



The impact of wildfire smoke and temperature on traumatic worker injury claims, Oregon 2009–2018

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Abstract

Background and Aims: As average temperatures rise and wildfire events increase in the United States, outdoor workers may be at an increased risk of injury. Recent research suggests that heat exposure increases outdoor workers' risk of traumatic injuries, but co-exposures of heat and wildfire smoke have not been evaluated.

Methods: Oregon workers' compensation data from 2009 to 2018 were linked to satellite data by the date of injury to determine if acute heat (maximum Heat Index) and wildfire smoke (presence/absence) were associated with a traumatic injury. North American Industry Classification System (NAICS) codes were utilized to identify accepted, disabling injury claims from construction (NAICS 23) and agriculture, forestry, fishing, and hunting (NAICS 11). Claims from April to October were analyzed using negative binomial models to calculate incident rate ratios (IRR) by heat and wildfire exposure for All workers and specifically for Agricultural (Ag)/Construction workers.

Results: During the study period, 91,895 accepted, traumatic injury claims were analyzed. All workers had an injury IRR of 1.04 (95% confidence interval [CI]: 1.02–1.06) while Ag/Construction workers had an IRR of 1.11 (95% CI: 1.06–1.16) when wildfire smoke was present. When the maximum Heat Index was 75°F or greater, the IRR significantly increased as temperatures increased. When the maximum Heat Index was above 80–84°F, All workers had an IRR of 1.04 (95% CI: 1.01–1.06) while Ag/construction workers had an IRR of 1.14 (95% CI: 1.08–1.21) with risk increasing with increased temperatures. In joint models, heat remained associated with injury rates, but not wildfire smoke. No multiplicative interactions between exposures were observed.

Conclusion: Increasing temperature was associated with increased rates of traumatic injury claims in Oregon that were more pronounced in Ag/Construction workers. Future work should focus on further understanding these associations and effective injury prevention strategies.

KEYWORDS

air quality, climate change, heat, occupational injuries, outdoor workers, workers' compensation

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1 | INTRODUCTION

Throughout the United States, workers in a variety of industries and occupations perform strenuous work in outdoor environments that are already impacted by climate change. Exposure to hot environments and extreme heat can result in illnesses such as heat stroke, heat exhaustion, heat syncope, heat cramps, and heat rashes, or death.¹ Heat can also increase the risk of workplace injuries, such as those caused by sweaty palms, fogged-up safety glasses, and dizziness.¹ Similarly, air pollution and wildfire smoke are both established contributors to adverse health outcomes such as the increased risk for cardiovascular diseases, respiratory morbidity, cardiac arrest and increased rates of emergency department visits, and overall healthcare utilization.^{2–11}

As reported by the United States Bureau of Labor Statistics, the agriculture, forestry, fishing, and hunting industry in Oregon had the highest private industry rate of nonfatal occupational injuries and illness with 5.2 per 100 full-time equivalents (FTEs) in 2019. Similarly in 2019, the Oregon construction industry had the fifth-highest rate of nonfatal occupational injuries and illnesses with 4.4 per 100 FTEs.¹² Increasing temperatures have been associated with increases in heat-related illnesses (HRI)^{13,14} and outdoor worker injury rates/risks,^{15–22} especially in occupations and industries where workers are required to perform strenuous work in outdoor environments. It is possible that heat and/or wildfire smoke together magnify injury rates, or something similar.

The frequency, duration, and intensity of extreme heat events are expected to increase throughout the world during the 21st century.²³ Consequently, a combination of climate change, land management, human activity, and the invasion of nonnative invasive grasses is predicted to increase the area burned and fire frequency across the Pacific Northwest and other areas around the world.²⁴ As climate change continues to influence extreme heat and wildfire events, outdoor workers will be the first to experience these conditions which pose a significant health risk in uncontrolled worksite environments.^{25,26} Identifying climatological factors that contribute to the injury burden of workers must be a priority as climate change further alters outdoor worksite environments.

Although the impact of heat on HRIs and injury rates have been studied, less is known about the impact of wildfire smoke in disproportionately exposed populations, such as workers in the agriculture or construction industries. In the summer of 2021, Oregon²⁷ and Washington²⁸ implemented new emergency rules to protect workers from extreme heat and air pollution from wildfire smoke. Currently, both Oregon and Washington have updated, permanent heat and wildfire smoke rules to protect workers.²⁹ Rulemaking for heat risks and burdens in outdoor and indoor work settings is currently underway at the United States Department of Labor's Occupational Safety and Health Administration (OSHA).³⁰ It is difficult to adequately protect workers from environmental factors when we do not fully understand the risks associated with exposures in workplaces where they cannot be adequately eliminated or controlled.

As average temperatures in Oregon rise and the threat of wildfires increases, it is important to understand the impact these environmental conditions have on worker injury rates. The objective of this study was to elucidate the relationships between traumatic injury rates for different industries, temperature, and the presence of wildfire smoke over a 10-year period using Oregon workers' compensation claims and modeled meteorological data.

