body temperature (CDC, 2020c; MPHAT, 2020). To promote social and physical distancing, it is recommended to have smaller "spike" or remote camps to insulate crews and modules from each other and other outside personnel (MPHAT, 2020). This also includes limiting contact with community members nearby wildfire incidents or traveling when fire personnel must work and interact with the public (e.g. public information meetings, fueling vehicles, picking up supplies, etc.). Working as a crew or module requires close contact (riding in crew vehicles, hiking, and working next to each other). If a crew can "insulate as a unit" or create a "module as one", they can limit outside exposure to SARS-CoV-2 and may be able to safely complete operational tasks in closer proximity (CDC, 2020c; MPHAT, 2020). However, this will require all fire personnel to be vigilant when interacting with the public and anyone outside of their crew or module on and off work. Cloth masks are recommended as a source control when interacting with individuals outside of the crew, module, or unit, and when not engaged in arduous work.

To remain ready to respond to wildfires and for the next work shift, wildland firefighters will need to refurbish tools and supplies daily. Frequent cleaning and disinfecting of high-touch surfaces, equipment (e.g., hand tools or radios), and vehicles is recommended to prevent exposure to SARS-CoV-2 and should be integrated into the daily work

routine (MPHAT, 2020). Lastly, all fire response personnel should self-monitor and report any COVID-19 symptoms before going to work or accepting a wildfire assignment (CDC, 2020c). Wildland firefighting management should maintain a healthy workforce of all personnel that respond and support wildfire response throughout the fire season by prioritizing proper rest, hydration, and nutrition for all fire personnel (Yang et al., 2014).

In addition to prevention and mitigation recommendations, testing and contact tracing guidance was developed by MPHAT for wildland fire operations. Current testing guidance recommends prioritizing viral testing among wildland firefighters for (1) individuals with signs and symptoms consistent with COVID-19, and (2) asymptomatic individuals with recent known or suspected exposure to SARS-CoV-2 (exposure being defined as within 6 ft for 15 cumulative minutes or more within a 24 h period) (MPHAT, 2020b). This recommendation is consistent with the CDC guidance "SARS-CoV-2 Testing Strategy: Considerations for Non-Healthcare Workplaces" (CDC, 2020d). In the future, surveillance and pooled testing for SARS-CoV-2 may provide more options for the wildland fire community to monitor infections at the population level. State, Tribal, Local, or Territorial (STLT) health departments are responsible for leading case investigations, contact tracing, and outbreak investigations as they have the authority within a jurisdiction to protect public health. For this reason, wildland fire agencies and managers were encouraged to assist STLT health departments to perform contact tracing at wildfire incidents and provide information on the workplace and help with the identification of exposures and contacts in the workplace (MPHAT, 2020a).

Although COVID-19 is a Nationally Notifiable Disease and must be reported to STLT health departments, fire agencies do not have a standardized and universal system for tracking COVID-19 cases among fire personnel on or off a wildfire incident. During the 2020 fire season, one COVID-19 outbreak among fire personnel was identified and reported by the Colorado Department of Public Health and Environment at the Cameron Peak Fire in Larimer County where 45 confirmed cases of COVID-19 have been reported as of November 2020 (CDPHE, 2020). Wildland fire agencies could benefit from the development of surveillance programs to understand COVID-19 incidence and prevalence among the wildland fire community. This information could also be used to assess the effectiveness of prevention and mitigation strategies.

Mitigating exposures to smoke can be difficult for wildland firefighters as smoke is part of the wildfire environment on the fire line and in ICPs. Wildland firefighters wear cloth masks as a source control for SARS-CoV-2 when social distancing is not feasible. However, cloth masks do not provide any protection against wildfire smoke exposure. Currently, there is no respirator available for wildland firefighters, such as a self-contained breathing apparatus worn by structural firefighters, that meets the National Fire Protection Association standard. There is no respirator that will provide protection for all inhalation hazards and is able to be worn in the extremes of the wildfire environment (Domitrovich et al., 2017). In addition, the National Wildfire Coordinating Group requires that only respirators approved by the National Institute for Occupational Safety and Health (NIOSH) will be used on the fireline; although, respiratory type products (such as bandanas) are marketed to wildland firefighters, they are not NIOSH-approved (NWCG, 2020). Job tasks known to have elevated smoke exposure include mop-up, holding, fire line construction, and firing (Adetona et al., 2017; Gaughan et al., 2014; Navarro et al., 2017; Reinhardt and Broyles, 2019). Mitigation strategies will be dependent on fire behavior, available resources and personnel, and operational objectives. Current mitigations proposed for this fire season include: rotating fire personnel in areas of high unavoidable smoke exposure, using air resource advisors to monitor and address smoke issues, and locating ICPs and remotes camps in areas with least smoke exposure practicable (Group NRC, 2020). Camps, where firefighters rest when off-shift, should not be sited in areas with a high likelihood of strong nighttime inversions,

which can trap smoke and lead to higher exposures to smoke (McNamara et al., 2012; Navarro et al., 2019).

