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Combined burden of heat and particulate matter air quality in WA agriculture

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Abstract

Objectives: To evaluate the combined burden of heat and air quality exposure in Washington State agriculture by: 1) characterizing the spatiotemporal pattern of heat and $PM_{2.5}$ exposures during wildfire seasons; 2) describing the potential impact of these combined exposures on agricultural worker populations; and 3) identifying data gaps for addressing this burden in rural areas.

Methods: We combined county-level data to explore data availability and estimate the burden of heat and $PM_{2.5}$ co-exposures for Washington agricultural workers from 2010 to 2018. Quarterly agricultural worker population estimates were linked with data from a weather station network and ambient air pollution monitoring sites. A geographical information system displayed counties, air monitoring sites, agricultural crops, and images from a smoke dispersion model during recent wildfire events.

Results: We found substantial spatial and temporal variability in high heat and $PM_{2.5}$ exposures. The largest peaks in $PM_{2.5}$ exposures tended to occur when the heat index was around 85°F and during summers when there were wildfires. Counties with the largest agricultural populations tended to have the greatest concurrent high heat and $PM_{2.5}$ exposures, and these exposures tended to be highest during the third quarter (July-September), when population counts were also highest. Additionally, we observed limited access to local air quality information in certain rural areas.

Conclusion: Our findings inform efforts about highest risk areas, times of year, and data availability in rural areas. Understanding the spatiotemporal pattern of exposures is consistent with the precision agriculture framework and is foundational to addressing equity in rural agricultural settings.

Keywords

Rural air pollution; heat index; wildfire smoke; agriculture; heat stress

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INTRODUCTION

Agricultural workers are at risk for adverse health effects from exposure to heat and poor air quality from wildfire smoke. Agriculture is a $10.6 billion cornerstone of the Washington economy [1] that produces more than 300 commodities on 36,000 farms covering nearly 15 million acres. Recently, these operations have employed up to 140,000 workers between June and October [2-4], which coincides with peak heat and wildfire season. In the United States (U.S.) between 2000 and 2010, 359 occupational heat-related deaths were captured in the Census of Fatal Occupational Injuries (mean fatality rate 0.22 per 1 million workers), with agriculture among industries with the highest rates [5]. Data indicate that U.S. crop workers are 20 times more likely to die from illnesses related to heat stress than U.S. civilian workers overall [6]. Although likely an underestimate due to under-reporting, the burden of non-fatal occupational heat-related illness (HRI) in Washington State (WA) agricultural and forestry workers from 1995-2009 using workers' compensation data indicated a mean July-September HRI incidence rate 15.7 per 100,000 full-time equivalent workers, with crop production workers at highest risk [7].

Evidence of the effects of wildfire smoke among agricultural workers is still emerging. Studies in other occupational settings, primarily among wildland firefighters, indicate that smoke exposure increases the risk of adverse outcomes, including respiratory and certain mental health outcomes [8]. In the general population, wildfire smoke is associated with respiratory irritation and symptoms and exacerbations of underlying asthma and chronic obstructive pulmonary disease. There is also some evidence of associations of smoke exposure with increased respiratory infections and all-cause mortality, and mixed evidence of smoke's effects on cardiovascular outcomes [9,10]. Wildfire smoke consists of primary pollutants such as particulate matter (PM), carbon monoxide (CO), oxides of nitrogen (NO_x), as well as organic compounds which can contribute to ozone and secondary organic aerosol formation [11].

Wildfire smoke and ambient heat exposures may co-exist [12]. High air temperatures increase the risk of wildfires. In WA alone, substantial wildfire activity occurred in 2014-15, and in 2018, wildfires burned more than 350,000 acres [13]. Smoke from these fires and British Columbia blanketed WA, including agriculturally intensive areas of Central WA. Results of a pilot survey of 18 primarily Spanish-speaking male and female agricultural workers in Central WA in 2019 indicated that 72% reported exposure to unhealthy amounts of wildfire smoke at work, yet the same percentage reported no change in routines or activities in response to smoke. All the surveyed workers reported they had little to no information on how to protect themselves from the smoke [14].

Several policies and campaigns intended to protect workers from heat and smoke exist. WA and California (CA) are the only US states with outdoor heat rules focused on workers [15,16]. The US Occupational Safety and Health Administration (OSHA) maintains a public service campaign that promotes water, rest, and shade [17]. Smoke exposure is addressed in CalOSHA's 'Protection from Wildfire Smoke' standard, which requires employers to take actions, including providing filtering facepiece particulate respirators that are 95% effective and not oil resistant (N95) to employees when the current air quality index (AQI) is at or above 151 (corresponding to a $PM_{2.5}$ at or above 55.5 μg/m^3) for $PM_{2.5}$ [18]. However, there is limited information about the effectiveness of N95 mask use among agricultural workers exposed to smoke and heat in field conditions. Currently, WA has no occupational smoke rules specific to exposure to $PM_{2.5}$ which is a primary health concern during wildfire events.

