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Original Article

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Potential impacts of Washington State's wildfire worker protection rule on construction workers

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Abstract

Driven by climate change, wildfires are increasing in frequency, duration, and intensity across the Western United States. Outdoor workers are being exposed to increasing wildfire-related particulate matter and smoke. Recognizing this emerging risk, Washington adopted an emergency rule and is presently engaged in creating a permanent rule to protect outdoor workers from wildfire smoke exposure. While there are growing bodies of literature on the exposure to and health effects of wildfire smoke in the general public and wildland firefighters, there is a gap in knowledge about wildfire smoke exposure among outdoor workers generally and construction workers specifically—a large category of outdoor workers in Washington totaling 200,000 people. Several data sources were linked in this study—including state-collected employment data and national ambient air quality data—to gain insight into the risk of $PM_{2.5}$ exposure among construction workers and evaluate the impacts of different air quality thresholds that would have triggered a new Washington emergency wildfire smoke rule aimed at protecting workers from high $PM_{2.5}$ exposure. Results indicate the number of poor air quality days has increased in August and September in recent years. Over the last decade, these months with the greatest potential for particulate matter exposure coincided with an annual peak in construction employment that was typically 9.4–42.7% larger across Washington counties (one county was 75.8%). Lastly, the 'encouraged' threshold of the Washington emergency rule (20.5 $\mu g\ m^{-3}$) would have resulted in 5.5 times more days subject to the wildfire rule on average across all Washington counties compared to its 'required' threshold (55.5 $\mu g\ m^{-3}$), and in 2020, the rule could have created demand for 1.35 million N-95 filtering facepiece respirators among construction workers. These results have important implications for both employers and policy makers as rules are developed. The potential policy implications of wildfire smoke exposure, exposure control

What's Important About This Paper?

Outdoor workers are being exposed to increasing concentrations of wildfire-related particulate matter and smoke. Recognizing this emerging risk, Washington and other Western States have adopted rules or are creating rules to protect outdoor workers from wildfire smoke exposure. While there are growing bodies of literature on the exposure to and health effects of wildfire smoke in the general public and wildland firefighters, there is a gap in knowledge about outdoor workers generally and construction workers specifically. This study evaluates the potential for exposure to wildfire-related $PM_{2.5}$ as defined under these rules and discusses the impact on the wildfire exposure protection rules on the Washington construction workforce.

strategies, and data gaps that would improve understanding of construction worker exposure to wildfire smoke are also discussed.

Keywords: forest fires; $PM_{2.5}$; respirator; wildland fire; wildfire smoke protection rule

Introduction

Wildfires in the Western USA have increased in frequency and are burning greater land areas for longer periods of time (Balmes, 2018). This trend, exacerbated by climate change (Abatzoglou and Williams, 2016), is increasing the lengths of wildfire seasons (Reisen *et al.*, 2015). In Washington (WA)—where the summer climate is dry, especially in the hot and arid region east of the Cascade Mountain Range—environmental conditions contribute to wildfire ignition and spread. Smoke and pollution from wildfires can travel large distances from burns, including urban areas (Wotawa, 2000; Stefanidou *et al.* 2008; Reisen *et al.*, 2015; Balmes, 2018). The 2018 and 2020 wildfire seasons were particularly active, gaining media attention (Fields and Baruchman, 2018; The Seattle Times, 2020), prompting coordinated alerts from regional air quality and health agencies (PSCAA et al., 2018), and leading to mitigation planning in urban centers (Contreras, 2019).

The composition of wildfire smoke is related to the environmental characteristics of the landscape that is burning (e.g. temperature, humidity, windspeed, fuel/forest type) (Stefanidou *et al.*, 2008; Reisen *et al.*, 2015; Balmes, 2018) and has the potential to evolve as residential and commercial structures fuel burns. Wildfire combustion yields a large range of solid, liquid and gaseous pollutants, including silica, carbon monoxide, carbon dioxide, oxides of nitrogen and sulfur, methane, acrolein, formaldehyde, volatile organic compounds, polyaromatics, aldehydes, dioxides, and furans (Materna *et al.*, 1992; Slaughter *et al.*, 2004; Statheropoulos and Karma, 2007; Stefanidou *et al.*, 2008; Reisen *et al.*, 2015). These constituents, as individual components or in mixture, may help explain recent observational and toxicological studies indicating wildfire smoke is more toxic than ambient particulate matter (PM) pollution (Kim Yong Ho et al., 2018; Aguilera *et al.*, 2021). Despite the increased risk of wildfire smoke, $PM_{2.5}$ is still considered the main wildfire pollutant affecting human health (Schwela *et al.*, 1999; Reid *et al.*, 2005).

During wildfire events US Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) (e.g. $PM_{2.5}$ >35 μg m^{-3} for a 24-h period) can be exceeded, with daily concentrations greater than 100 μg m^{-3} (Liu *et al.*, 2015). However, these concentrations still generally fall well below occupational standards for PM exposure (e.g. Occupational Safety and Health Administration (OSHA) 5 mg m^{-3} 8-h time-weighted average for respirable dust). Despite the large gap in these standards resulting from EPA and OSHA's differing regulatory aims and populations of interest, there is a notable lack of guidance for employers and employees related to wildfire smoke exposure.

In fact, California (CA) is currently the only US state that has adopted permanent rules to protect non-firefighting workers from wildfire smoke exposure, including requirements for hazard identification, communication, training, and control of wildfire smoke exposure at and above an hourly equivalent $PM_{2.5}$ concentration of 55.5 μg m^{-3} [Air Quality Index (AQI) level of 151] (CA, 2019). The US EPA AQI is a tool for communicating information on daily ambient air quality as it relates to human health-based pollutant standards (i.e. NAAQS) (US EPA, 2021a). While Northwest states—Oregon (OR) and WA—are currently engaged in similar rule-making, their details are only currently emerging. The WA Department of Labor and Industries (L&I) implemented an emergency occupational wildfire protection rule for 2021 (effective through November 2021), with an 'encouraged' threshold of 20.5 μg m^{-3}

(equivalent to a Washington Air Quality Advisory (WAQA) = 101 and AQI = 69) and a 'required' threshold of 55.5 μg m^{-3} (WAQA = 173; AQI = 151), while continuing to work on a permanent rule. The rule proposed by OR OSHA, has thresholds of 35.5 μg m^{-3} (AQI = 101) and 55.5 μg m^{-3} (AQI = 151) for successively stronger requirements to protect workers from wildfire smoke exposure (OR OSHA, 2020). Supplementary Table S1 (available at *Annals of Work Exposures and Health* online) provides the AQI and WAQA Level of Concern (e.g. 'good' through 'hazardous'), air quality Index Values, and the corresponding Federal (AQI) and Washington (WAQA) $PM_{2.5}$ concentrations. It is important to note that the wildfire smoke protection rules in CA, OR, and WA do not require the identification of wildfire smoke or wildfire-related $PM_{2.5}$ specifically, yet rely on general ambient $PM_{2.5}$ concentrations, for example as reported by government regulatory agencies.

