Exposure to wildfire smoke and particulate matter among Washington State construction workers; potential impacts and implications for worker protection

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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.

In this study, we link several data sources including state-collected employment data and national ambient air quality data to gain insight into the risk of wildfire exposure among construction workers in Washington. Our results indicate the number of poor air quality days has increased in August and September in recent years. We also observed that over the last decade these months with the greatest potential for wildfire smoke exposure coincide with an annual peak in construction employment that was typically 9.4 to 42.7% larger across Washington counties (one county was 75.8%). Lastly, we considered different air quality thresholds and retrospectively tallied days in Washington that would have triggered rules protecting workers from wildfire smoke. We found the “encouraged” threshold of the Washington emergency rule (20.5 μg/m³) would result in 5.5 times more days subject to the wildfire rule on average across all Washington counties compared to its “required” threshold (55.5 μg/m³), 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. We also discuss the potential economic and policy implications of wildfire smoke exposure, exposure control strategies, and data gaps that would improve our understanding of construction worker exposure to wildfire smoke.

Keywords: PM₂.₅, forest fires, wildland fire, climate change, respirator

NOTE: This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice.
INTRODUCTION

Wildfires in the Western US have increased in frequency and are burning greater land areas for longer periods of time (Balmes 2018). This trend, exacerbated by climate change, is increasing the lengths of wildfire seasons (Reisen et al. 2015). In Washington (WA), where the summer climate is dry – especially east of the Cascade Mountain Range where conditions are hot and arid – environmental conditions contribute to wildfire ignition and spread. Smoke and pollution from wildfires can travel large distances from burns, including to 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. Incomplete wildfire combustion yields a large range of solid, liquid and gaseous pollutants (Stefanidou et al. 2008), including a range of potentially harmful pollutants such as silica, carbon monoxide, carbon dioxide, oxides of nitrogen and sulfur, methane, acrolein, formaldehyde, dioxins (Stefanidou et al. 2008), and hydrocarbons, including volatile organic compounds, polyaromatics, aldehydes, and furans (Materna et al. 1992; Slaughter et al. 2004; Statheropoulos and Karma 2007; 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 however, PM$_{2.5}$ is still considered the main wildfire pollutant affecting human health (Schwela et al. 1999; Reid et al. 2005).

Occupational standards for PM exposure are not commonly exceeded for people, unless they are directly in the vicinity of the fire (e.g., OSHA’s 5 mg/m$^3$ 8-hr time-weighted average for respirable dust), but the US Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) standards (e.g., PM$_{2.5}$ >35 μg/m$^3$ for a 24-hr period) can be exceeded by 1.2 to 10 times during wildfire events (Liu et al. 2015).
Despite the large gap in these regulatory standards, 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 above an hourly Air Quality Index (AQI) level of 151 (PM$_{2.5} = 55.5$ μg/m$^3$) (CA 2019). While other Northwest states – Oregon (OR) and WA – are currently engaged in similar rulemaking, their details, are only currently emerging. The WA Department of Labor and Industries (L&I) has 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 Occupational Safety and Health (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).

A range of deleterious health effects have been associated with exposure to wildfire smoke. 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 et al. 1993); decreased lung function (Slaughter et al. 2004); and cardiovascular effects (Liu et al. 2015). Individuals with pre-existing conditions, specifically respiratory and cardiovascular, are at higher risk (Liu et al. 2015). While these health effects have been studied in the general population, outdoor workers such as those in construction industries, may be at increased risk because many spend a considerable amount of time outside (Schulte and Chun 2009) and have a higher level of physical exertion and subsequent respiration rate than the general public. Furthermore, 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) – reflecting an expanding construction workforce in WA.
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. In conjunction with a growing construction workforce, seasonal trends in that workforce coincide with the wildfire season (summer in the Pacific Northwest), adding to the overall health burden. Exposure to or the health effects from wildfire smoke have been described in the general public (Shusterman et al. 1993; Reisen et al. 2015; Liu et al. 2015), agricultural workers (Austin et al. 2021), and wildland firefighters (Shusterman et al. 1993; Slaughter et al. 2004; Reinhardt and Ottmar 2004; Stefanidou et al. 2008; Aisbett et al. 2012; Adetona et al. 2013; Wu et al. 2021); yet no studies we are aware of have examined exposure to wildfire pollution among construction workers. There is therefore an important gap in published literature on the impacts of wildfire smoke on construction workers. The aims of this study were to: 1) characterize the temporal patterns of poor air quality and construction employment across Washington State counties, 2) estimate potential exposure to wildfire smoke among WA construction workers, 3) discuss the potential implications for state-level worker protection rulemaking in Washington, and 3) 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**

Our analysis included all counties for Washington State, but we have highlighted three counties: 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 to other WA counties (Liu et al. 2021).