There has been little work to date to characterize the *combined* burden of air quality and heat in rural areas. Although epidemiologic studies have examined potential interactions between air pollution and heat exposure, few studies have looked at the relationship between heat exposure, smoke constituents and local rural dispersion [12] relevant to agricultural worker health risks. As with other environmental exposures, communities with the most social and economic disadvantage may be most exposed and may also lack the means to address exposures and health effects [19]. We sought to evaluate the combined burden of heat and particulate matter air quality exposures in WA agriculture by: 1) characterizing the spatiotemporal pattern of heat and $PM_{2.5}$ exposures; 2) describing the potential impact of these combined exposures on agricultural working populations; and 3) identifying gaps in data needed to address this burden in rural areas.

METHODS

We combined county-level data between 2010 and 2018 to estimate the potential burden of heat and $PM_{2.5}$ co-exposures for agricultural workers in WA and describe data availability. Hourly data from a network of weather stations [20] and ambient $PM_{2.5}$ data [21] were linked with quarterly agricultural worker population estimates [22]. The ambient air pollution monitoring data presented here were submitted to the US EPA by local, tribal and State monitoring networks and included both Federal Reference and Equivalence Methods (FRM/FEM) as well as non FRM/FEM. In WA State, data collected in many urban and rural locations are non FRM/FEM, and these data are considered adequate by the US EPA for inclusion in calculating the AQI but are not used for regulatory purposes. Weather stations were selected if established prior to January 1, 2010. The Haversine formula [23] was used to compute the great-circle distance between each air monitoring site (n=77) and the nearest weather station (n=36). Hourly heat index values were computed using the Rothfusz equation [24]. To investigate independent and combined high exposure scenarios, we used index screening thresholds of 85 °F for the heat index [25] and 35 μg/m^3 for the hourly $PM_{2.5}$ [26]. A more conservative heat index screening threshold of 85 °F has been recommended based on actual HRI cases [27]. For counties with more than one $PM_{2.5}$ value in each hour (i.e. more than one air monitoring station in the county), the highest value was used in order to be public health protective.

Agricultural worker population (NAICS 11 Sector Code) averages were calculated by quarter between 2010 and 2018 for all WA counties. These data were obtained from the United States Census Bureau's Quarterly Workforce Indicator estimates and downloaded by 4-digit NAICS subsector. Employment was characterized as the estimate of the total number of jobs on the first day of the reference quarter. These federal workforce estimates were checked against Washington State estimates [3]. A geographical information system was created to display counties, crop area [2] for agricultural commodities with the largest workforces, air monitoring sites, weather station sites, and smoke dispersion models.

Images from the BlueSky smoke dispersion model were used to illustrate the dynamic dispersion of a smoke plume over the course of a highly impacted period from July 27 - August 7, 2018 [28]. The rasterized daily average $PM_{2.5}$ concentrations attributed to wildland fire from BlueSky's Modeled Pacific Northwest forecasted smoke domain on a 4-km scale was plotted in R v. 3.5.1 using the leaflet package.

RESULTS

Weather stations have a higher density than air monitoring stations in the intensive agricultural regions of central and eastern WA. It was not possible to use weather data collected at the air monitoring stations, as the relative humidity (RH) values were not consistently reported in the EPA database, which collects data from local, tribal and State monitoring networks. When matching weather and air monitoring stations, some sites were separated by more than 10 mi (16.1 km). Except for Spokane County, all these sites were west of the Cascade Mountains. The minimum, median, mean, and maximum distance between sites were 0.2, 3.1, 4.4, 22.4 miles (0.3, 5.0, 7.1, 36.2 km), respectively.

Figure 1 indicates air quality monitor coverage by county between 2010-2018 as blue dots. Also displayed are the spatial and temporal distribution of smoke, as predicted by the BlueSky dispersion model from July 29th - August 7th 2018. East of the Cascades, only 35 $PM_{2.5}$ monitoring sites covered a land area of about 45,000 mi^2 (116,550 km^2). This amounts to an area of about 1,286 mi^2 (3,330 km^2) per monitor or distances that could reach beyond 36 mi (58 km), on average. We additionally observed limited or no air quality monitors in certain rural counties, some with high agricultural production.

We found substantial spatial (by county) and temporal (by month/quarter and year) variability in high heat and $PM_{2.5}$ exposures. The largest peaks in $PM_{2.5}$ exposures tended to occur at times and in locations where the heat index was near or above 85 °F and during summers when there were wildfires. Counties with the largest agricultural populations typically had the greatest concurrent high heat and $PM_{2.5}$ exposures. These exposures tended to peak during the third quarter (July-September), when agricultural worker population counts were also highest. Supplement 1 presents the summary statistics for heat index and $PM_{2.5}$ concentrations by county. There were eight counties in the State without any $PM_{2.5}$ monitoring data. There were three counties (Garfield, Klickitat, Pend Oreille) with less than two summertime periods of $PM_{2.5}$ data, and these were excluded from the analysis.

Annual (29,499) and seasonal (21,873 in January-March and 35,671 in July-September) estimates indicate that Yakima had the largest number of agricultural workers (Table 1), followed by Grant, Chelan, Benton, and Franklin Counties. The top commodity in terms of sales for each of these counties was tree fruit. Annual federal agricultural workforce estimates for WA were only 2-3% higher than the state's employment agency estimates, which was likely due to the exclusion of the following NAICS codes from the latter: 113 (forestry and logging), 114 (fishing, hunting, and trapping), and 1153 (support activities for forestry) [3].