2 | MATERIALS AND METHODS

2.1 | Study population and worker employment estimates

The Department of Consumer and Business Services (DCBS), which maintains the workers' compensation database, allows researchers to request data for research purposes. We examined all accepted, disabling worker injury claims that occurred between 2009 and 2018 in Oregon. Disabling claims are defined by DCBS as "any injury that causes the worker to temporary disability (time-loss), permanent disability, or death." A disabling injury is defined as when the employee misses 3 or more days of regularly scheduled work, was hospitalized overnight, was likely to experience permanent disability, or died. Accepted claims are those in which an insurer accepts responsibility for the payment of the benefits on a claim filed by an injured worker. At this point the insurer provides written notice of accepted conditions based on the diagnosis of the attending physician or nurse practitioner.³¹ All accepted, disabling claims are required to be reported to the DCBS's Workers Compensation Division.

Data were obtained with a data agreement from the DCBS Workers' Compensation Division, which covers all Oregon workers except certain corporate officers, partners and family-owned businesses, and contractors. When the Bureau of Labor Statistics' total number of workers in Oregon was compared to the DCBS's estimate of the total number of Oregon workers covered by workers' compensation from 2016 to 2020,³² there was less than a 1% difference from 2016 to 2018. Sociodemographic characteristics, Standard Occupational Classification (SOC) and North American Industry Classification System (NAICS), injury location (county and zip code) and date, and Occupational Injury and Illness Classification System (OIICS) codes were used from each injury claim in the Oregon Workers' Compensation Data (WCD). The workers' compensation claims data contained v1.01 and v2.01 OIICS coding. All injury claims with nature coded as 0 (v1.01) or 1 (v2.01) at the first digit were classified as traumatic injuries and included while all other nature codes were excluded. The Oregon WCD claims contain the location (zip code and county) for each injury. The zip code where the injury occurred was used for this study. Injury claims were removed if the zip code was not a valid Oregon zip code in the WCD. The data were then formatted into a time-series data set with the number of injury claims per day in every zip code in Oregon from January 1 2009 to December 31, 2018. We choose to classify claims with NAICS 11

(agriculture, forestry, fishing, and hunting) and NAICS 23 (Construction) sectors as Ag/Construction in this study. Although not all workers in these two industries are outdoor workers, only industry sectors were used to classify workers to limit the risk of overestimating or underestimating the number of workers in each zip code.

Industry sector employment estimates at the zip code level were not publicly available at the time of this study. To generate monthly, industry sector employment estimates for all Oregon zip codes, a combination of county and zip code level employment estimates was used to estimate the number of workers for all industries. Specifically, the employment and wages by industry (Oregon Employment Department website [QCEW]) data from the Oregon Employment Department³³ and the zip code Business Patterns Survey (BPS) data from the United States Census Bureau³⁴ were used. Supporting Information: Table 1 provides a visual aid to how zip code employment estimates were calculated. Additional information on how Oregon zip code industry sector employment estimates were created can be found in the Supporting Information.

2.2 | Meteorological and wildfire smoke data

The availability of free satellite imagery for a variety of environmental conditions has given researchers additional methods for generating high-resolution exposure metrics. Based on previous studies on heat stress,^{17,18} we chose to use daily data from Gridded Surface Meteorological (gridMET) to generate heat exposure metrics. Grid-Met is a high-spatial-resolution (~4 km, 1/24th degree) surface meteorological data set covering the continuous United States since 1979.³⁵ This data set blends the gridded climate temporal attributes from the PRISM Climate Group³⁶ and regional reanalysis of National Land Data Assimilation System phase 2 (NLDAS-2) using climatically aided interpolation.^{35,37} The validity of the data is compared to extensive networks of land-based weather stations including RAWS,³⁸ AgriMet,³⁹ AgWeatherNet,⁴⁰ and USHCN-2.⁴¹ Variables included daily minimum and maximum dry bulb temperature, as well as daily minimum and maximum relative humidity. Daily gridMET data from January 1, 2009 to December 31, 2018, was spatially merged and averaged over individual Oregon zip codes. There were no missing days of the gridMET data over the study period. Categorical exposure temperature ranges with 5° increments were created for the daily maximum (max) Heat Index (°F) using air temperature and relative humidity. The equations from the source code for the US National Weather Service's online Heat Index calculator were used.⁴² Analyses were performed for the warmer months of the year, April 1 to October 31 within Oregon. This time period was selected because the average max Heat Index was above 55°F and the highest max Heat Index was at least 90°F. Observations that occurred between November 1 and March 31 were removed from the analysis.