Data Sources

Employment Data

We gathered monthly employment data 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, in industries covered by unemployment insurance, by industry and county. 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. We examined available data from non-farm monthly employment from 2002-2020 related to construction industries, which followed the 2002 2- and 3-digit NAICS codes. To show longer term trends for all of WA, we plotted monthly employment totals from 2002-2020 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, we restricted ESD data 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 (6-digit) codes, was available from ESD QCEW. We restricted these data to industries within the construction sector (NAICS code 23) in 2020. From these data, we evaluated the number of construction workers potentially engaged in outdoor construction and who would therefore be exposed to wildfire smoke.

PM$_{2.5}$ and Air Quality Index Data

We collected PM$_{2.5}$ data for WA 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 and calculated daily PM$_{2.5}$ averages for each county. Some WA counties do not have any monitoring sites, therefore no PM$_{2.5}$ data were available for this part of our 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 below.

We also obtained county-level daily Air Quality Index (AQI) data based on PM$_{2.5}$ (US EPA 2020). The AQI is the EPA’s summary measure and communication tool for air pollution and level of health concern; it is informed by 5 pollutants: ground-level ozone, particle pollution, carbon monoxide, sulfur dioxide, and nitrogen dioxide. AQI levels are defined according to thresholds for each pollutant; for PM$_{2.5}$ the levels are: “good” (AQI = 0-50; PM$_{2.5}$ = 0-12.0 μg/m$^3$), “moderate” (AQI = 51-100; PM$_{2.5}$ = 12.1-35.4 μg/m$^3$), “unhealthy for sensitive groups” (AQI = 101-150; PM$_{2.5}$ = 35.5-55.4 μg/m$^3$), “unhealthy” (AQI = 151-200; PM$_{2.5}$ = 55.5-150.4 μg/m$^3$), “very unhealthy” (AQI = 201-300; PM$_{2.5}$ = 150.5-250.4 μg/m$^3$), and “hazardous” (AQI ≥ 301; PM$_{2.5}$ ≥ 250.5 μg/m$^3$). Our analysis was restricted to days with AQI levels defined by PM$_{2.5}$, the pollutant defining days subject to wildfire protection rules. We tallied the number of days per month for each county with poor AQI levels ranging from moderate to hazardous, then averaged tallies by month over the 2011-2020 period to estimate the mean number of days per month with AQI levels worse than “good”.

**Data Analysis**

We focused our combined analysis of air quality and construction employment on the 10 years 2011-2020. 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, we averaged monthly ESD counts of construction workers over the 2011-2020 period, then calculated a percent change from the month with the lowest count of construction workers as the reference point (January for most counties). With this procedure, we were able to assess the average monthly change in the WA construction workforce at the county level. We plotted this change in monthly construction employment with 1) boxplots of mean daily PM$_{2.5}$ concentration for each month and 2) the mean number of days with AQI warnings over the
2011-2020 period. For each county we tallied 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. We tallied by month the number of days that exceeded 1) 20.5 µg/m$^3$ (AQI = 69) for the 2011-2020 period and 2) 55.5 µg/m$^3$ (AQI = 151) for 2020. The CA and WA rules are triggered by outdoor work of duration greater than one hour, above a threshold based on AQI as defined as EPA’s NowCast (an average of current and past concentrations over the prior 12 hours). The intent of EPA’s NowCast is to provide current air quality information that better reflects 24-hour exposures, for which much of the epidemiologic evidence is based (US EPA 2021). Because our analysis is retrospective, and thus, we can compute 24-hour average exposures, we have used daily averages, which sufficiently reflects the intent of current AQI. For each county we computed the Pearson correlation between 1) percent construction workforce county-level daily PM$_{2.5}$ concentration and 2) percent construction workforce and the mean number of days with AQI warnings worse than “moderate”, each at the monthly time scale. Wildfire exposure rules are applicable for either PM$_{2.5}$ concentrations or PM$_{2.5}$ AQI values, therefore we have included both in our analysis.

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

With State-level data employment data classified by 6-digit NAICS codes, we restricted our analysis to the NAICS 2-digit sector code 23, focusing on the numbers of construction workers within 3-digit NAICS subsector codes 236, 237, and 238. We then evaluated the potential for outdoor work among these 6-digit construction codes, 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 we tabulated the number of construction workers at the beginning of each month, multiplied by the number of days where PM$_{2.5}$ in the county exceeded each threshold for each month, and 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 Figure 1 and for each WA county in Figure S1. 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 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 Figure 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.