A range of deleterious health effects have been associated with exposure to wildfire smoke in the general public and firefighters. The most consistent evidence shows relationships with respiratory morbidity, specifically asthma exacerbations and chronic obstructive pulmonary disease, and a growing body of evidence of respiratory infections and all-cause mortality (Reid *et al.*, 2016; Doubleday *et al.*, 2020). Other potential outcomes include irritant reactions, such as headache, conjunctivitis, nasopharyngitis, sinusitis, tracheitis, and acute bronchitis (Shusterman, Kaplan, and Canabarro, 1993); decreased lung function (Slaughter *et al.*, 2004); and cardiovascular effects (Stefanidou *et al.*, 2008; Liu *et al.*, 2015). Outdoor workers—such as those in construction industries—may be at increased risk due to several exposure-related factors potentially contributing to a higher dose of wildfire-related $PM_{2.5}$ compared to the general public. First, many construction workers spend a considerable amount of time outside (Schulte and Chun, 2009). Second, these workers may have a higher level of physical exertion, leading to higher respiration rates and tidal volumes and subsequent minute ventilation (Tipton *et al.*, 2017; Nicolò *et al.*, 2018). Third, with physical exertion, workers may be more likely to breathe orally (Niinimaa *et al.*, 1980), bypassing nasal filtration mechanisms (Schwab and Zenkel, 1998).

Construction workers already face many occupational hazards and are consistently subject to some of the highest rates of occupational accident, injury, and death. In 2018, the latest year with complete data, over 11.18 million construction workers made up 7.18% of the national workforce, yet accounted for 20.2% of fatalities and 5.8% of non-fatal injuries and illnesses (CDC, 2020). In addition to traditional hazards [e.g. falls, electrocution, hearing loss, musculoskeletal disorders, and respiratory diseases (CPWR, 2018)], construction workers are now exposed to increased PM from wildfires from the ambient environment. Commercial and residential construction in WA is increasing—for example, from 39 021 residential units in 2000, to 48 4240 in 2019 (with a decrease to 43 881 in 2020 likely due to the COVID-19 pandemic) (US Census Bureau, 2020). This expanding construction workforce also varies seasonally, coinciding with the Pacific Northwest's summer wildfire season, contributing to the overall population at risk and health burden in WA.

Exposure to wildfire smoke has been described in agricultural workers (Austin *et al.*, 2021) and wildland firefighters, who may have $PM_{2.5}$ exposures orders of magnitude greater than non-firefighters (Reinhardt and Ottmar, 2004; Adetona *et al.*, 2013; Wu *et al.*, 2021). However, no studies we are aware of have examined potential exposure to wildfire pollution among construction workers, especially as it is defined with $PM_{2.5}$ thresholds under new occupational wildfire smoke protection rules. There is therefore an important gap in the published literature on the impacts of wildfire smoke on construction workers. The aims of this study were to (i) characterize the temporal patterns of poor air quality and construction employment across WA counties, (ii) estimate potential exposure to high ambient $PM_{2.5}$ concentrations among WA construction workers, (iii) discuss the potential implications for state-level worker protection rulemaking in Washington, and (iv) identify data gaps that would improve our understanding of the health risks and exposure to ambient air/wildfire pollution among WA construction workers.

Methods

Study area

The present analysis included all counties for Washington State, but three counties are highlighted: King, Spokane, and Yakima. These counties are a sample of the geographic variability in WA and include a large metropolitan area (Seattle), rural and agricultural communities, and biomes east and west of the Cascade Mountain Range. These were also counties that bore a greater wildfire-related health burden in 2020, compared with other WA counties (Liu *et al.*, 2021).

Data sources

Employment data

Monthly employment data were gathered from the Washington Employment Security Department (ESD) Quarterly Census of Employment and Wages (QCEW)

(WA ESD, 2020). These data are collected cooperatively by the ESD and the US Bureau of Labor Statistics and report employment and wage information by industry and county in industries covered by unemployment insurance. Data are collected from quarterly unemployment tax forms filed by employers. Industries are categorized following North American Industrial Classification System (NAICS) codes. Data are considered of 'excellent' accuracy/reliability, with only occasional interruptions due to employers being reclassified into a different industry or moving counties. Available data from nonfarm monthly employment from 2002 to 2020 related to construction industries, which followed the 2002 two- and three-digit NAICS codes were used to show longer term trends for all of WA, by plotting monthly employment totals for 'construction' (NAICS sector code 23), 'construction of buildings' (NAICS subsector code 236), 'heavy and civil engineering construction' (NAICS subsector code 237), and 'specialty trade contractors' (NAICS subsector code 238). For further analysis at the county level, ESD data were restricted to the construction sector for the 10-year period 2011–2020.

At the State level, more detailed information on the types of construction, in the form of NAICS national industry (six-digit) codes, was available from ESD QCEW. These data were restricted to industries within the construction sector (NAICS code 23) in 2020, from which the number of construction workers potentially engaged in outdoor construction and who would therefore be considered exposed to wildfire smoke was evaluated.

$PM_{2.5}$ and Air Quality Index data

$PM_{2.5}$ data from 109 WA monitoring sites were collected from the US Environmental Protection Agency (EPA) Air Quality System (AQS) for 2011–2020 (US EPA, 2020), including measurements from all Federal Reference Method (FRM), Federal Equivalent Method (FEM), and non-FRM/FEM monitors. From these data, daily $PM_{2.5}$ averages were calculated for each county. Some WA counties do not have any monitoring sites; therefore, no $PM_{2.5}$ data were available for this part of this analysis. We used the concentration thresholds defined in proposed and promulgated worker protection rules, as well as the NAAQS $PM_{2.5}$ standard, to identify counties and days impacted by wildfire smoke as described in the Data Analysis section.