To estimate wildfire smoke exposure we used the National Oceanic and Atmospheric Administration (NOAA) and National Environmental Satellite, Data and Information Service

(NESDIS) product the hazard mapping system (HMS).⁴³ The HMS product combines near real-time satellite observations over a 3 h period to generate daily wildfire smoke plume products. The resolution of the data is ~1.3 km. Using ArcGIS, the daily wildfire smoke plumes intersected with all zip codes in Oregon. If any area within the zip code indicated the presence of wildfire smoke plumes, the zip code was marked as exposed for that day. The heat and wildfire smoke data were then merged with the WCD time-series data set and the monthly zip code employment estimates.

2.3 | Statistical analysis

To determine the best model fit, graphs of the residuals from count models (Poisson, zero-inflated Poisson, and negative binomial) were evaluated using the same covariates. The covariates included year (2009–2018), month (April–October), weekday (yes/no), zip code (zip code where the injuries occurred), and zip code employment range (1: <95; 2: 95–500; 3: 500–4000; 4: >4000). Some or all of these covariates were used in other studies that utilized negative binomial regression models.^{19,21,22} Akaike information criteria (AIC) and predicted probabilities from the models were also compared. Lastly, the continuous monthly employment estimates were used to represent the total number of workers that were at risk in each zip code for every injury using the exposure function in STATA. Correlation coefficients were computed between max Heat Index and wildfire smoke to check for collinearity. None of the correlations were above 0.4. The highest correlation (0.38) was between max Heat Index and wildfire smoke.

The negative binomial model provided a better fit to the data than the Poisson or zero-inflated Poisson models. Likelihood-ratio tests for over-dispersion also found that the negative binomial regression yielded a better model fit. This was expected due to the large number of zeros that were present in the data set because the number of accepted, disabling claims in the WCD was under 200,000. Oregon has more than 400 zip codes and, if each injury occurred on a different day in a different zip code, there would still be over half a million days with no injuries.

Four sets of negative binomial regression models were used to calculate incidence rate ratios (IRR) and the corresponding 95% confidence intervals (95% CIs) to examine the impact of temperature and the presence of wildfire smoke on worker claim rates. *Set 1* was the effect of a single exposure (max Heat Index or the presence of wildfire smoke). *Set 2* examined the effect of coexposure to max Heat Index and the presence of wildfire smoke. *Set 3* elucidated if there were any multiplicative interactions between max Heat Index and the presence of wildfire smoke. *Set 4* restricted the models to only examine days when wildfire smoke was or was not present and the effect of max Heat Index. Each set of models was also run for subsamples of All workers and Ag/Construction workers so IRRs for the exposure metrics could be compared for each set.

Several sensitivity analyses were performed to evaluate the robustness of our results. Sensitivity analyses included selecting

claims that occurred during the summer months (July–September), removing zip codes where the monthly employment estimate was less than 100 for Ag/Construction workers, and removing the employment estimates used to estimate the number of workers at risk. All analyses were conducted using STATA 14 (StataCorp. 2015. *Stata: Release 14*. Statistical Software; StataCorp LLC). This study was approved by the Oregon State University Human Research Protection Program & Institutional Review Board (Study Number: IRB-20200907).

3 | RESULTS

3.1 | Description of traumatic injury claims

Of the 194,653 claims from the Oregon workers' compensation claims data, 2748 (1.4%) occurred outside the state of Oregon. The date the injury occurred was used to remove 5654 (2.9%) claims that occurred before January 1, 2009, or after December 31, 2018. Claims where OIICS codes were missing or described the injury as a nontraumatic injury or illness were removed from the analysis ($n = 21,230$, 10.9%). Missing and incorrect Oregon zip codes ($n = 9525$, 4.9%) were identified and excluded from the analysis. Lastly, only injury claims that contained zip code exposure estimates for daily maximum temperature and zip code employment estimates were included, excluding another 4743 (2.4%) claims. The total number of injury claims from all industries, Oregon employment estimates, and yearly injury rates for the 150,762 claims can be found in Supporting Information: Table 2. Of the remaining 150,762 (77.5%) of the Oregon workers' compensation injury claims, 91,895 (47.2%) occurred between April 1 and October 31 and were used in the analyses.

Overall, the total number of yearly injury claims of workers from all industries has been steadily increasing from 2009 to 2018 but the

incident rate ratio has remained relatively stable from 2009 to 2018 (range: 1.01–1.12). The number of injuries in December was the lowest, likely due to holidays and the seasonal nature of some occupations. Unadjusted and adjusted IRR for Oregon injury claims by year, month, and day of the week can be found in Supporting Information: Table 2. Lastly, the majority of the injury claims ($n = 129,345$; 86.0%) occurred during the workweek (Monday–Friday).

Zip code employment estimates were based on QCEW county monthly employment and zip code BPS total employment estimates. Overall, the trends in the employment estimates by year and month are similar between the QCEW county data and the estimated zip code employment data. The QCEW county-based monthly employment averages by year and month appear in Supporting Information: Table 3. The zip code employment estimates are also presented in Supporting Information: Table 3.