Tables 1 and S1 provide statewide detail about the 3- and 6-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, 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 we 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. For all counties in the State, 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 (Figures 3 and S2). 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 (Table S2). 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 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/m³ from 2011-2020. Similar results for 2020 are presented in Table S3, and incorporate annual estimates of construction employment with monthly results tabulated for the “required” threshold of 55.5 µg/m³ (AQI = 101). 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**

We observed variability in the average number of days with AQI worse than “good” over the 2011-2020 period (Figures 4 and S3). Among highlighted counties, Yakima had the greatest number of poor air quality days, for all AQI categories “moderate” and worse (N = 1,196) 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 was 2.7 times greater for 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. We also observed an increase in the number of days with poor AQI in more recent years (Figure 5), 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 PM₂.₅ concentrations are presented in Figures 3 and S2. The months when the construction workforce is largest (August and September) coincide with months with the greatest number of high daily average PM₂.₅ concentrations. A similar pattern holds for construction employment and AQI (Figures 4 and Figure S3). We observed that construction employment is generally highest in the summer months, when there are 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 PM₂.₅ concentration or the average number of poor AQI days per month and the percent of the construction workforce is presented in Tables 2 and
S3. Among highlighted counties, we observed moderately strong correlation between PM$_{2.5}$ concentration and change in construction workforce for King County ($p_{\text{King}} = 0.63$), moderate correlation for Spokane County ($p_{\text{Spokane}} = 0.501$), but no correlation for Yakima County ($p_{\text{Yakima}} = 0.109$). Between the average number of days with AQI warnings and the change in construction workforce, the correlation was moderate for King and Spokane Counties ($p_{\text{King}} = 0.517$; $p_{\text{Spokane}} = 0.508$) but weak for Yakima County ($p_{\text{Yakima}} = 0.196$). Low to moderate correlations were observed for most WA counties, with the highest correlation between PM$_{2.5}$ concentration and change in construction workforce ($p_{\text{Garfield}} = 0.882$) and between the average number of days with AQI warnings and the change in construction workforce ($p_{\text{Garfield}} = 0.882$). 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.

Estimated wildfire exposure, according to PM$_{2.5}$ concentration thresholds, among WA construction workers is shown in Figure 6. Recent wildfire events in August 2017, August 2018, and September 2020 each resulted in more than 1 million construction worker-days of exposure for each of 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. We have extended 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 = 69) threshold. Under the assumptions that the annual average number of construction workers for each county would use one respirator for each day above the threshold, the increased demand for filtering facepiece respirators totaled 1.35 million (Table S3).
DISCUSSION

Even as PM$_{2.5}$ concentrations have decreased across the US 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; 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). Our analysis 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 due to wildfire smoke and exposures are higher. 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.

Potential Economic Implications

While not well understood, L&I injury data suggests that between 2011-2020, as many as 14,768 workers’ compensation claims, for all covered workers in the state, may be related to atmospheric and environmental conditions, incurring a total of $109 million in claim costs (WA L&I 2020a). Moreover, the data indicate an upward trend in annual costs from these claims over the last decade. However, these injuries were not limited to construction workers and also were reported for agriculture and first-line responders like firefighters and police. Due to the data reporting limitations in current L&I data, it is unclear how many of these claims are specifically associated with wildfire smoke exposures, or how many injuries that are related to wildfire smoke exposure are not reported. In addition, workers’ compensation claims may not show the full picture of the effects of wildfire exposure on the WA workforce. For instance, there may be under-appreciated mental health impacts from working in unsafe conditions with little ability to control a hazard that spans their work, home, and community lives; inability to work for those who may need to provide care for their family if needed due to smoke exposure; and lost wages and productivity from cancelled work.
Outdoor workers other than those working in construction are impacted by wildfire smoke also. For example, an analysis of agricultural workers in WA also found substantial overlap between the times of the year and locations in which the numbers of agricultural workers and PM$_{2.5}$ concentrations are highest (Austin et al. 2021). In that study, an average of 3,023 (King County) and 33,755 (Yakima County) people worked in agriculture during the 3$^{rd}$ quarter (July-September) between the years 2010-2018. While there also tends to be large numbers of construction workers employed during these months in WA, there is a difference in that greater numbers of construction workers tend to be in urban rather than rural areas. While most of the construction workers are employed in King, Pierce, and Snohomish Counties, some of the worst air quality occurs in Chelan, Okanogan, and Yakima Counties. Such differences highlight the need to assess exposures to outdoor workers in different industries.

**Policy and Rulemaking**

The status of outdoor workers in WA, including construction workers, came into clear focus last year 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 2020. 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 had 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 2020b). 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 ($PM_{2.5} \geq 55.5 \, \mu g/m^3$), with directives for employers to provide and require employees to use N-95 respirators when AQI is above 500 ($PM_{2.5} > 500.4 \, \mu g/m^3$) (CA 2019). The CA rule is based on current AQI as defined as EPA’s NowCast, which is an (unevenly)
weighted average of current and past hourly concentrations over a 12-hour period and is used to assess “current” conditions until an entire day’s hourly concentrations have been monitored and the 24-hour average PM$_{2.5}$ concentration can be used for the AQI calculation.

WA LNI’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 above a threshold of 55.5 µg/m$^3$ (AQI = 151). Though at 20.5 µg/m$^3$ (AQI = 69), employers are “encouraged” to implement exposure controls and are required to provide training. In this paper, we have retrospectively examined these thresholds 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.