County-level daily AQI data based on $PM_{2.5}$ were also obtained from the AQS (US EPA, 2020). The AQI is the EPA's summary measure for air pollution and level of health concern; it is informed by five pollutants: ground-level ozone, particle pollution, carbon monoxide, sulfur dioxide, and nitrogen dioxide. AQI levels are defined according to thresholds for each pollutant; the levels are summarized for $PM_{2.5}$ in Supplementary Table S1 (available at *Annals of Work Exposures and Health* online). This analysis was restricted to days with AQI levels defined by $PM_{2.5}$, the pollutant defining days subject to wildfire protection rules. The number of days per month for each county with poor AQI levels ranging from 'moderate' to 'hazardous' were tallied, then averaged by month over the 2011–2020 period to estimate the mean number of days per month with AQI levels worse than 'good' ($PM_{2.5} \geq 12.1$ µg m^{-3}; AQI and WAQA ≥ 51).

Data analysis

The combined analysis of air quality and construction employment was focused on the 10 years from 2011 through 2020. This period of time started following the multi-year economic recession beginning in 2008 and included the COVID-19 pandemic in 2020. To represent the annual cyclical pattern of construction employment, monthly ESD counts of construction workers were averaged over the 2011–2020 period, then a percent change from the month with the lowest count of construction workers as the reference point was calculated (January for most counties). With this procedure, the average monthly change in the WA construction workforce at the county level was estimated. This change in monthly construction employment was plotted with (i) boxplots of mean daily $PM_{2.5}$ concentration for each month and (ii) the mean number of days with AQI warnings over the 2011–2020 period.

Although the wildfire smoke protection rules in CA, OR, and WA are intended to protect workers from wildfire smoke, as worded, they are based on exceedances of specified thresholds for ambient $PM_{2.5}$ concentrations to protect general population health. The thresholds for each state were considered in our analysis as follows. For each county, the number of days that exceeded several $PM_{2.5}$ thresholds including 20.5 µg m^{-3} (AQI = 69; WAQA = 101, the 'encouraged' threshold in the WA emergency rule (WA L&I, 2021)); 35 µg m^{-3} (EPA NAAQS (US EPA, 2016), which is also close to the 35.5 µg m^{-3} (AQI = 101) threshold proposed in OR (OR OSHA, 2020); and 55.5 µg m^{-3} (AQI = 151), the first action level of the CA rule (CA, 2019) and the 'required' threshold in the WA emergency rule were tallied. Additionally, the number of days per month that exceeded (i) 20.5 µg m^{-3} (AQI = 69) for the 2011–2020 period and (ii) 55.5 µg m^{-3} (AQI = 151) for 2020 were also tallied. The CA and WA rules are triggered by outdoor work of duration greater than 1 h, above a threshold based on AQI as defined as EPA's NowCast (an average of current and past concentrations over the prior 12 h). The intent of EPA's NowCast is to provide current air quality information that better reflects 24-h exposures, for which much of the epidemiologic evidence is based (US EPA, 2021b). Because this analysis was retrospective, and thus, 24-h average exposures can be computed, daily averages were used, which sufficiently reflects the intent of current AQI. For each county the Pearson correlation between (i) percent construction workforce county-level daily $PM_{2.5}$ concentration and (ii) percent construction workforce and the mean number of days with AQI warnings worse than 'moderate', each at the monthly time scale was computed. Wildfire exposure rules are applicable for either $PM_{2.5}$ concentrations or $PM_{2.5}$ AQI values, therefore both were included both in this analysis.

A map displaying construction employment according to 2020 ESD data by county with overlaid AQS monitoring locations was prepared to illustrate the relationship between construction worker population and the degree to which WA counties have air quality data.

State-level employment data classified by six-digit NAICS codes were restricted in further analysis to the NAICS two-digit sector code 23, focusing on the numbers of construction workers within three-digit NAICS subsector codes 236, 237, and 238. The potential for outdoor work among these six-digit construction codes was then evaluated, which would lead to increased exposure to wildfire-related smoke and PM.

To estimate construction worker-days of exposure to wildfire smoke in WA, for each county the number of construction workers at the beginning of each month was tabulated then multiplied by the number of days where $PM_{2.5}$ in the county exceeded each threshold for each month, then summed across WA counties.

All data analysis was performed in R version 4.0.3.

Results

Employment

Trends in construction employment from 2002 through 2020 for Washington State are shown in Fig. 1 and for each WA county in Supplementary Fig. S1 (available at *Annals of Work Exposures and Health* online). Though King County had the largest number of construction workers, most counties generally followed similar long- and short-term trends. The number of construction workers declined dramatically in the recession that began in 2008, and after reaching a minimum in 2011 steadily increased through 2019 until the spring of 2020 where a sharp decrease then increase reflected the economic impacts of the COVID-19 pandemic. For example, in King County, in the 'construction' sector, there

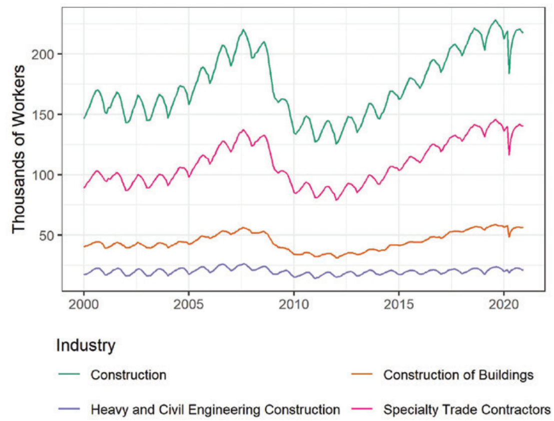

Figure 1. Monthly counts of Washington State construction workers. Construction of Buildings (NAICS code 236), Heavy and Civil Engineering Construction (NAICS code 237), and Specialty Trade Contractors (NAICS code 238) sum to Construction (NAICS code 23).

was a pre-recession high in September 2007 of 74,800, a February 2011 minimum of 43,300, and a high of 76,800 construction workers in August 2019. By the end of 2020, construction employment had nearly recovered to pre-pandemic levels. A distinct annual cyclical pattern in employment occurred throughout the time period, with the number of construction workers lowest during the winter months (December–February) and highest during the summer months (July–September). The distribution of construction workers by county for WA in 2020 is shown in Fig. 2 (with the locations of EPA AQS monitors). The counties with the greatest number of construction workers were Snohomish, King, and Pierce Counties (in Western Washington) and Spokane County in Eastern Washington.