Overall, the max Heat Index and presence of wildfire smoke show similar trends of increasing during the summer months in Oregon. Supporting Information: Table 4 shows the total number of injuries and average maximum Heat Index for all of Oregon as well as the number of days with wildfire smoke present by month. Approximately 51.1% of the days in August from 2009 to 2018 had wildfire smoke present (Figure 1). July (23.0%) and September (25.7%) were the only other months with more than 6% of days that had wildfire smoke present in the Oregon zip codes included in this study.

3.2 | Effect of wildfire smoke and max Heat Index on traumatic injury claims

Table 1 shows the total number of claims with wildfire smoke present in all the zip codes in Oregon when an injury occurred during the study period (April–October). Wildfire smoke was present for 16.0%

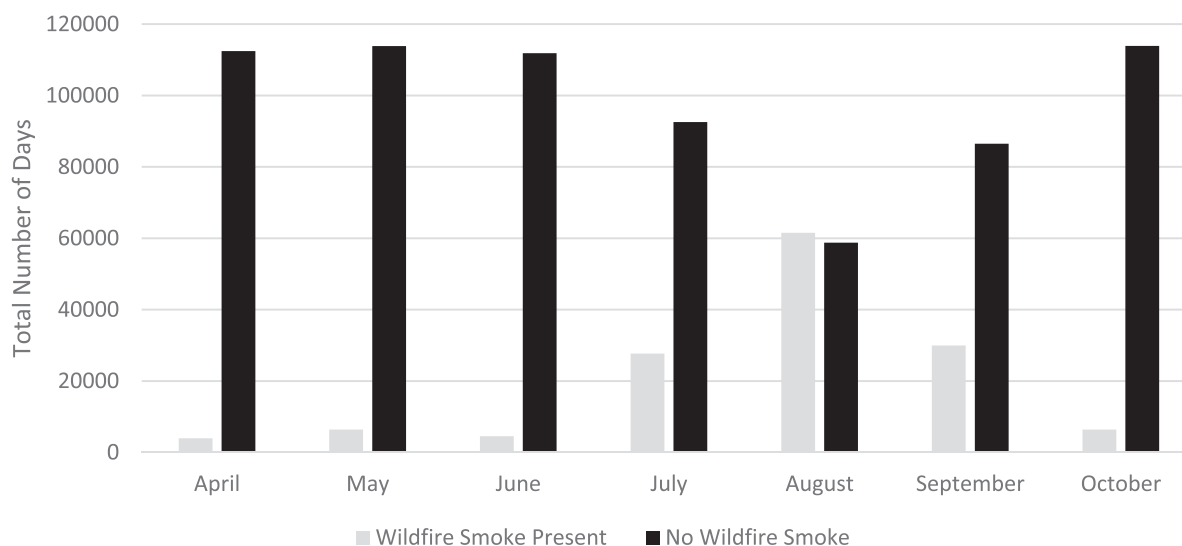


FIGURE 1 Total number of days for all Oregon zip codes, with and without the presence of wildfire smoke by month, 2009–2018

($n = 14,677$) of the injury claims for All workers while Ag/Construction workers had the highest percentage (18.4%) of injuries when wildfire smoke was present. The presence of wildfire smoke was significantly associated with injury claim counts for All workers and Ag/Construction workers. The IRRs and 95% CI for the association between wildfire smoke presence and traumatic injuries within Oregon are presented in Table 1. The IRR of 1.11 (95% CI: 1.06–1.16) for Ag/Construction workers was greater than the IRR for All workers (IRR = 1.04; 95% CI: 1.02–1.06).

For All workers, the majority of the injury claims ($n = 58,865$, 64.1%) occurred below a max Heat Index of 80°F. The total number of injury claims decreased for both All workers and the Ag/Construction workers as temperature ranges increased. When the percentage of injuries is compared between All workers and Ag/Construction workers, Ag/Construction workers' IRRs significantly increased as temperatures increased All workers (Table 2).

The IRRs and 95% CIs for the associations between max Heat Index and traumatic injury claims are present in Table 2. For All workers, higher temperature ranges were associated with an increase in the IRR for injury claims. The highest IRR for All workers was when the Heat Index was 115–119°F (IRR = 1.06; 95% CI: 1.04–1.09). As the max Heat Index increased above 75°F, the IRRs for Ag/Construction workers were significantly different from one with an increasing trend and the same trend can be seen for All workers. The IRRs for Ag/Construction workers were higher than the IRRs for All workers as temperatures increased. When the temperatures were 115–119°F, Ag/Construction workers had an IRR of 1.29 (95% CI: 1.12–1.48).