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, 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 (Figures 3 and S2) and AQI (Figures 4 and S3) and in the weaker correlations between workers and PM$_{2.5}$ and AQI for several counties. Among highlighted counties, Yakima is an example of a county with high PM$_{2.5}$ concentrations unrelated to wildfires, and exemplifies the fact that PM$_{2.5}$ doesn’t necessarily correspond to the summer months when there are high levels of construction activities and workers.
**Worker Protection and Controls**

The WA worker 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 wildfire smoke at PM$_{2.5}$ concentrations above 20.5 µg/m$^3$ (AQI = 69), employers must take action at 55.5 µg/m$^3$ (AQI = 150) 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 above 20.5 µg/m$^3$ (AQI = 69), and would be required to above 55.5 µg/m$^3$ (AQI = 150), avoiding requirements for fit testing and medical evaluation. For 2020 under the 55.5 µg/m$^3$ (AQI = 150) threshold, this would have totaled 1.35 million respirators (Table S3). 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, and overestimates respirator demand because some construction workers may be wearing respirators as normal practice, not all construction workers would be outdoor workers, nor would all elect to wear a respirator for protection against wildfire 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 basis 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 et al. 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. non-commercial 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 in our study, mostly related to limited data availability. Under the current occupational health paradigm, we would have ideally had respirable PM fraction data for a large number of workers in different trades or industry categories at times with and without wildfire smoke exposure. We recognize that worker exposure assessment to ambient air pollution may require a different approach, yet the complications 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-hour occupational exposure workers face must be clearly addressed in future work. In this study we used EPA’s daily AQS PM$_{2.5}$ and AQI data at the county level, collected to protect public and environmental health, resulting in a crude measure of exposure for WA construction workers. Even for this ecologic analysis we encountered 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)).
We also had challenges related to data availability. Due to the size of some counties (e.g., Garfield County), there were times within our 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. We were also limited by the lack of health outcome data for construction workers related to wildfire smoke exposure and were unable to study the 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.

Our 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, which are growing in frequency, duration, and intensity. 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. WA L&I is currently engaged in rulemaking to protect outdoor workers from
exposure to wildfire smoke. We have retrospectively tallied the days that would have been subject to the L&I’s “encouraged” threshold of 20.5 μg/m³ (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/m³ (AQI = 151), especially if explicit provisions are not made to exclude high pollution days not associated with wildfires (e.g., high pollution levels resulting from home heating in the winter). WA seeks to protect outdoor workers by requiring employers make respiratory protection available to employees for voluntary use on days where concentrations exceed a prescribed threshold; for the emergency rule’s 55.5 μg/m³ (AQI = 151) concentration, we estimated in 2020 that could have potentially created demand for 1.35 million N-95 filtering facepiece respirators for construction workers. Our 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.

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DATA AVAILABILITY STATEMENT

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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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).
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.)
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. (Note: axes were restricted, omitting 2 and 3 data points above 300 µg/m$^3$ for Spokane and Yakima Counties, respectively.)
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.
Figure 5: Average number of days per month with AQI warnings by county by month for 2-year periods; 2011-2020.
Figure 6. Estimated exposure to wildfire smoke among WA construction workers according to various PM$_{2.5}$ thresholds.
| NAICS code | Industry                                        | Potential for Outdoor Work | Firms | Workers | Percent of 2-digit NAICS | Percent of 3-digit NAICS |
|------------|------------------------------------------------|-----------------------------|-------|---------|--------------------------|--------------------------|
| 23         | Construction                                    |                             | 26977 | 199784  | 100.0                    |                          |
|            |                                                  |                             |       |         |                          |                          |
| 236        | Construction of buildings                       |                             | 9478  | 51636   | 25.8                     | 100.0                    |
| 236220     | Commercial building construction                | Medium                      | 986   | 18808   | 9.4                      | 36.4                     |
| 236115     | New single family general contractors           | Medium                      | 4338  | 14723   | 7.4                      | 28.5                     |
| 236118     | Residential remodelers                          | Medium                      | 3844  | 11908   | 6.0                      | 23.1                     |
|            | Other (NAICS 236116, 236117, 236210)            | Medium                      | 310   | 6198    | 3.0                      | 12.0                     |
| 237        | Heavy and civil engineering construction        |                             | 1084  | 20576   | 10.3                     | 100.0                    |
| 237310     | Highway, street, and bridge construction         | High                        | 239   | 6550    | 3.3                      | 31.8                     |
| 237110     | Water and sewer system construction             | High                        | 320   | 4205    | 2.1                      | 20.4                     |
| 237130     | 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                     |                             | 16416 | 127573  | 63.9                     | 100.0                    |
| 238212     | Nonresidential electrical contractors           | Medium                      | 677   | 15418   | 7.7                      | 12.1                     |
| 238222     | Nonresidential plumbing and HVAC contractors    | Medium                      | 460   | 14076   | 7.0                      | 11.0                     |
| 238221     | Residential plumbing and HVAC contractors       | Medium                      | 1600  | 11992   | 6.0                      | 9.4                      |
|            | Other (NAICS codes 238211, 238311, 238321, 238911, 238912, 238161, 238312, 238111, 238351, 238131, 238992, 238991, 238322, 238162, 238112, 238171, 238122, 238331, 238152, 238341, 238142, 238392, 238352, 238141, 238151, 238192, 238391, 238132, 238332, 238121, 238291, 238191, 238172, 238342) | Mixed | 13684 | 86090   | 43.0                     | 67.5                     |
Table 2. Pearson correlation between percent of construction workforce and air quality measures (AQI worse than “moderate”). Variables were averaged by month over the 2011-2020 time period.