Table 1 and Supplementary Table S2 (available at *Annals of Work Exposures and Health* online) provide statewide detail about the three- and six-digit NAICS codes for construction workers in WA. Many construction workers have a high potential for outdoor work, and therefore exposure to ambient environmental conditions such as wildfire smoke, including civil and environmental engineering construction (NAICS code 237). Other types of construction, including construction of buildings (NAICS code 236) have a medium potential for outdoor work, which would largely depend on factors such as whether or not the heating, ventilation, and air conditioning (HVAC) system is operating and workers occupy indoor spaces supplied with filtered air. Specialty trade contractors (NAICS code 238) make up a large percent of WA construction workers, at 63.9% in 2020, and have mixed potential for outdoor work,

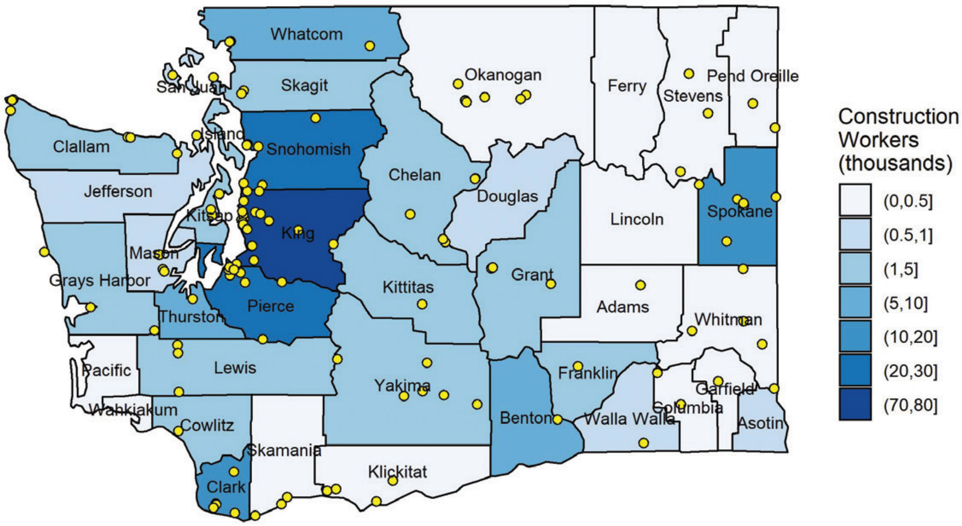

Figure 2. Map of Washington State with counties shaded according to construction employment (annual average of 2020 ESD data) and AQS monitor locations (points). (Note: construction employment for Garfield County was 2017 due to data availability).

Table 1. Summary of the number of construction workers by NAICS code in WA for 2020 (note that table for all NAICS codes available in Supplementary Materials)

NAICS code		Industry	Potential for outdoor work	Firms	Workers	Percent of two-digit NAICS	Percent of three-digit NAICS
23		Construction		26 977	199 784	100.0	
236		Construction of buildings		9478	51 636	25.8	100.0
	236 220	Commercial building construction	Medium	986	18 808	9.4	36.4
	236 115	New single family general contractors	Medium	4338	14 723	7.4	28.5
	236 118	Residential remodelers	Medium	3844	11 908	6.0	23.1
		Other (NAICS 236116, 236117, 236210)	Medium	310	6198	3.0	12.0
237		Heavy and civil engineering construction		1084	20 576	10.3	100.0
	237 310	Highway, street, and bridge construction	High	239	6550	3.3	31.8
	237 110	Water and sewer system construction	High	320	4205	2.1	20.4
	237 130	Power and communication system construction	High	197	4195	2.1	20.4
		Other (NAICS 237120, 237210, 237990)	High	329	5626	2.8	27.3
238		Specialty trade contractors		16 416	127 573	63.9	100.0
	238 212	Nonresidential electrical contractors	Medium	677	15 418	7.7	12.1
	238 222	Nonresidential plumbing and HVAC contractors	Medium	460	14 076	7.0	11.0
	238 221	Residential plumbing and HVAC contractors	Medium	1600	11 992	6.0	9.4
		Other (NAICS codes 238211, 238311, 238321, 238911, 238912, 238161, 238312, 238111, 238351, 238131, 238992, 238292, 238991, 238322, 238162, 238112, 238171, 238122, 238331, 238152, 238341, 238142, 238392, 238352, 238141, 238151, 238192, 238391, 238132, 238332, 238121, 238291, 238191, 238172, 238342)	Mixed	13 684	86 090	43.0	67.5

largely depending on the trade. For instance, residential roofing contractors (NAICS code 238161) have a high potential for outdoor work, in contrast to residential finish carpentry contractors (NAICS code 238351). Collectively, the NAICS codes assessed as having a high potential for outdoor work constitute 28.5% of construction workers in WA, while those with medium potential made up 68.1%.

Over the 2011–2020 period, the construction workforce varied seasonally. For King, Spokane, and Yakima Counties, January was on average the month with the least number of construction workers (with the drop in April for King County resulting from inclusion of data during the 2020 COVID-19 pandemic). Using January as a baseline, the construction workforce increased throughout the year into summer where the workforce was an average of 9.4% larger in King County (September), and 23.7 and 26.2% larger in Spokane and Yakima Counties (August), respectively. Across all counties, the construction workforce was between 9.4 and 42.7% greater in summer, with Garfield County 75.8% larger.

$PM_{2.5}$ air pollution

$PM_{2.5}$ varied over the course of the year for all WA counties (Fig. 3 and Supplementary Fig. S2, available at *Annals of Work Exposures and Health* online). Among highlighted counties over the 2011–2020 period, the highest median daily $PM_{2.5}$ concentrations were in Yakima County in winter (November = 12.0 µg m^{-3}, December = 13.1 µg m^{-3}, and January = 12.9 µg m^{-3}). These winter concentrations were higher than the summer months of the wildfire season (July = 6.8 µg m^{-3}, August = 8.5 µg m^{-3}, and September = 7.5 µg m^{-3}). A similar pattern existed for King and Spokane Counties, with median daily winter $PM_{2.5}$ concentrations greater than summer, reflecting pollution from home heating (which in rural areas may be with wood-burning stoves or boilers), agricultural burning (as permitted by the State), and environmental conditions (e.g. atmospheric inversions). However, these elevated wintertime measures of central tendency belie the more extreme daily concentrations observed, which occurred mostly in August and September. Over this 10-year period, months where the daily $PM_{2.5}$ concentration exceeded the WA emergency wildfire rule's 'encouraged' threshold of 20.5 µg m^{-3} (AQI = 69) were generally August and September, but for some counties the rule may have also been applicable in months without wildfires (Supplementary Table S3, available at *Annals of Work Exposures and Health* online). Of the highlighted counties, Yakima exceeded 20.5 µg m^{-3}, 46 and 50 days in August and September, respectively, over this 10-year period, compared to King County which experienced