Table 1 shows the number of hours of HI and $PM_{2.5}$ exceedances over the period from 2010-2018 by quarter and county. The average number of workers employed by county over this time period is also presented. The eight counties with over 4000 agricultural workers each in the third quarter (Q3) also experienced the most concurrent heat and particle exposure periods. Yakima county, with over 35,000 Q3 workers experienced the 2nd highest instance of concurrent episodes (n = 17). There were counties with sizeable agricultural workforces (Whatcom, King and Skagit) that had substantially fewer joint occurrences. These counties are all on the West side of the Cascade mountains where heat exposures are less of a concern due to current and historically cooler weather. Figure 2 graphically represents the burden of heat and particle exposures on agricultural worker populations and demonstrates the importance of the exposures occurring in Q3.

As case examples, we plotted the time series of HI and $PM_{2.5}$ for Okanogan and Yakima counties (Figure 3) for Q3 from 2015-2018. These were selected to represent the county with the highest worker population and the county with the highest frequency of joint exposures. This figure demonstrates the regional nature of wildfire events, year after year. However, it is also clear that the peak concentrations, peak HI and duration of the smoke events are spatially variable.

DISCUSSION

In this analysis of heat and particulate matter air quality in WA agriculture, we found substantial spatial (i.e. by county) and temporal (i.e. by month/quarter and year) variability in high heat and $PM_{2.5}$ exposures. The largest peaks in $PM_{2.5}$ exposures tended to occur at times and in locations were the heat index was around 85 °F and during summers when there were wildfires. Counties with the largest agricultural populations tended to have the greatest concurrent high heat and $PM_{2.5}$ exposures. These exposures tended to be highest during the third quarter (July-September) when potentially exposed population counts -- particularly in tree fruit and crop support subsectors -- were also highest. We additionally observed limited air quality monitor data in certain rural areas. These nuanced findings can inform prioritization of prevention efforts and future research to improve access to air quality and heat exposure data in rural areas to guide decision-making.

The risks of adverse health effects from both heat and $PM_{2.5}$ in agriculture are influenced by several factors. These factors include: work outdoors during the summer in areas prone to wildfire smoke; cardiorespiratory/metabolic demands of work; minimal control over work during smoke and heat events; and potential exposures outside of work (e.g. few opportunities for cooling or clean air outside of work). In addition to outdoor agricultural workers, other outdoor workers and indoor workers may also be at risk of adverse heat and air quality-related health effects.

The health implications of heat stress and smoke exposure among agricultural workers are substantial. Heat stress induces a physiological response in humans (heat strain) intended to maintain thermal equilibrium. Heat exposure causes occupational HRIs, including heat rash, heat cramps, heat syncope, and heat exhaustion [6]. When human thermoregulatory responses are overwhelmed, severe heat-related illness and death from heat stroke can occur.

Exertional heat stroke can occur in young, otherwise healthy workers performing heavy physical labor, including agricultural workers. Occupational heat stress is also associated with traumatic injuries [29,30] and acute kidney injury in agricultural workers [31,32] and can lead to adverse birth outcomes among heat-exposed pregnant workers [33]. Exposure to wildfire smoke is associated with respiratory irritation and symptoms and exacerbations of underlying asthma and chronic obstructive pulmonary disease [9]. Ongoing research is exploring associations of smoke exposure with respiratory infections, cardiovascular outcomes, and all-cause mortality [9]. Though health effects of short-term exposure to wildfire smoke tend to be self-limited, more work is needed to understand the health effects of longer-term cumulative exposure, interactions of wildfire smoke and agricultural burn and other pollutant exposures, and interactions of workplace exposures with home and community exposures.

The number of potentially exposed agricultural workers in this study is likely an underestimate. The QWI estimates [22] did not include foreign workers hired under the U.S. Department of Labor Temporary Agricultural Foreign Labor Certification (H-2A) Program [34]. Yet, between 2000 and 2015, the number of certified H-2A workers in Washington increased from approximately 3,000 to 12,000 [35]. This number of H-2A workers is expected to increase based on demand [36]. Our burden estimates for heat and combined exposures are based on a threshold of 85°F. However, certain workers may be at risk for adverse effects of heat below this threshold. Though OSHA identifies conditions with a heat index of <91°F as ‘lower risk’ [17], an analysis of U.S. HRIs from 2011-2016 found that among 25 outdoor HRIs, six fatalities occurred when the heat index was <91°F [27]. While the heat index takes into account only dry air temperature and humidity, heat stress is influenced by dry air temperature and internal heat generated from heavy physical work, as well as clothing, solar radiation, humidity, and wind. The risk for HRI is additionally influenced by other workplace and individual factors [6]. Workers performing heavy physical work with few breaks, double layer clothing, and personal risk factors are likely at risk for adverse heat health effects below 85°F. In our analysis, lowering this threshold by 5°F would have the effect of increasing the number of combined hours of exposure to high heat and particulate matter air quality by up to 2 times.