| Correlation Variables | King County | Spokane County | Yakima County |
|-----------------------|-------------|----------------|---------------|
| PM$_{2.5}$ (µg/m$^3$) - Workers (%) | 0.629 | 0.501 | 0.109 |
| AQI (days/month) - Workers (%) | 0.517 | 0.508 | 0.196 |
Figure S1. Monthly counts of WA construction workers.
Figure S2. Mean daily PM$_{2.5}$ concentration and average monthly percent difference in construction workers from the month with the lowest number of workers for all WA counties; 2011-2020. (Note: axes were restricted, omitting outlying data points above 300 µg/m$^3$.)
Figure S3. 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 averaged over 2011-2020 for all WA counties.
Table S1. Summary of the number of construction workers by NAICS code in WA for 2020.

| NAICS code | Industry                                           | Potential for Outdoor Work | Firms   | Workers  | Percent of 2-digit NAICS | Percent of 3-digit NAICS |
|------------|----------------------------------------------------|-----------------------------|---------|----------|--------------------------|--------------------------|
| 23         | Construction                                       |                             | 26977   | 199784   | 100.0                    | 100.0                    |
| 236        | Construction of buildings                          |                             |         |          |                          |                          |
| 236115     | New single family general contractors              | Medium                      | 9478    | 51636    | 25.8                     | 100.0                    |
| 236116     | New multifamily general contractors                | Medium                      | 58      | 1022     | 0.5                      | 2.0                      |
| 236117     | New housing for-sale builders                      | Medium                      | 192     | 1639     | 0.8                      | 3.2                      |
| 236118     | Residential remodelers                             | Medium                      | 3844    | 11908    | 6.0                      | 23.1                     |
| 236210     | Industrial building construction                    | Medium                      | 60      | 3537     | 1.8                      | 6.8                      |
| 236220     | Commercial building construction                    | Medium                      | 986     | 18808    | 9.4                      | 36.4                     |
| 237        | Heavy and civil engineering construction            |                             | 1084    | 20576    | 10.3                     | 100.0                    |
| 237110     | Water and sewer system construction                | High                        | 320     | 4205     | 2.1                      | 20.4                     |
| 237120     | Oil and gas pipeline construction                   | High                        | 37      | 1169     | 0.6                      | 5.7                      |
| 237130     | Power and communication system construction         | High                        | 197     | 4195     | 2.1                      | 20.4                     |
| 237210     | Land subdivision                                   | High                        | 109     | 1117     | 0.6                      | 5.4                      |
| 237310     | Highway, street, and bridge construction            | High                        | 239     | 6550     | 3.3                      | 31.8                     |
| 237990     | Other heavy construction                            | High                        | 183     | 3340     | 1.7                      | 16.2                     |
| 238        | Specialty trade contractors                        |                             | 16416   | 127573   | 63.9                     | 100.0                    |
| 238111     | Residential poured foundation contractors          | High                        | 905     | 4130     | 2.1                      | 3.2                      |
| 238112     | Nonresidential poured foundation contractors       | High                        | 95      | 2230     | 1.1                      | 1.7                      |
| 238121     | Residential structural steel contractors            | High                        | 30      | 458      | 0.2                      | 0.4                      |
| 238122     | Nonresidential structural steel contractors         | High                        | 66      | 1923     | 1.0                      | 1.5                      |
| 238131     | Residential framing contractors                     | High                        | 748     | 3978     | 2.0                      | 3.1                      |
| 238132     | Nonresidential framing contractors                  | High                        | 78      | 645      | 0.3                      | 0.5                      |
| 238141     | Residential masonry contractors                     | High                        | 303     | 860      | 0.4                      | 0.7                      |
| 238142     | Nonresidential masonry contractors                  | High                        | 65      | 1077     | 0.5                      | 0.8                      |