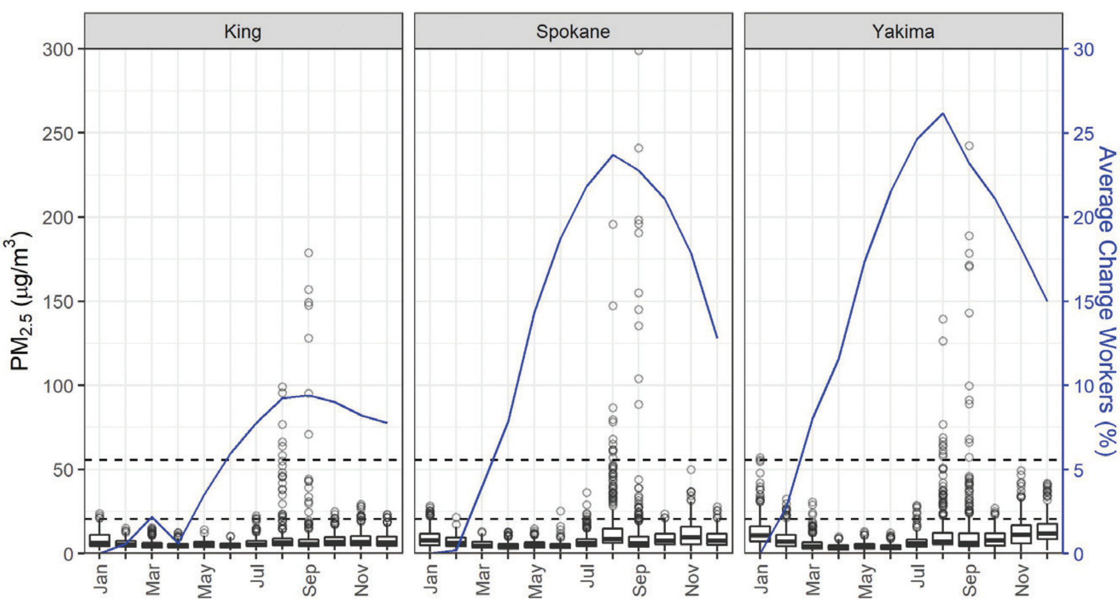

Figure 3. Daily $PM_{2.5}$ concentrations and average monthly percent difference in construction workers from the month with the lowest number of workers for King, Spokane, and Yakima, WA counties; 2011–2020. Dashed lines indicate WA's 'encouraged' and 'required' $PM_{2.5}$ thresholds (20.4 and 55.5 µg m^{-3}, respectively). (Note: axes were restricted, omitting 2 and 3 data points above 300 µg m^{-3} for Spokane and Yakima Counties, respectively).

about one half to one third as many days. Of all WA counties, Okanagan had the greatest number of days (67 in August), followed by Chelan (59 in August) above 20.5 μg m^{-3} from 2011 to 2020. Similar results for 2020 are presented in Supplementary Table S4 (available at *Annals of Work Exposures and Health* online) and incorporate annual estimates of construction employment with monthly results tabulated for the 'required' threshold of 55.5 μg m^{-3} (AQI = 151). In 2020, most of the days that would have triggered this threshold in the WA rule were in September, corresponding with the major wildfire event.

Air Quality Index

There was variability in the average number of days with AQI worse than 'good' over the 2011–2020 period (Fig. 4 and Supplementary Fig. S3, available at *Annals of Work Exposures and Health* online). Among highlighted counties, Yakima had the greatest number of poor air quality days, for all AQI categories 'moderate' and worse (N = 1196) and when restricting to the more severe AQI categories (i.e. omitting 'moderate' AQI days; N = 147 days). For the 'moderate' and worse days, this was 1.5 times greater than Spokane County and 1.8 times greater than King County, and for the more severe AQI days, this was 2.7 times greater than Spokane County and 3.7 times greater than King County. For all WA counties, all or nearly all of the days with the worst AQI levels ('very unhealthy', 'unhealthy', and 'hazardous') occurred in August or September. There was also an increase in the number of days with poor AQI in more recent years (Supplementary Fig. S4, available at *Annals of Work Exposures and Health* online), with the worst air quality days in August and September.

Relationship between air quality and seasonal construction workforce

Summaries of the relationship between seasonal construction employment and $PM_{2.5}$ concentrations are presented in Fig. 3 and Supplementary Fig. S2 (available at *Annals of Work Exposures and Health* online). The months when the construction workforce is largest (August and September) coincide with months with the greatest number of high daily average $PM_{2.5}$ concentrations. A similar pattern holds for construction employment and AQI (Fig. 4 and Supplementary Fig. S3, available at *Annals of Work Exposures and Health* online). Construction employment was generally highest in the summer months, when there were more days with higher AQI warnings.

Restricting AQI days to the most severe categories ('unhealthy for sensitive groups', 'unhealthy', and 'very unhealthy'), the Pearson correlation coefficients between the daily $PM_{2.5}$ concentration or the average number of poor AQI days per month and the percent of the construction workforce is presented in Supplementary Table S5, available at *Annals of Work Exposures and Health* online. Among highlighted counties, there was