The IRRs and 95% CIs for the associations between max Heat Index, the presence of wildfire smoke, and traumatic injury claims are in Table 3. When max Heat Index and wildfire smoke were placed in the same model (i.e., as coexposures), wildfire smoke was not

TABLE 1 Total number of injury claims by smoke exposure and estimated adjusted IRRs of injury claim counts by presence of wildfire smoke, All workers then restricted to Ag/Construction

Smoke exposure	All workers ($n = 91,895$)			Ag/Construction workers ($n = 13,405$)		
	n (col %)	Adjusted IRR	95% CI	n (col %)	Adjusted IRR	95% CI
No	77,218 (84.0)	Ref	Ref	10,935 (81.6)	Ref	Ref
Yes	14,677 (16.0)	1.04	1.02–1.06	2470 (18.4)	1.11	1.06–1.16

Note: Adjusted negative binomial model: $\ln(\text{injury counts}) = \beta_0 + \beta_1(\text{year}) + \beta_2(\text{month}) + \beta_3(\text{weekday}) + \beta_4(\text{zip code}) + \beta_5(\text{zip code employ ranges}) + \beta_6(\text{smoke exposure})$. Bold values are significant at $p < 0.05$.

Abbreviations: CI, confidence interval; IRRs, incident rate ratios.

TABLE 2 Estimated adjusted IRRs of injury claim counts for max heat index, All workers then restricted to Ag/Construction workers

Max heat index (°F)	All workers ($n = 91,895$)			Ag/Construction workers ($n = 13,405$)		
	n (col %)	Adjusted IRR	95% CI	n (col %)	Adjusted IRR	95% CI
<65	25,059 (27.3)	Ref	Ref	3408 25.4	Ref	Ref
65–69	10,552 (11.5)	0.99	0.97–1.01	1440 10.7	1.02	0.95–1.08
70–74	11,880 (12.9)	0.99	0.97–1.01	1606 12.0	1.00	0.94–1.07
75–79	11,374 (12.4)	1.04	1.01–1.06	1733 12.9	1.14	1.08–1.21
80–84	5745 (6.3)	1.04	1.01–1.07	899 6.7	1.16	1.08–1.25
85–89	4950 (5.4)	1.05	1.01–1.08	766 5.7	1.15	1.06–1.25
90–94	4798 (5.2)	1.05	1.01–1.08	826 6.2	1.29	1.19–1.39
95–99	3848 (4.2)	1.07	1.03–1.11	617 4.6	1.22	1.12–1.34
100–104	3031 (3.3)	1.06	1.02–1.10	463 3.5	1.19	1.07–1.32
105–109	2626 (2.9)	1.06	1.02–1.11	398 3.0	1.21	1.08–1.35
110–114	2028 (2.2)	1.06	1.01–1.11	315 2.3	1.21	1.08–1.37
115–119	1560 (1.7)	1.11	1.05–1.17	243 1.8	1.29	1.12–1.48
≥120	4444 (4.8)	1.05	1.02–1.09	691 5.2	1.24	1.11–1.35

Note: Adjusted negative binomial model: $\ln(\text{injury counts}) = \beta_0 + \beta_1(\text{year}) + \beta_2(\text{month}) + \beta_3(\text{weekday}) + \beta_4(\text{zip code}) + \beta_5(\text{zip code employ ranges}) + \beta_6(\text{max heat index})$. Bold values are significant at $p < 0.05$.

Abbreviations: CI, confidence interval; IRRs, incident rate ratios.

TABLE 3 Estimated adjusted IRRs of injury claim counts for max heat index and the presence of wildfire smoke (mutually adjusted in the same model), All workers then restricted to Ag/Construction workers

Max heat index (°F)	n (col %)	Smoke present (%)	All workers (n = 91,895)		Ag/Construction workers (n = 13,405)	
			Adjusted IRR	95% CI	Adjusted IRR	95% CI
<65	25,059 (27.3)	1.5	Ref	Ref	Ref	Ref
65–69	10,552 (11.5)	5.0	0.99	0.97–1.01	1.01	0.95–1.08
70–74	11,880 (12.9)	9.3	0.99	0.96–1.01	1.00	0.94–1.06
75–79	11,374 (12.4)	14.6	1.03	1.01–1.06	1.14	1.07–1.21
80–84	5745 (6.3)	20.3	1.03	1.00–1.06	1.16	1.07–1.25
85–89	4950 (5.4)	29.8	1.04	1.01–1.08	1.15	1.05–1.25
90–94	4798 (5.2)	29.0	1.04	1.01–1.08	1.28	1.18–1.38
95–99	3848 (4.2)	33.1	1.07	1.03–1.11	1.21	1.11–1.33
100–104	3031 (3.3)	38.9	1.05	1.01–1.10	1.18	1.06–1.31
105–109	2626 (2.9)	38.8	1.05	1.01–1.10	1.20	1.07–1.34
110–114	2028 (2.2)	39.0	1.05	1.00–1.10	1.20	1.06–1.36
115–119	1560 (1.7)	40.4	1.10	1.04–1.16	1.28	1.11–1.46
≥120	4444 (4.8)	47.1	1.04	1.01–1.08	1.22	1.12–1.34
Smoke exposure	n (col %)	Mean Heat Index (°F)	Adjusted IRR	95% CI	Adjusted IRR	95% CI
No	77,218 (84.0)	72.0	Ref	Ref	Ref	Ref
Yes	14,677 (16.0)	91.5	1.01	0.99–1.04	1.03	0.96–1.08

Note: Adjusted model: injcounts ~year (2009–2018) + month (April–October) + day (weekday or weekend) + zipcode (categorical with over 400 options) + zipcode employ ranges (1: <= 95; 2: 95–500; 3: 500–4000; 4: > 4000) + max Heat Index + smoke exposure, exposure (zip code Employment Estimate). Bold values are significant at $p < 0.05$.