| 238151     | Residential glass and glazing contractors           | Medium                      | 142     | 847      | 0.4                      | 0.7                      |
| 238152     | Nonresidential glass and glazing contractors        | Medium                      | 67      | 1403     | 0.7                      | 1.1                      |
| 238161     | Residential roofing contractors                     | High                        | 847     | 4749     | 2.4                      | 3.7                      |
| 238162     | Nonresidential roofing contractors                  | High                        | 93      | 2536     | 1.3                      | 2.0                      |
| 238171     | Residential siding contractors                      | High                        | 515     | 2111     | 1.1                      | 1.7                      |
| 238172     | Nonresidential siding contractors                   | High                        | 22      | 373      | 0.2                      | 0.3                      |
| 238191     | Other residential exterior contractors              | High                        | 123     | 385      | 0.2                      | 0.3                      |
| 238192     | Other nonresidential exterior contractors           | High                        | 85      | 786      | 0.4                      | 0.6                      |
| 238211     | Residential electrical contractors                  | Medium                      | 1470    | 7459     | 3.7                      | 5.8                      |
| 238212     | Nonresidential electrical contractors               | Medium                      | 677     | 15418    | 7.7                      | 12.1                     |
| 238221     | Residential plumbing and HVAC contractors           | Medium                      | 1600    | 11992    | 6.0                      | 9.4                      |
| 238222     | Nonresidential plumbing and HVAC contractors        | Medium                      | 460     | 14076    | 7.0                      | 11.0                     |
| 238291     | Other residential equipment contractors             | Medium                      | 61      | 417      | 0.2                      | 0.3                      |
| 238292     | Other nonresidential equipment contractors          | Medium                      | 207     | 3231     | 1.6                      | 2.5                      |
| 238311     | Residential drywall contractors                     | Medium                      | 737     | 6533     | 3.3                      | 5.1                      |
| 238312     | Nonresidential drywall contractors                  | Medium                      | 115     | 4227     | 2.1                      | 3.3                      |
| 238321     | Residential painting contractors                    | Medium                      | 1846    | 6281     | 3.1                      | 4.9                      |
| 238322     | Nonresidential painting contractors                 | Medium                      | 194     | 2589     | 1.3                      | 2.0                      |
| 238331     | Residential flooring contractors                    | Medium                      | 890     | 1828     | 0.9                      | 1.4                      |
| Code     | Description                                      | Size  | Revenue | Annual Profit Margin | Monthly Profit Margin |
|----------|--------------------------------------------------|-------|---------|-----------------------|-----------------------|
| 238332   | Nonresidential flooring contractors              | Medium| 72      | 611                   | 0.3                   | 0.5                   |
| 238341   | Residential tile and terrazzo contractors        | Medium| 407     | 1368                  | 0.7                   | 1.1                   |
| 238342   | Nonresidential tile and terrazzo contractors     | Medium| 23      | 165                   | 0.1                   | 0.1                   |
| 238351   | Residential finish carpentry contractors         | Low   | 894     | 4065                  | 2.0                   | 3.2                   |
| 238352   | Nonresidential finish carpentry contractors      | Low   | 95      | 890                   | 0.4                   | 0.7                   |
| 238391   | Other residential finishing contractors          | Low   | 93      | 691                   | 0.3                   | 0.5                   |
| 238392   | Other nonresidential finishing contractors        | Low   | 139     | 997                   | 0.5                   | 0.8                   |
| 238911   | Residential site preparation contractors         | High  | 1013    | 5172                  | 2.6                   | 4.1                   |
| 238912   | Nonresidential site preparation contractors      | High  | 293     | 4777                  | 2.4                   | 3.7                   |
| 238991   | All other residential trade contractors           | Medium| 695     | 2976                  | 1.5                   | 2.3                   |
| 238992   | All other nonresidential trade contractors        | Medium| 256     | 3322                  | 1.7                   | 2.6                   |
Table S2. Summary of the number of days that exceeded daily PM$_{2.5}$ concentration thresholds for each WA county with PM$_{2.5}$ data, 2011-2020.