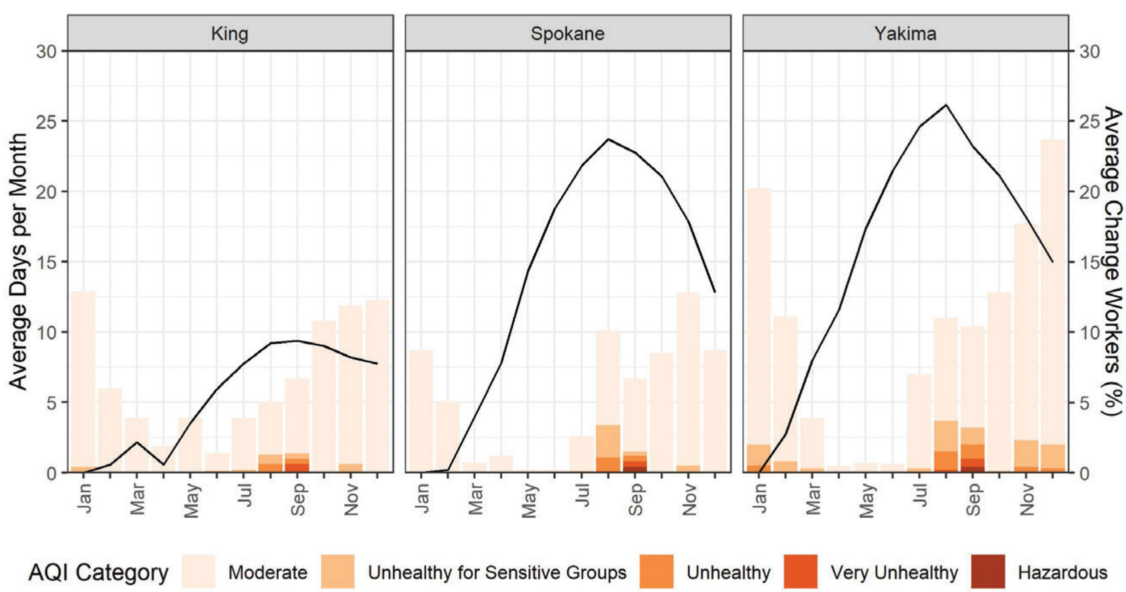

Figure 4. Average number of days per month with AQI worse than 'good' and average monthly percent difference in construction workers from the month with the lowest number of workers for King, Spokane, and Yakima, WA counties; 2011–2020.

moderately strong correlation between $PM_{2.5}$ concentration and change in construction workforce for King County (p_{King} = 0.629), moderate correlation for Spokane County ($p_{Spokane}$ = 0.501), but no correlation for Yakima County (p_{Yakima} = 0.109). Between the average number of days with AQI warnings and the change in construction workforce, the correlation was moderate for King and Spokane Counties (p_{King} = 0.517; $p_{Spokane}$ = 0.508) but weak for Yakima County (p_{Yakima} = 0.196). Low to moderate correlations were observed for most WA counties, with the highest correlation between $PM_{2.5}$ concentration and change in construction workforce ($p_{Garfield}$ = 0.882) and between the average number of days with AQI warnings and the change in construction workforce ($p_{Garfield}$ = 0.821). This observation with Garfield County however, may be influenced by the fact that there was no air quality data available prior to 2017 and recent years have been more impacted by wildfire smoke, and the large seasonal changes in the size of County's construction workforce. Overall, there does not appear to be a relationship between the percent of county populations that are considered urban or rural and the correlations between the monthly measures of construction workforce and air quality (Supplementary Table S5, available at *Annals of Work Exposures and Health* online).

Estimated wildfire exposure, according to $PM_{2.5}$ concentration thresholds, among WA construction workers is shown in Fig. 5. Recent wildfire events in August 2017, August 2018, and September 2020 each resulted in more than 1 million construction worker-days of exposure for the three wildfire protection thresholds considered. As expected, the lowest threshold (20.5 µg m^{-3}; AQI = 69) results in a larger number of worker-days of exposure, for example in August 2018, there were an estimated 2 330 000 construction worker-days of exposure compared to 880 500 construction worker-days under the 55.5 µg m^{-3} (AQI = 151) threshold. Additionally, the lower threshold also captured high pollution days in winter that were unlikely to be caused by wildfires. Extending the concept of construction worker-days of exposure to estimate the demand for respiratory protection in 2020 that could have been induced by the 55.5 µg m^{-3} (AQI = 151) threshold resulted in a calculated demand for filtering facepiece respirators totaling 1.35 million (Supplementary Table S4, available at *Annals of Work Exposures and Health* online) under the assumption that the annual average number of construction workers for each county would use one respirator for each day above the threshold.

Discussion

Even as $PM_{2.5}$ concentrations have decreased across the USA due to reduced industrial and vehicle emissions, the Northwest has not enjoyed the same improvements in air quality because of wildfires (Ford *et al.*, 2018;

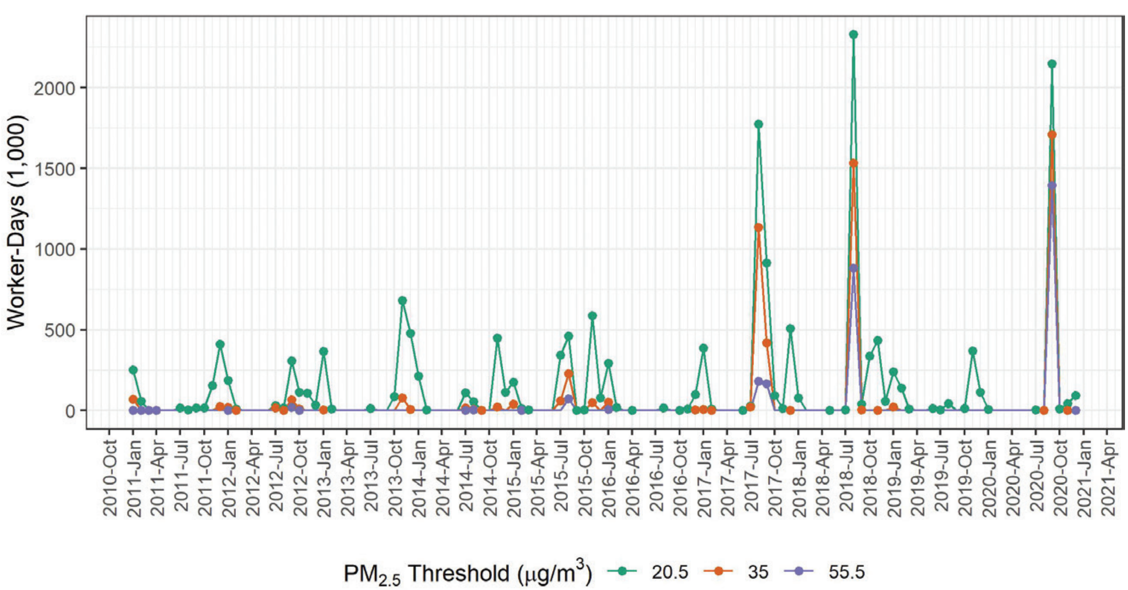

Figure 5. Estimated exposure to wildfire smoke among WA construction workers according to various $PM_{2.5}$ thresholds (20.5, 35, and 55.5 µg m^{-3} $PM_{2.5}$ correspond to the WA 'encouraged' threshold, US EPA NAAQS, and the WA 'required' threshold, respectively).