To reduce cumulative exposures to smoke across a fire assignment, wildfire incident management personnel should rotate and re-assign crews and resources after completing job tasks associated with higher smoke exposures to job tasks that have lower expected smoke exposures. Reductions in exposure across multiple assignments may reduce cumulative exposure across a career. Past exposure assessments completed by the USFS demonstrate that wildland firefighters are good estimators of their own exposures, as self-reporting of categorical smoke exposure (low to high) is associated with measured concentrations of PM₄ (Navarro KM, Butler C, O'Dell K, et al. *Exposure to Particulate Matter and Estimation of Volatile Organic Compound Across Wildland Firefighter Job Tasks. In Preparation 2020*). Self-reported qualitative smoke exposure could be used by wildfire incident management personnel to track cumulative exposure throughout individual fire assignments or across the fire season. Additional mitigation strategies should be considered for crews, modules, or individuals reporting high cumulative smoke exposure. All fire personnel should try to mitigate smoke exposure, when tactics can be adjusted, while meeting operational objectives on the fire line and fire management goals.

Through this review, we demonstrated that exposure to smoke may be associated with SARS-CoV-2 infections and severity of illness outcomes. However, there are some limitations to consider when interpreting our analysis of the literature. First, this review was not conducted as a systematic review of the literature, but instead as a rapid review to provide evidence for the association between smoke and SARS-CoV-2 infection and illness outcomes. Since this is an emerging topic, a systematic approach may not have provided enough information to present and provide an adequate discussion of this topic. Second, since there are limited health studies for wildland firefighters, we reviewed epidemiology studies assessing respiratory infections in the general public from exposure to wildfire smoke. We understand that the general public will have different health risk factors and possibly lower exposures to smoke when compared to wildland firefighter who are required to pass physical fitness tests and perform arduous work, but there is not an adequate similar occupational group to compare exposures and health outcomes. Although structural firefighters may perform similar duties, their exposures are varied due to different combustion sources and they are able to use respiratory protection. Lastly, since this is an emerging topic and new research is constantly being conducted and published, it is difficult to have consistently up-to-date information when publishing a review of the literature on SARS-CoV-2.

The wildfire environment includes many risks and hazards such as burnovers/entrapments, heat-related illnesses and injuries, vehicle-related injuries (including aircraft), slips, trips, and falls, falling trees and others (Britton et al., 2013). These risks may be independent or interdependent and are often managed through the "Operational Risk Management" framework, which is a continuous assessment process of identifying hazards and implementing controls to make decisions and reduce unintended outcomes. Every risk is assessed by its probability (likelihood of mishap if risk is present) and severity (consequences if mishap occurs) (US Forest Service, 2020). Wildland firefighting management has a mission to manage fire, while considering all risks to maintain a healthy workforce throughout the fire season. The risk of SARS-CoV-2 infections and COVID-19 illness during the 2020 fire season is an additional risk to consider when assessing all risks and hazards in the wildfire environment. It is important for all fire personnel to understand the risk of smoke and how to mitigate exposure.

7. Conclusion

Studies have demonstrated that exposure to wildfire smoke is associated with airway inflammation, cell toxicity, oxidative stress, and increased risk of respiratory infections. Occupational wildfire smoke

exposure may modify firefighter susceptibility to SARS-CoV-2 infection or their risk for developing severe COVID-19 illness. Preventing the transmission of SARS-CoV-2 infection may be difficult in the extreme work environments of wildland firefighting personnel. All wildland fire personnel should stay up-to-date on the basic understanding of COVID-19, how the disease is thought to spread, disease symptoms, and what measures can be taken to prevent or minimize transmission. Prevention measures for wildland firefighters should include social and physical distancing as a unit, cloth masks when operating outside their unit, frequent cleaning and disinfecting, and screening of fire personnel daily for symptoms of COVID-19.

Disclaimer

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Kathleen M. Navarro: Conceptualization, Writing – original draft. **Kathleen A. Clark:** Conceptualization, Investigation, Writing – original draft. **Daniel J. Hardt:** Investigation, Writing – original draft. **Colleen E. Reid:** Conceptualization, Investigation, Writing – review & editing. **Peter W. Lahm:** Conceptualization, Writing – review & editing. **Joseph W. Domitrovich:** Conceptualization, Writing – review & editing. **Corey R. Butler:** Conceptualization, Writing – review & editing. **John R. Balmes:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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