Heat and smoke not only have potential direct effects on agricultural worker health but may also affect well-being through effects on crops. Apples, hops, cherries, and grapes are among Washington’s top ten agricultural commodities [4]. Tree fruit can be negatively impacted through sunburn or heat stress. High levels of sunlight and heat increase tree transpiration and reduce moisture content, resulting in lower yields with smaller and poorer quality fruit [37]. Smoke-tainted beverage crops, especially wine grapes, may develop unpleasant flavors. These effects of heat and smoke on crops have a financial impact on growers, winemakers, and workers. Growers are increasingly adopting precision agriculture--which is the use of information technology, local measurements, and big data--in farm management decisions, such as when to address crop heat stress through evaporative cooling or smoke exposure through crop protection or harvest timing.

Though we were able to characterize the combined burden of heat and $PM_{2.5}$ where data were available, we found that certain rural areas have limited access to air quality monitors and data. One approach to addressing gaps in regulatory monitoring is to use lower-cost sensors to develop spatially dense monitoring networks. A study of a large network of low-cost air quality monitors deployed in the Imperial Valley in Southeastern California found that more than ten times as many neighborhood-level air pollution episodes were identified among a community air monitoring network compared to government monitors [38]. A higher-density network could allow growers to better measure and anticipate exposures in order to protect workers and crops. High density networks for air quality and heat could not only support the precision agriculture framework for growers but also form the foundation for better understanding and the spatiotemporal pattern of exposures, which is critical for addressing equity in rural agricultural communities. One potential solution is adding air quality monitors to the AgWeatherNet platform [20], which has about 150 sites east of the Cascades.

Social-ecological models in occupational and environmental health frame prevention opportunities at multiple levels, including individual, interpersonal, workplace, community, policy, and land-use/built environment levels [30]. More work is needed to evaluate the acceptability, practicality, and effectiveness of approaches that might simultaneously address both heat and smoke exposures in the field. Further study of how high density, low cost, real-time air quality and heat monitoring networks and prediction modeling tools, including smoke dispersion models, might support decision-making to protect agricultural community health is also needed. Evaluation of current and proposed policies, including CalOSHA’s ‘Protection from Wildfire Smoke’ standard [18] and the proposed Farmworker Smoke Protection Act (FSPA 2019) [39], and the development of new evidence-based policies that consider joint impacts of heat and $PM_{2.5}$ are needed to protect agricultural communities. Focus groups conducted in a California agricultural community identified ambient heat as an important barrier to N95 use [40]. The novel approach presented here provides regulators and occupational health agencies concrete tools to identify and prioritize burdens on agricultural communities by directly relating worker populations and exposure occurrences. Assessment of the implications for agricultural health of ‘upstream’ policies focused on forest management for wildfire prevention [13] and land use planning to enhance community cooling opportunities and climate change mitigation are also needed.

Strengths of this study include selecting protective thresholds for heat and $PM_{2.5}$ exposures. This is particularly important since the joint impact on health outcomes is not currently well understood. However, this work did not consider other co-pollutants or potential differences in the dose-response function to wildfire smoke as opposed to other sources. The employment statistics, provided by the quarterly workforce indicators program, provide good estimates of total employment across counties, however as discussed above do not include the H-2A workforce and may severely underestimate the migrant workforce.

CONCLUSION

Smoke and heat exposures are projected to increase in the future [6,13], including in agriculturally intensive areas of Central WA. It is therefore becoming increasingly important to develop effective approaches for the prevention of adverse health effects from smoke and heat exposures, which tend to co-occur at times and in areas with the largest potentially exposed agricultural populations. We identified a need for improved access to data in rural agricultural areas that have gaps in regulatory and state monitoring. Our findings provide spatially explicit information about the potential burden of combined heat and particulate matter air quality exposures in WA that will inform the prioritization of prevention efforts to highest risk areas and times of year. Future research is needed to improve data availability and access in rural areas. Understanding the spatiotemporal pattern of exposures is foundational to addressing equity in rural agricultural settings. Using a data-driven approach is consistent with the emerging precision agriculture framework adopted by many producers.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Weather data provided courtesy of David Brown and Sean Hill. Copyright by Washington State University AgWeatherNet.

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REFERENCES

[1]. Washington State Department of Agriculture [Internet]. [cited 2019 Dec 30]. Available from: https://agr.wa.gov/washington-agriculture.

[2]. Agricultural Land Use Washington State Department of Agriculture [Internet]. [cited 2019 Dec 30]. Available from: https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use.

[3]. Aviles Gustavo, Moll Josh, Paterson Toby, Zadworny Zoe. 2017 Agricultural Workforce Report. Employment Security Department, Washington State; 2019. p. 45.

[4]. United States Department of Agriculture NASS. 2018 State Agriculture Overview for Washington [Internet]. [cited 2019 Dec 30]. Available from: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=WASHINGTON.

[5]. Gubernot DM, Anderson GB, Hunting KL. Characterizing occupational heat-related mortality in the United States, 2000–2010: An analysis using the census of fatal occupational injuries database. Am J Ind Med. 2015;58:203–211. [PubMed: 25603942]

[6]. Jackson LL, Rosenberg HR. Preventing heat-related illness among agricultural workers. J Agromedicine. 2010;15:200–215. [PubMed: 20665306]

[7]. Bonauto D, Anderson R, Rauser E, et al. Occupational heat illness in Washington State, 1995–2005. Am J Ind Med. 2007;50:940–950. [PubMed: 17972253]

[8]. Groot E, Caturay A, Khan Y, et al. A systematic review of the health impacts of occupational exposure to wildland fires. Int J Occup Med Environ Health. 2019;

[9]. Reid CE, Brauer M, Johnston FH, et al. Critical Review of Health Impacts of Wildfire Smoke Exposure. Environ Health Perspect. 2016;124:1334–1343. [PubMed: 27082891]

[10]. Doubleday A, Schulte J, Sheppard L, et al. Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: a case-crossover study. Environ Health. 2020;19:4. [PubMed: 31931820]

[11]. Reisen F, Duran SM, Flannigan M, et al. Wildfire smoke and public health risk. Int J Wildland Fire. 2015;24:1029.