McClure and Jaffe, 2018). The continued influence of climate change is projected to increase wildfire-related $PM_{2.5}$ as well as the associated effects on human health (Ford *et al.*, 2018). As others have noted, workers such as agricultural and construction workers are at higher risk for wildfire smoke exposure, due to their prolonged outdoor work hours (Postma, 2020; Austin *et al.*, 2021). This study's estimate of the percent of WA construction workers with the potential to perform outdoor work (between 28.5 and 68.1%) and the observed number of days exceeding wildfire-related $PM_{2.5}$ thresholds (between 488 and 2704 across all WA counties over the last decade, depending on the threshold considered) supports the conclusion that construction workers in WA face exposure to wildfire smoke. Furthermore, the cyclical nature of construction employment in WA means there are more construction workers on the job during summer months, at the same time when air quality is potentially poorer and exposures are higher due to wildfire smoke. With nearly 200,000 workers in WA employed in construction and construction-related industries in 2020 (WA ESD, 2020), the impact is potentially quite large.

Policy and rulemaking

The status of outdoor workers in WA, including construction workers, came into clear focus in 2020 during the COVID-19 pandemic—many workers were classified as essential workers that continued to work outdoors during one of the State's largest wildfire events in September. Additionally, since employers were not required to provide protection to workers exposed to wildfire smoke, either in the form of administrative or engineering controls or personal protective equipment (PPE), workers remained vulnerable to wildfire smoke inhalation. Against this backdrop, WA L&I recognized that exposure to wildfire smoke posed a hazard to outdoor workers, specifically those in construction and agriculture, and is currently engaged in a permanent rule-making process aimed at protecting workers (296-62-085 WAC; General Occupational Health Standards) (WA L&I, 2020). After the 2020 wildfire season, L&I fast-tracked an emergency rule for the 2021 wildfire season (enacted in mid-July 2021), as stakeholders debated a permanent rule based on a more or less stringent air quality standard (i.e. WAQA) compared to CA. CA's worker protection rule for wildfire smoke is applicable when the $PM_{2.5}$ AQI meets or exceeds 151 ($PM_{2.5} \geq 55.5$ μg m^{-3}), with directives for employers to provide and require employees to use N-95 respirators when AQI is above 500 ($PM_{2.5} > 500.4$ μg m^{-3}) (CA, 2019). The CA rule is based on current AQI as defined by EPA's NowCast, which is an (unevenly) weighted average of current and past hourly concentrations over a 12-h period and is used to assess 'current' conditions until an entire day's hourly concentrations have been monitored and the 24-h average $PM_{2.5}$ concentration can be used for the AQI calculation.

WA L&I's emergency rule includes requirements for hazard communication of poor air quality levels and availability of protective measures; training, monitoring, and provisions for smoke-related health symptoms; and a hierarchy of controls that includes respiratory protection and engineering and administrative controls at a threshold of 55.5 μg m^{-3} (AQI = 151). At 20.5 μg m^{-3} (AQI = 69) however, employers are 'encouraged' to implement exposure controls and are required to provide training. In this paper, these thresholds were examined retrospectively over the last 10 years, estimating the average number of days per month that would have triggered wildfire exposure protection requirements. In WA, September was the month most impacted by poor air quality due to wildfire smoke, followed by August—generally coinciding with peak construction workforces that are between 9.4 and 42.7% larger across WA counties. We also observed days outside the months of August and September where counties exceeded these thresholds.

Compared to CA and the 'required' WA threshold, WA's 'encouraged' threshold of 20.5 μg m^{-3} (AQI = 69) is much lower, and if not clearly outlined when applicable, may trigger wildfire rule requirements during high air pollution events that are not related to wildfires. For example, 44% of the days exceeding the 20.5 μg m^{-3} threshold occurred in months other than August and September (Supplementary Table S3, available at *Annals of Work Exposures and Health* online). A limitation of the wording of the current WA rule is that high ambient $PM_{2.5}$ concentrations above the specified thresholds that are from any source would technically trigger the rule's requirements. For example, in many areas of WA, wood is used as a home heating fuel and the State permits agricultural burning; under certain atmospheric conditions common in winter months, these practices may cause local concentrations to exceed 20.5 μg m^{-3} (AQI = 69). Our results demonstrate this potential, both in the daily average $PM_{2.5}$ concentrations (Fig. 3 and Supplementary Fig. S2, available at *Annals of Work Exposures and Health* online) and AQI (Fig. 4 and Supplementary Fig. S3, available at *Annals of Work Exposures and Health* online) and in the weaker correlations between workers and $PM_{2.5}$ and AQI for several counties (Supplementary Table S5, available at *Annals of Work Exposures and Health* online). Among highlighted counties, Yakima had high $PM_{2.5}$ concentrations unrelated to wildfires, and demonstrates that high $PM_{2.5}$ concentrations don't necessarily correspond to the summer months when there are high numbers of construction workers.

Worker protection and controls

The WA emergency wildfire smoke protection rule draws on the hierarchy of controls to protect outdoor workers from wildfire smoke exposure. While encouraging employers to reduce employee exposure to $PM_{2.5}$ concentrations at 20.5 µg m^{-3} (AQI = 69), employers must take action at 55.5 µg m^{-3} (AQI = 151) and work to reduce exposure below that level whenever feasible with engineering controls such as 'enclosed buildings, structures, or vehicles where the air is adequately filtered'. When engineering controls insufficiently reduce employee exposure, administrative controls, such as work relocation, work schedule alterations, reduced work intensity, and increased rest periods should be implemented. Under the emergency rule, employers in WA would be encouraged to make respiratory protection (i.e. NIOSH-approved N-95 filtering facepiece respirators or KN-95 if N-95 is unavailable) available for voluntary use at 20.5 µg m^{-3} (AQI = 69), and would be required to at 55.5 µg m^{-3} (AQI = 151), avoiding requirements for fit testing and medical evaluation. For 2020 under the 55.5 µg m^{-3} (AQI = 151) threshold, this would have totaled 1.35 million respirators (Supplementary Table S4, available at *Annals of Work Exposures and Health* online). This estimate likely underestimates respirator demand because counties without $PM_{2.5}$ concentration data (e.g. Douglas, Island, and Pacific, Counties among others) were not factored into this estimate. In contrast, this estimate likely overestimates respirator demand because some construction workers may be wearing respirators as normal practice, not all construction workers are outdoor workers (Table 1 and Supplementary Table S2, available at *Annals of Work Exposures and Health* online), nor would all elect to wear a respirator for protection against wildfire smoke exposure. The WA rule also requires improvements in medical surveillance and reporting of wildfire smoke in injury claims, which may help address current limitations in L&I data.