Abbreviations: CI, confidence interval; IRRs, incident rate ratios.

significantly associated with traumatic injury claims. Although there were no significant associations between traumatic injury counts and wildfire smoke, Ag/Construction workers still had a higher IRR of 1.03 (95% CI: 0.96–1.08) than All workers (IRR = 1.01, 95% CI: 0.99–1.01). Similar to when max Heat Index was the only exposure in the model, as temperatures increased, the IRR for all Heat Index ranges above 75°F were significantly associated with traumatic injury claims for both worker groups. When the max Heat Index was ≥120°F, Ag/Construction workers had a higher IRR of 1.22 (95% CI: 1.12–1.34) than All workers who had an IRR of 1.04 (95% CI: 1.01–1.08).

3.3 | Effect of interaction between max Heat Index and wildfire smoke on injury claim IRRs

The p values for the associations between traumatic injury claims and the interaction between max Heat Index and the presence of wildfire smoke are in Supporting Information: Table 5. Traumatic injury claims were not significantly associated with the interaction between wildfire smoke and max Heat Index for All workers or Ag/Construction workers.

3.4 | Sensitivity analysis

When workers' compensation claims were limited to only those when that occurred during the summer (July–September), for Ag/Construction workers, all of the max Heat Index ranges were significantly associated with traumatic injuries except for 70–74°F. The highest IRR for Ag/Construction workers was 1.47 (95% CI: 1.20–1.81) when the max Heat Index was 115–119°F. Max Heat Index was not significantly associated with traumatic injuries for any temperature range for All workers except 115–119°F (IRR = 1.09; 95% CI: 1.00–1.18). The presence of wildfire smoke was not significant for All workers or Ag/Construction workers. The full results of this sensitivity analysis can be found in Supporting Information: Table 6.

After removing all the observations when the monthly employment estimate was below 100 individuals, the results are very similar to the results found in Table 3. All of the IRRs for Ag/Construction workers were significantly associated with traumatic injuries when the max Heat Index was above 75°F. The presence of wildfire smoke was not significant for All workers or Ag/Construction workers. The full results of this sensitivity analysis can be found in Supporting Information: Table 7.

Removing the monthly employment estimates used to represent the number of workers at risk resulted in similar trends in results. All of the IRRs for Ag/Construction workers were significantly associated with traumatic injuries when the max Heat Index was above 75°F but the IRRs were all higher. A similar trend can be found for All workers as well. The full results of this sensitivity analysis can be found in Supporting Information: Table 8.

4 | DISCUSSION

Our findings of a positive association between rates of traumatic injury claims and heat levels in Oregon workers is a first step towards understanding how these exposures can impact workers. This study adds to the growing amount of literature by creating exposure metrics from meteorological conditions using modeled meteorological data, methods for calculating industry sector employment estimates at the zip code level, and the examination of potential interactions between heat and air pollution and occupational injuries.

This study showed a significant association between the presence of wildfire smoke with increased rates of traumatic injury claims for All workers and Ag/Construction workers using workers' compensation data. However, once the Heat Index was put in the same model all the results for wildfire smoke became insignificant. This could be due to the high correlation between heat levels and wildfire smoke or the exposure metrics used for wildfire smoke. Our study provides researchers with additional supporting evidence that there could be a link between wildfire smoke and occupational injuries. Although wildfire smoke can cause physical harm to workers' respiratory systems, it can affect visibility and potentially change employer or worker behaviors. For example, if wildfire smoke makes performing workers' normal tasks impossible and the work environment cannot be changed, employees may be asked to perform job tasks they are not as familiar with or stop work altogether. A better understanding of why there are positive associations between the presence of wildfire smoke and traumatic injury claims should be a priority for occupational health practitioners.