[12]. De Sario M, Katsouyanni K, Michelozzi P. Climate change, extreme weather events, air pollution and respiratory health in Europe. Eur Respir J. 2013;42:826–843. [PubMed: 23314896]

[13]. Resources WSD of N. Washington State Wildland Fire Protection 10-Year Strategic Plan: Solutions for A Prepared, Safe, Resilient Washington [Internet]. Washington State Department of Natural Resources; 2019 [cited 2019 Dec 30]. Available from: https://www.dnr.wa.gov/publications/rp_wildfire_strategic_plan.pdf.

[14]. Cruz I. A Pilot Survey of Farmworkers' Perceptions of Wildfire-Related Exposures. 2019.

[15]. Outdoor Heat Exposure [Internet]. 2012. Available from: https://app.leg.wa.gov/WAC/default.aspx?cite=296-307-097.

[16]. Heat Illness Prevention [Internet]. Available from: https://www.dir.ca.gov/Title8/3395.html.

[17]. OSHA, USA. OSHA's Campaign to Prevent Heat Illness in Outdoor Workers: Using the Heat Index [Internet]. [cited 2019 Dec 30]. Available from: https://www.osha.gov/SLTC/heatillness/heat_index/.

[18]. Relations S of CD of I. Protection from Wildfire Smoke - Emergency [Internet]. Available from: https://www.dir.ca.gov/OSHSB/Protection-from-Wildfire-Smoke-Emergency.html.

[19]. Davies IP, Haugo RD, Robertson JC, et al. The unequal vulnerability of communities of color to wildfire. Jones JA, editor. PLOS ONE. 2018;13:e0205825. [PubMed: 30388129]

[20]. WSU AgWeatherNet [Internet]. [cited 2019 Dec 30]. Available from: https://weather.wsu.edu/.

[21]. US EPA Air Quality System (AQS) [Internet]. 2013 [cited 2019 Dec 30]. Available from: https://www.epa.gov/aqs.

[22]. QWI Explorer [Internet]. [cited 2019 Dec 30]. Available from: https://qwiexplorer.ces.census.gov/static/explore.html?s=107a49&v=line&t=ac0&fc=true&st=WA#x=0&g=0.

[23]. Haversine function R Documentation [Internet]. [cited 2019 Dec 30]. Available from: https://www.rdocumentation.org/packages/pracma/versions/1.9.9/topics/haversine.

[24]. Heat Index Equation [Internet]. [cited 2019 Dec 30]. Available from: https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml.

[25]. Jacklitsch Brenda, Williams Jon, Musolin Kristin, et al. NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS; 2016. Report No.: Publication 2016-106. .

[26]. US EPA NAAQS Table [Internet]. 2014 [cited 2019 Dec 30]. Available from: https://www.epa.gov/criteria-air-pollutants/naaqs-table.

[27]. Tustin AW, Cannon DL, Arbury SB, et al. Risk Factors for Heat-Related Illness in U.S. Workers: An OSHA Case Series. J Occup Environ Med. 2018;60:e383–e389. [PubMed: 29851740]

[28]. U.S. Forest Service. BlueSky Framework [Internet]. [cited 2019 Dec 30]. Available from: https://tools.airfire.org/websky/v1/#status.

[29]. Binazzi A, Levi M, Bonafede M, et al. Evaluation of the impact of heat stress on the occurrence of occupational injuries: Meta-analysis of observational studies. Am J Ind Med. 2019;62:233–243. [PubMed: 30675732]

[30]. Spector JT, Bonauto DK, Sheppard L, et al. A Case-Crossover Study of Heat Exposure and Injury Risk in Outdoor Agricultural Workers. Ren X, editor. PLOS ONE. 2016;11:e0164498. [PubMed: 27716794]

[31]. Flouris AD, Dinas PC, Ioannou LG, et al. Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. Lancet Planet Health. 2018;2:e521–e531. [PubMed: 30526938]

[32]. Moyce S, Mitchell D, Armitage T, et al. Heat strain, volume depletion and kidney function in California agricultural workers. Occup Environ Med. 2017;74:402–409. [PubMed: 28093502]

[33]. Kuehn L, McCormick S. Heat Exposure and Maternal Health in the Face of Climate Change. Int J Environ Res Public Health. 2017;14:853.

[34]. Department of Labor, US. Temporary Agricultural Employment of Foreign Workers [Internet]. [cited 2019 Dec 30]. Available from: https://www.dol.gov/agencies/whd/agriculture/h2a.

[35]. Economic Contributions of Washington H-2A Workers [Internet]. 2017. Available from: https://www.wafla.org/resources/Documents/Press%20Releases/2017/Econ.%20Contrib.%20of%20WA%20H-2A%20Workers%205-2017.pdf.