Beyond these measures, health and safety professionals can conduct research on and advocate for less traditional control strategies. For example, some construction workers are paid on a piece-rate basis, and a movement towards an hourly wage may reduce the physical exertion and corresponding exposure to wildfire smoke accompanying a faster work pace. In the agricultural sector, there is some evidence that method of payment is associated with acute kidney injury (Moyce *et al.*, 2017) and heat-related illness (Spector, Krenz, and Blank, 2015); however, this has not been studied in the construction industry for occupational wildfire smoke exposure. Employers also have an opportunity to combine training to related workplace hazards. For example, WA already has a rule protecting workers from outdoor heat (WAC 296-62-095), and because heat and wildfire exposure often coincide, employers could incorporate training about wildfire smoke and heat together. If there are diurnal patterns of air pollution, another administrative control strategy may be to pause work activities during parts of the day with higher concentrations. However, this requires employers to stay attuned to current local air quality conditions, rather than a daily AQI level or a forecasted AQI level for the next workday. Furthermore, workers without wage protection will still come to work in potentially unsafe conditions because they depend on the compensation. When it is not feasible to move all work indoors, another strategy may be to offer shelters or indoor spaces that are supplied with filtered air for rest periods and breaks, thus reducing exposure to wildfire smoke over the course of the day. Recent studies indicate that even consumer-grade portable air cleaners (i.e. noncommercial or non-industrial) can meaningfully reduce wildfire smoke concentrations indoors (Barn *et al.*, 2008; Stauffer *et al.*, 2020; Xiang *et al.*, 2021).

Study limitations and data gaps

There were several limitations of this study, mostly related to limited data availability. Under the current occupational health paradigm, respirable PM fraction data for a large number of workers in different trades or industry categories at times with and without wildfire smoke exposure would ideally have been available. Worker exposure assessment to ambient air pollution may require a different approach, yet the differences of different PM size fractions (respirable PM with a 50% biologically based cut point of 4 µm versus $PM_{2.5}$ with an instrument-based 2.5 µm cut point) and the continuous ambient and 8-h occupational exposure workers face must not be ignored in future work. In this study, the EPA's daily AQS $PM_{2.5}$ and AQI data at the county level were used; these measurements were taken with the purpose of protecting public and environmental health, and result in a crude measure of exposure for WA construction workers. Even for this ecologic analysis, there were data limitations, for example several WA counties did not have agency monitors for $PM_{2.5}$. Future studies could leverage low-cost sensors to gather more extensive personal exposure data on wildfire and PM exposures as those tools develop [e.g. the US EPA and US Forest Service Fire and Smoke Map (US FS and US EPA, 2020)].

Additional challenges related to data availability included the size of some counties (e.g. Garfield County), resulting in times within the study period without employment data. Similarly, several counties lacked air quality data (e.g. Douglas, Island, and Pacific Counties), which would require interpolation to estimate county-level air quality, or had incomplete data available (e.g. Garfield, Pend Oreille, and San Juan Counties) requiring averages that included periods without data. There was also a lack of health outcome data, preventing the study of health impacts of wildfire smoke exposure among WA construction workers.

As worker protection rules that focus on outdoor ambient conditions are promulgated (e.g. wildfire smoke and heat), there may be value in better characterizing numbers of outdoor workers for different NAICS codes and for other occupational classification systems, such as O*NET. In this study, for example, experience and judgement was used to evaluate the potential for outdoor work for construction NAICS codes. This qualitative approach avoided a number of further assumptions lacking supporting data that could be misleading, project a false sense of confidence, or induce errors in estimation, compared to a more quantitative model to estimate the proportion of outdoor workers. Potentially helpful pieces of information that would improve the characterization of outdoor workers is a standardized measure reporting whether or not a worker in particular occupation typically occupies a space supplied by filtered air or an HVAC system, or without a complete building envelope.

This study highlights the apparent conflict between occupational and environmental standards, whereas the general public may receive guidance on how to reduce exposures during wildfire smoke episodes, there is a notable lack of work-specific guidance for employers and employees. Inconsistencies also exist among federal and state health-based guidance for ambient $PM_{2.5}$, and states have implemented or proposed occupational thresholds derived from guidance that may be more stringent than federal standards. In WA for example, the WAQA index indicates that levels above 20.5 μg m^{-3} (AQI = 69) are unhealthy for sensitive groups, compared to the US EPA AQI that communicates similar risk for sensitive groups but at 35.5 μg m^{-3} (AQI = 101). Consistent guidance and messaging would help employers abide by occupational health requirements to protect their employees.

Conclusion

Construction workers in Washington State are facing increased exposure to wildfires. Combined with long-term growth of the WA construction workforce, the annual cyclical nature results in a situation where more workers are exposed during the new 'wildfire season' in August and September. This study retrospectively tallied the days that would have been subject to the WA L&I's 'encouraged' wildfire protection threshold of 20.5 μg m^{-3} (AQI = 69) over the last decade for each WA county and found it would result in 5.5 times more days subject to the wildfire protection rule than the WA 'required' threshold of 55.5 μg m^{-3} (AQI = 151) (2704 versus 488 days across all calendar months and WA counties), especially if explicit provisions are not made to exclude high pollution days not associated with wildfires. The estimated demand for N-95 filtering facepiece respirators for construction workers in 2020 under WA's emergency rule could have been as high as 1.35 million. These results can help inform both employers and policy makers as these rules are developed and, in some respects, can be generalized to other outdoor workers that the WA rule seeks to protect.

Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Data availability

The data that support the findings of this study are available in the public domain: US EPA AQS (https://aqs.epa.gov/aqsweb/airdata/download_files.html) and WA ESD (https://esd.wa.gov/labormarketinfo/covered-employment and https://esd.wa.gov/labormarketinfo/employment-estimates).

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