Heat has been shown to impact rates of occupational HRIs^{13,14,21} and injury rates/risks^{15,18–20,22,44} in other countries and states. The only study of workers' compensation data, that we have identified, that examined the impact of heat and air pollution was conducted in three Italian cities using 468,807 work-related injuries (WRI) claims.¹⁶ Daily maximum dry bulb temperature was not found to be significantly associated with WRIs for all industries but was significant for those working in the construction industry.¹⁶ Schifano and colleagues found that increasing concentrations of ambient particulate matter less than 10 μm (PM₁₀) was associated with an increase in WRIs during Italy's warm season (May–September). Although we did not utilize particulate matter, our study found that the presence of wildfire smoke was significantly associated with traumatic injury claims for Ag/Construction workers (IRR = 1.11; 95% CI: 1.06–1.16). However, when we included temperature in the same model with wildfire smoke, all the IRRs for wildfire smoke were no

longer significant. This could be partially due to the wildfire smoke variable being highly correlated with max Heat Index (0.38).

Importantly, future studies should examine the associations between the presence of wildfire smoke and stationary monitors for PM_{2.5} and PM₁₀. Understanding the relationship between satellite wildfire smoke data and stationary particulate matter monitors in the United States should be a priority. While it is well understood that PM_{2.5} accounts for most of the health burden of outdoor air pollution in the United States, the health effects of climate-induced changes in PM_{2.5} are poorly quantified.⁴⁵ Similarly, the impacts of wildfire smoke have mostly been limited to studies of wildland firefighters' health,^{46–50} overall healthcare utilization, and emergency department visits.^{3,7,8} Future studies should explore alternative methods of examining the impact of wildfire smoke on worker health. In Oregon, there are only a few air pollution monitors that capture PM_{2.5} which limited our ability to link it with HMS data. Researchers should use alternative satellite imagery sources and air pollution monitors on the ground to investigate different mechanisms that could impact outdoor workers' health.

Of all the previous studies we identified that used workers' compensation data, only two^{17,18} used satellite meteorological data to calculate heat exposure metrics to evaluate injury risk. One analysis focused on outdoor agricultural workers and the other construction workers. Spector et al.¹⁸ found that the traumatic injury odds ratio (OR) for agricultural workers was 1.14 (95% CI: 1.06–1.22), 1.15 (95% CI: 1.06–1.25), and 1.10 (95% CI: 1.01–1.20) for daily humidex of 77–84.2°F, 86–91.4°F, and ≥93.2°F when compared to humidex below 77°F. For construction, Calkins and colleagues found that the traumatic injury OR was 1.005 (1.003–1.007) per 1.8°F increase in humidex. Both of these analyses highlight that the injury risk for Ag/Construction workers increases as the temperatures increase. Both previous studies utilized a case-crossover study design and assessed nonlinearity using splines and similar stratified analyses. Our analysis was able to compare the IRR for traumatic injury claims for All workers and Ag/Construction workers using stratified analyses. We consistently found that Ag/Construction workers had higher IRRs than All workers as temperatures increased for max Heat Index, regardless of the presence of wildfire smoke. However, when the max Heat Index was 75°F or greater, both All workers and Ag/Construction workers were found to have significantly higher injury rates when compared to days when the max Heat Index was less than 65°F.

The results of higher injury claim rates for All workers and even greater rates for the Ag/Construction workers demonstrate that there are opportunities for more specific exposure assessments and analyses. While it is well understood that agricultural and construction industries have high rates of traumatic injuries, the findings suggest that these industries have gradually higher IRRs as temperatures increase. The question that needs to be investigated is why. While we choose to classify agricultural and construction workers together, future studies could focus on specific industries or occupations that perform most of their work outdoors. The workers' compensation data contains additional details about the type of injury, how it occurred, and what specific body part was injured that

could be leveraged to examine what types of injuries are associated with wildfire smoke. Understanding what specific industries/occupations have increased risks could help future projects identify what mechanisms are driving the findings in this study.

Studies on heat and occupational injuries commonly use a case-crossover design with referent selection (control periods) to calculate ORs but there are some limitations to using this design. The injury claim details within workers' compensation data give researchers a snapshot in time with little information about the worker's location before the injury. This would make selecting control periods for exposures difficult since case-crossover studies use an individual as their own control. In this study, monthly zip code employment estimates were calculated for Ag/Construction workers so we could calculate the incidence rate ratio for traumatic injuries and compare them to All workers. Our study did not include individual-level information about the demographic or socioeconomic information about the workers or the work tasks being performed, hours, job tenure, or time of injury. Future studies could use our approach and leverage the additional individual-level detail in workers' compensation data to elucidate specific populations that are the most at risk during extreme heat or wildfire smoke events.

On July 8, 2021 Oregon OSHA adopted temporary emergency heat rules (437-002-0155 and 437-004-1130) to protect workers from hot environments and workplaces.⁵¹ When the Heat Index equaled or exceeded 80°F, shade was required to be provided by natural or artificial means. Additionally, employers had to ensure that employees have an adequate supply of drinking water at all times and at no cost. When the Heat Index equaled or exceeded 90°F, employers were required to implement high heat practices and emergency medical plans that complied with 437-002-0161. Lastly, employers had to develop effective acclimatization practices that allow employees to gradually adapt to working at sites where the ambient temperature exceeds a Heat Index of 90°F. Although the Oregon OSHA heat threshold limits start when the Heat Index equals or exceeds 80°F, we found that traumatic injury rates were significantly associated with heat when the max Heat Index was 75°F or higher for All workers and Ag/Construction workers.⁵² As more states reconsider their rules or begin their rulemaking processes, and as Oregon OSHA develops its permanent rule, this should be considered.