[36]. Hertz T. Wage, Employment and Demographic Trends for Hired Farmworkers in the US. Rural Policies Employ [Internet]. WORLD SCIENTIFIC (EUROPE); 2019 [cited 2019 Dec 30]. p. 221–236. Available from: 10.1142/9781786347091_0014.

[37]. Extension WSU Environmental Stress [Internet]. [cited 2019 Dec 30]. Available from: http://treefruit.wsu.edu/web-article/environmental-stress/.

[38]. Seto, Carvlin, Austin, et al. Next-Generation Community Air Quality Sensors for Identifying Air Pollution Episodes. Int J Environ Res Public Health. 2019;16:3268.

[39]. Merkley, Wyden. Farmworker Smoke Protection Act [Internet]. 2019. Available from: https://www.congress.gov/bill/116th-congress/senate-bill/1815/all-info.

[40]. Forum on Medical and Public Health for Disasters and Emergencies, Roundtable on Population Health Improvement, Roundtable on the Promotion of Health Equity, et al. Implications of the California Wildfires for Health, Communities, and Preparedness: Proceedings of a Workshop [Internet]. Olson S, editor. Washington, D.C.: National Academies Press; 2019 [cited 2019 Dec 30]. Available from: https://www.nap.edu/catalog/25622.

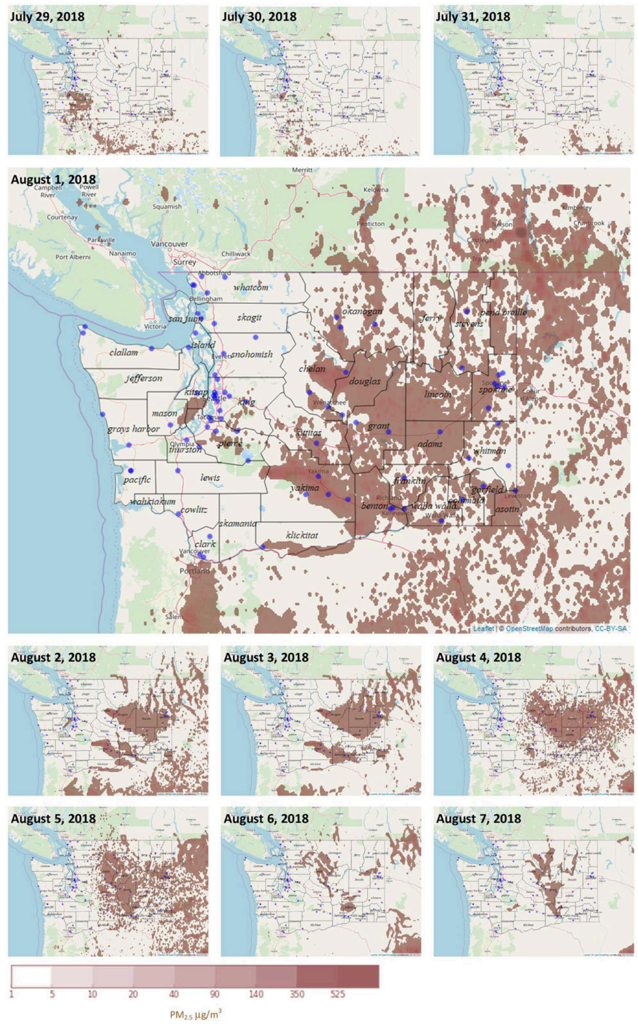

Figure 1 -

BlueSky average daily $PM_{2.5}$ images for two major wildfire episodes in 2018 across counties in the State of Washington. Blue dots represent current federal and state air monitoring sites