| County     | N >35 µg/m$^3$ | N >20.5 µg/m$^3$ | N >55.5 µg/m$^3$ | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|----------------|------------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Adams      | 34             | 73               | 21               | 0   | 0   | 0   | 0   | 0   | 2   | 46  | 23  | 1   | 0   | 0   | 1   |
| Asotin     | 54             | 185              | 23               | 10  | 0   | 0   | 0   | 0   | 2   | 43  | 43  | 28  | 40  | 19  |     |
| Benton     | 29             | 82               | 15               | 7   | 0   | 0   | 0   | 0   | 0   | 36  | 22  | 1   | 13  | 3   |     |
| Chelan     | 76             | 171              | 45               | 8   | 2   | 0   | 0   | 0   | 0   | 6   | 59  | 45  | 11  | 23  | 17  |
| Clallam    | 14             | 23               | 12               | 0   | 0   | 0   | 0   | 0   | 0   | 14  | 9   | 0   | 0   | 0   |     |
| Clark      | 32             | 122              | 11               | 28  | 6   | 0   | 0   | 0   | 0   | 1   | 16  | 16  | 2   | 27  | 26  |
| Columbia   | 25             | 47               | 12               | 0   | 0   | 0   | 0   | 0   | 0   | 25  | 15  | 0   | 7   | 0   |     |
| Cowlitz    | 16             | 48               | 11               | 4   | 1   | 0   | 0   | 0   | 0   | 11  | 12  | 0   | 15  | 5   |     |
| Franklin   | 29             | 71               | 14               | 2   | 0   | 0   | 0   | 0   | 0   | 1   | 37  | 22  | 0   | 7   | 2   |
| Garfield   | 19             | 39               | 11               | 0   | 0   | 0   | 0   | 0   | 0   | 22  | 15  | 2   | 0   | 0   |     |
| Grant      | 37             | 93               | 20               | 4   | 0   | 0   | 0   | 0   | 0   | 49  | 28  | 0   | 6   | 3   |     |
| Grays Harbor | 12          | 22               | 9                | 0   | 0   | 0   | 0   | 0   | 0   | 9   | 11  | 1   | 1   | 0   |     |
| Jefferson  | 17             | 23               | 10               | 0   | 1   | 0   | 0   | 0   | 0   | 12  | 9   | 0   | 1   | 0   |     |
| King       | 26             | 65               | 13               | 5   | 0   | 0   | 0   | 0   | 0   | 3   | 22  | 15  | 5   | 10  | 5   |
| Kitsap     | 20             | 44               | 9                | 4   | 0   | 0   | 0   | 0   | 0   | 7   | 16  | 14  | 0   | 3   | 0   |
| Kittitas   | 65             | 164              | 24               | 31  | 8   | 0   | 0   | 0   | 0   | 2   | 34  | 40  | 9   | 16  | 24  |
| Klickitat  | 18             | 39               | 10               | 0   | 0   | 0   | 0   | 0   | 0   | 15  | 16  | 0   | 4   | 4   |     |
| Lewis      | 9              | 36               | 5                | 1   | 0   | 0   | 0   | 0   | 0   | 18  | 3   | 1   | 11  | 2   |     |
|               | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Mason         | 19  | 64  | 10  | 10  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 17  | 15  | 3   |
| Okanogan      | 76  | 155 | 47  | 6   | 1   | 0   | 1   | 1   | 0   | 8   | 67  | 40  | 0   | 12  | 19  |
| Pend Oreille  | 5   | 5   | 5   | 0   | 1   | 1   | 3   | 0   | --  | --  | --  | --  | --  | --  | 0   |
| Pierce        | 31  | 135 | 14  | 36  | 2   | 0   | 0   | 0   | 0   | 6   | 19  | 18  | 7   | 22  | 25  |
| San Juan      | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | --  | --  | --  | --  | --  | --  | --  |
| Skagit        | 5   | 14  | 3   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 12  | 1   | 0   | 0   | 0   |
| Snohomish     | 28  | 140 | 10  | 33  | 5   | 0   | 0   | 0   | 0   | 5   | 22  | 15  | 0   | 29  | 31  |
| Spokane       | 53  | 163 | 23  | 14  | 1   | 0   | 0   | 0   | 1   | 6   | 50  | 35  | 4   | 44  | 8   |
| Stevens       | 53  | 107 | 22  | 4   | 0   | 0   | 0   | 0   | 0   | 4   | 57  | 23  | 1   | 16  | 2   |
| Thurston      | 25  | 115 | 14  | 30  | 3   | 0   | 0   | 0   | 0   | 0   | 16  | 17  | 8   | 24  | 17  |
| Walla Walla   | 33  | 80  | 15  | 3   | 0   | 0   | 0   | 0   | 0   | 34  | 19  | 6   | 12  | 6   |
| Whatcom       | 22  | 40  | 10  | 0   | 0   | 0   | 0   | 0   | 0   | 2   | 22  | 13  | 0   | 3   |
| Whitman       | 28  | 60  | 13  | 0   | 0   | 0   | 0   | 0   | 0   | 39  | 21  | 0   | 0   |
| Yakima        | 70  | 279 | 27  | 47  | 16  | 4   | 0   | 0   | 0   | 6   | 46  | 50  | 12  | 49  | 49  |
Table S3. Summary of construction workers, the number of days per year that exceeded PM$_{2.5}$ concentration thresholds, and the estimated demand for respiratory protection based on the 55.5 µg/m$^3$ threshold for each WA county in 2020. (Note: construction employment for Garfield County was 2017 due to data availability.)