Lastly, our study used the United States BLS QCEW county and zip code BPS employment estimates to calculate monthly industry sector employment estimates to represent the number of workers who were at risk in each zip code in Oregon. This allowed us to calculate injury IRRs for different industries so we could conduct restricted analyses to compare how these rates changed over the temperature ranges for both groups.

4.1 | Strengths and limitations

The zip code employment estimates for industries sectors that we used to calculate worker counts for different industries were calculated using a combination of QCEW county data and zip code BPS data. While the zip code employment estimates may not be completely accurate in

every zip code over the 10-year study period, the month, year, zip code, and average zip code employment estimate categories were included in the models to limit their effect. There were missing zip code employment estimates for specific zip codes that limited our ability to estimate workers in those zip codes. Additionally, some agricultural workers are not captured in the QCEW county or zip code occupational employment surveillance systems. Since the month variable is in the model alongside the monthly industry sector employment estimates, the employment estimates should not impact the model results because the comparisons are all between months. It is possible that the observed effects could be due to seasonal, hazardous job tasks or an increase in hours worked by employees during the hotter summer days and months. The workers' compensation data do not consistently provide enough detail to determine how long workers were at work or whether the job task they were performing during the injury was only prevalent during certain times of the year. We used seasonally adjusted QCEW employment estimates to calculate monthly employment estimates for each zip code in Oregon and did not calculate the hours worked per employee. The zip code BPS data excludes self-employed individuals, employees of private households, railroad employees, agricultural, and most government employees. Specifically, workers in zip codes with NAICS codes 111, 112, 482, 491, 525110, 525120, 525190, 525920, 541120, 814, and 92 were excluded from the survey.

Our study used high-resolution daily meteorological and wildfire smoke data to calculate daily exposure metrics for every zip code in Oregon which is different from many of the other studies that used stationary monitors in the United States. We chose to use Heat Index measurements instead of humidex or dry bulb temperature. One limitation of using the Heat Index is that temperatures below 80°F may not always be reliable. The gridMET data used does have some limitations. We choose to use daily summary statistics (minimum, mean, max) for temperature and relative humidity and did not explore using hourly climatological satellite modeled data. Although this limited our ability to describe the exact temperatures the injuries occurred in, we wanted to focus on daily exposures in this first study. The gridMET data likely does not capture microclimates that arise at spatial scales finer than the native resolution of the grid or parent data set (<4 km), so it is possible some temperature measurements are below or above what the temperature was in certain zip codes. Although the meteorological and wildfire smoke data were high-resolution, any satellite data we could have used is subject to some common limitations. The HMS wildfire smoke data can be affected on cloudy days and the data does not provide information on what level of the atmosphere the smoke resides in. The presence of wildfire smoke and temperature were positively correlated with one another which could confound the results for wildfire smoke.

5 | CONCLUSIONS

We observed strong and consistent positive associations between temperature and worker injuries, especially amongst agricultural and construction workers. These occupations have some of the highest

rates of occupational nonfatal and fatal injuries in the United States, but the impacts of heat and wildfire smoke may not have been given full consideration as significant risk factors historically. Our results suggest that state occupational health practitioners should look to incorporate occupational health policies and practices to protect workers from extreme heat and wildfire smoke exposures, which will likely become more frequent in the future with climate change.

AUTHOR CONTRIBUTIONS

Richard Evoy: Conceptualization; data curation; formal analysis; methodology; validation; writing—original draft; writing—review & editing.

Perry Hystad: Methodology; writing—review & editing. **Harold Bae:** Methodology; writing—review & editing. **Laurel Kincl:** Conceptualization; methodology; writing – original draft; writing – review & editing.

ACKNOWLEDGMENTS

The authors acknowledge the staff at the Oregon Department of Consumer and Business Services for their dedication to providing high-quality workers' compensation data.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article due to the data use agreement between Oregon State University and the Oregon Workers' Compensation Division.

ETHICS STATEMENT

This study was approved by the Oregon State University Human Research Protection Program & Institutional Review Board. Study Number: IRB-2020-0907. It was classified as research, but it did not involve human subjects. The Oregon workers' compensation data had personal identifying information removed before it was sent to the researchers.

TRANSPARENCY STATEMENT

The lead author Richard Evoy affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Evoy R, Hystad P, Bae H, Kincl L. The impact of wildfire smoke and temperature on traumatic worker injury claims, Oregon 2009–2018. *Health Sci Rep.* 2022;5:e820. [doi:10.1002/hsr2.820](https://doi.org/10.1002/hsr2.820)