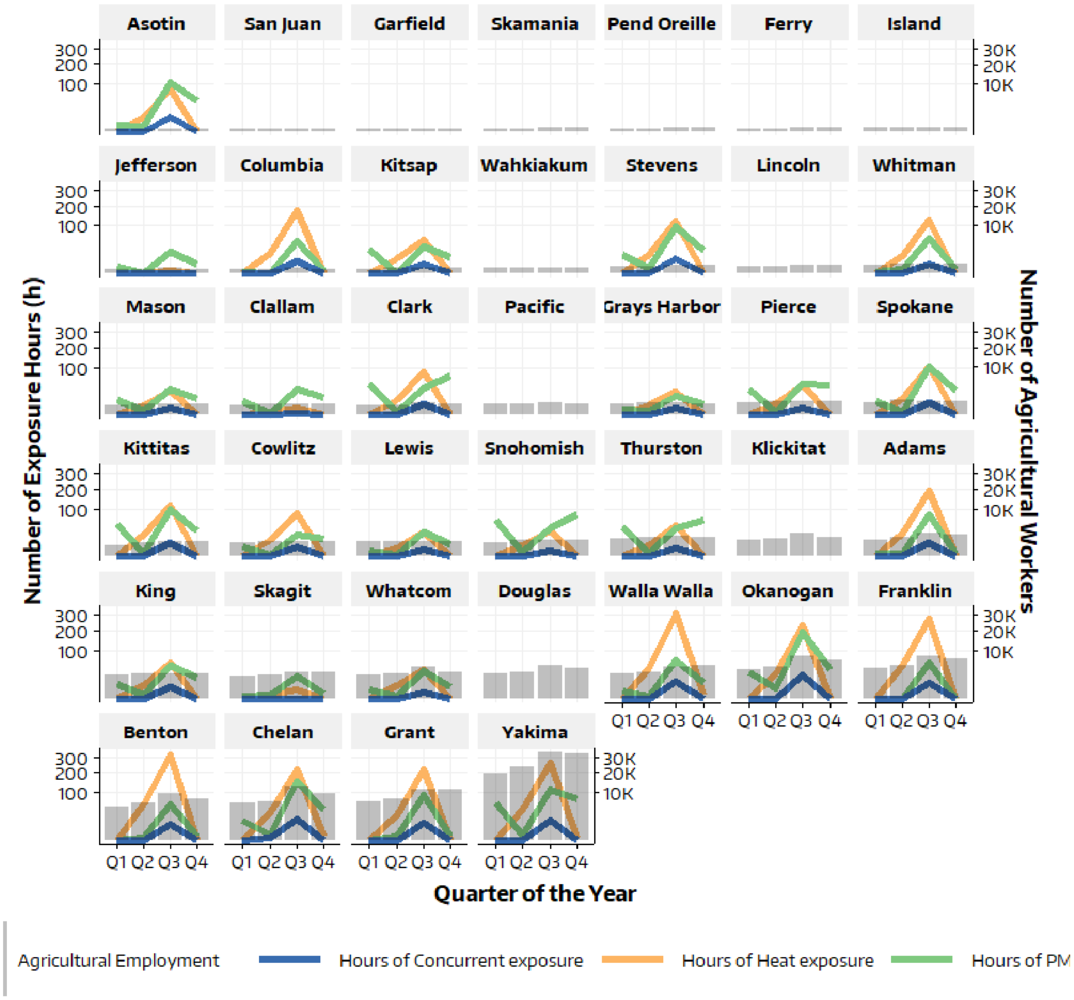

Figure 2 –.
Graphical representation of the quarterly distribution of agricultural worker population (grey shaded bar) and excess heat and PM exposures (green and orange lines). The dark blue lines represent the combined heat and smoke events. The counties with no available $PM_{2.5}$ data are presented on the plot, but the hours of heat, $PM_{2.5}$ and combined exposures are not displayed.