| County   | Workers | N >35 µg/m$^3$ | N >20.5 µg/m$^3$ | N >55.5 µg/m$^3$ | Days where PM$_{2.5}$ > 55.5 µg/m$^3$ | Respirator Demand |
|----------|---------|---------------|-----------------|-----------------|-------------------------------------|-------------------|
|          |         |               |                 |                 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |                 |
| Adams    | 96      | 8             | 8               | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 768             |
| Asotin   | 521     | 12            | 25              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 1   | 4168            |
| Benton   | 7346    | 8             | 11              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 58768           |
| Chelan   | 1823    | 12            | 13              | 11              | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 11  | 0   | 0   | 0   | 20053           |
| Clallam  | 1155    | 7             | 7               | 6               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 6   | 0   | 0   | 0   | 6930            |
| Clark    | 14348   | 8             | 11              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 114784          |
| Columbia | 130     | 8             | 8               | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 1040            |
| Cowlitz  | 2723    | 9             | 10              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 21784           |
| Douglas  | 688     | --            | --              | --              | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --              |
| Ferry    | 49      | --            | --              | --              | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --              |
| Franklin | 2399    | 8             | 9               | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 19192           |
| Garfield | 3       | 9             | 11              | 7               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 21              |
| Grant    | 1669    | 10            | 11              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 0   | 13352           |
| Grays Harbor | 1103 | 8             | 9               | 6               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 6   | 0   | 0   | 0   | 6618            |
| Island   | 1122    | --            | --              | --              | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --              |
| Jefferson| 667     | 8             | 8               | 6               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 6   | 0   | 0   | 0   | 4002            |
| King     | 72046   | 9             | 11              | 7               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 504322          |
| Kitsap   | 4587    | 9             | 12              | 6               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 6   | 0   | 0   | 0   | 27522           |
| Kittitas | 1083    | 11            | 13              | 7               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 7581            |
| Klickitat| 268     | 9             | 10              | 8               | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | -- | -- | 2144            |
| County      | 1320 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|-------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Lewis       | 1320 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| Lincoln     | 260  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Mason       | 644  | 9   | 12  | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 4508|
| Okanogan    | 462  | 11  | 14  | 9   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 9   | 0   | 0   | 0   | 4158|
| Pacific     | 275  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Pend Oreille| 132  | 0   | 0   | 0   | 0   | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | --  | 0   |
| Pierce      | 23449| 8   | 13  | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 164143|
| San Juan    | 703  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Skagit      | 3794 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| Skamania    | 85   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Snohomish   | 23137| 9   | 13  | 6   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 138822|
| Spokane     | 12602| 7   | 11  | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 88214 |
| Stevens     | 459  | 9   | 11  | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 3213 |
| Thurston    | 6173 | 7   | 12  | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 43211|
| Wahkiakum   | 46   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Walla Walla | 929  | 8   | 9   | 8   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 8   | 0   | 0   | 7432 |
| Whatcom     | 6761 | 9   | 9   | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 47327|
| Whitman     | 429  | 7   | 8   | 7   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 7   | 0   | 0   | 0   | 3003 |
| Yakima      | 3727 | 13  | 24  | 8   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 29816|
Table S4. Summary of Pearson correlation between the percent construction workforce and measures of air quality on the monthly timescale for Washington State counties, 2011-2020.

| County   | Average AQI days per month | Average PM$_{2.5}$ ($\mu$g/m$^3$) |
|----------|----------------------------|-----------------------------------|
| Adams    | 0.119                      | 0.04                              |
| Asotin   | 0.51                       | 0.392                             |
| Benton   | 0.348                      | 0.148                             |
| Chelan   | 0.469                      | 0.215                             |
| Clallam  | 0.547                      | 0.456                             |
| Clark    | 0.32                       | 0.351                             |
| Columbia | 0.59                       | 0.637                             |
| Cowlitz  | 0.678                      | 0.162                             |
| Franklin | 0.465                      | 0.428                             |
| Garfield | 0.821                      | 0.882                             |
| Grant    | 0.46                       | 0.341                             |
| Grays Harbor | 0.66   | 0.536                         |
| Jefferson | 0.528                     | 0.453                             |
| King     | 0.517                      | 0.629                             |
| Kitsap   | 0.533                      | 0.592                             |
| Kittitas | 0.286                      | 0.262                             |
| Klickitat| 0.518                      | 0.533                             |
| Lewis    | 0.443                      | 0.267                             |
| Mason    | 0.658                      | 0.115                             |
| Okanogan | 0.467                      | 0.194                             |
| Pend Oreille | -0.401                     | 0.246                         |
| Pierce   | 0.453                      | 0.379                             |
| San Juan | --                         | -0.212                           |
| Skagit   | 0.333                      | 0.459                             |
| Snohomish| 0.334                      | 0.106                             |
| Spokane  | 0.508                      | 0.501                             |
| Stevens  | 0.506                      | 0.232                             |
| Thurston | 0.363                      | 0.152                             |
| Walla Walla | 0.462                     | 0.245                         |
| Whatcom  | 0.404                      | 0.277                             |
| Whitman  | 0.503                      | 0.591                             |
| Yakima   | 0.196                      | 0.109                             |