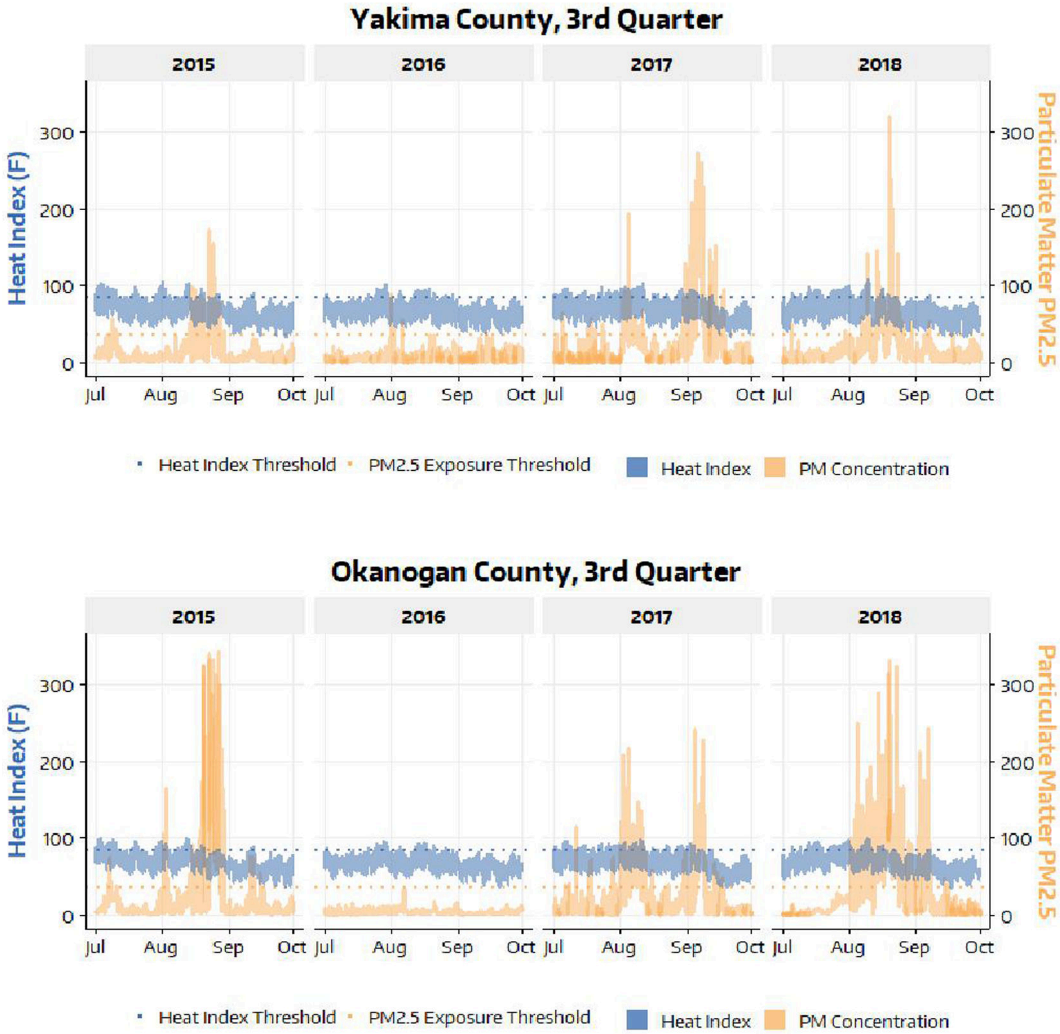

Figure 3 -

Time series of $PM_{2.5}$ and Heat Index over Q3 of the years 2015-2018. Also displayed as dotted lines are the heat index of 85 F and the $PM_{2.5}$ threshold of 35 μg/m^3 that were used in this analysis.

Table 1 -

Quarterly summaries by Washington State county of the total agricultural worker population, the number of hours of excess heat (HI > 85F) the number of hours of excess $PM_{2.5}$ (>35 μg/m^3) as well as the total hours of concurrent heat and $PM_{2.5}$ exposures over the years 2010-2018.

County	Quarter 1 (Jan – Mar)				Quarter 2 (Apr – Jun)				Quarter 3 (Jul – Sep)				Quarter 4 (Oct – Dec)				YEARLY
	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	
Yakima	**19514**	0	59	0	**22875**	40	1	0	**33755**	263	112	17	**32560**	0	73	0	**29499**
Grant	**6245**	0	0	0	**7512**	28	1	0	**10798**	215	90	13	**10877**	0	1	0	**9113**
Chelan	**6077**	0	17	0	**6387**	33	1	0	**11972**	219	150	20	**9518**	0	39	0	**8881**
Benton	**4536**	0	0	0	**5803**	55	0	0	**9390**	320	56	11	**7123**	0	1	0	**6981**
Franklin	**3898**	0	0	0	**4852**	46	0	0	**7746**	274	55	10	**6616**	0	0	0	**6020**
Okanogan	**3488**	0	28	0	**4148**	27	4	0	**7628**	231	191	23	**6544**	0	37	0	**5398**
Walla Walla	**2589**	0	2	0	**2957**	38	0	0	**4465**	314	64	11	**4568**	0	10	0	**3782**
Whatcom	**2445**	0	3	0	**2812**	7	0	0	**4132**	37	33	1	**2909**	0	5	0	**3358**
King	**2270**	0	9	0	**2550**	8	0	0	**2759**	54	45	5	**2707**	0	19	0	**2659**
Skagit	**2068**	0	0	0	**2461**	0	0	0	**3023**	4	21	0	**3012**	0	1	0	**2653**
Adams	**1128**	0	0	0	**1688**	24	0	0	**2483**	193	75	9	**2142**	0	0	0	**2066**
Thurston	**1499**	0	38	0	**1592**	6	1	0	**1742**	43	35	3	**1684**	0	58	0	**1867**
Snohomish	**915**	0	58	0	**1121**	5	1	0	**1248**	29	36	2	**1147**	0	78	0	**1309**
Spokane	**716**	0	9	0	**933**	12	0	0	**832**	105	103	7	**910**	0	27	0	**1222**
Lewis	**1026**	0	1	0	**1102**	3	0	0	**1070**	25	28	2	**1053**	0	6	0	**1158**
Cowlitz	**918**	0	4	0	**1072**	13	0	0	**1086**	80	22	4	**1001**	0	14	0	**1106**
Pierce	**726**	0	30	0	**842**	5	0	0	**881**	40	44	3	**838**	0	39	0	**941**
Kittitas	**616**	0	48	0	**848**	20	0	0	**941**	115	99	9	**991**	0	31	0	**855**
Grays Harbor	**562**	0	1	0	**652**	4	1	0	**634**	24	15	2	**603**	0	6	0	**667**
Clallam	**477**	0	8	0	**508**	0	0	0	**550**	2	28	0	**529**	0	13	0	**630**
Clark	**469**	0	43	0	**466**	10	0	0	**714**	81	34	6	**537**	0	66	0	**622**
Mason	**476**	0	11	0	**489**	4	1	0	**529**	26	28	2	**509**	0	12	0	**559**
Whitman	**328**	0	0	0	**361**	13	1	0	**434**	124	54	4	**413**	0	1	0	**412**
Stevens	**223**	0	15	0	**202**	15	2	0	**279**	120	97	10	**282**	0	23	0	**325**

County	Quarter 1 (Jan – Mar)				Quarter 2 (Apr – Jun)				Quarter 3 (Jul – Sep)				Quarter 4 (Oct – Dec)				YEARLY
	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	Workers	High heat hours	High $PM_{2.5}$ hours	High heat & $PM_{2.5}$ hours	
Kitsap	**95**	0	26	0	**141**	10	0	0	**127**	50	32	4	**117**	0	11	0	**233**
Jefferson	**67**	0	2	0	**104**	0	0	0	**115**	0	20	0	**97**	0	4	0	**165**
Columbia	**80**	0	0	0	**92**	19	0	0	**122**	176	44	6	**107**	0	1	0	**151**
Asotin	**26**	0	2	0	**27**	9	1	0	**30**	82	107	10	**30**	0	41	0	**66**