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To cite this article: Miriam E Marlier *et al* 2022 *Environ. Res. Lett.* **17** 094045

ENVIRONMENTAL RESEARCH
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RECEIVED
20 January 2022

REVISED
25 July 2022

ACCEPTED FOR PUBLICATION
24 August 2022

PUBLISHED
12 September 2022

LETTER

Exposure of agricultural workers in California to wildfire smoke under past and future climate conditions

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Keywords: climate change, wildfires, air pollution, agricultural workers

Supplementary material for this article is available online

Abstract
Wildfire activity in the western U.S. has increased in frequency and severity in recent decades. Wildfire smoke emissions contribute to elevated fine particulate matter ($PM_{2.5}$) concentrations that are dangerous to public health. Due to the outdoor and physically demanding nature of their work, agricultural workers are particularly vulnerable to wildfire smoke pollution. In this study, we quantify the potential exposure of agricultural workers in California to past (2004–2009) and future (2046–2051) smoke $PM_{2.5}$. We find that while absolute increases in smoke $PM_{2.5}$ exposure are largest in northern California, agricultural regions in the Central Valley and Central Coast may be highly vulnerable to future increases in smoke $PM_{2.5}$ concentrations. We find an increase from 6 to 8 million worker smoke exposure days (+35%) of 'smokewave' exposure for agricultural workers across the state under future climate conditions, with the largest increases in Tulare, Monterey, and Fresno counties. Under future climate conditions, we find 1.9 million worker smoke exposure days of agricultural worker exposure to levels of total $PM_{2.5}$ pollution deemed 'Unhealthy for Sensitive Groups.' This is a 190% increase over past climate conditions. Wildfire smoke $PM_{2.5}$ contributes, on average, to more than 90% of these daily $PM_{2.5}$ exceedances compared with non-fire sources of air pollution. Using the recent extreme wildfire season of 2020 as a case study, we show that existing monitoring networks do not provide adequate sampling of $PM_{2.5}$ in many future at-risk wildfire regions with large numbers of agricultural workers. Policies will need to consider the changing patterns of smoke $PM_{2.5}$ exposure under future climate conditions to better protect outdoor agricultural workers.

1. Introduction

The western U.S. has been a hotspot of fire activity over the past few decades (Westerling *et al* 2006). Wildfire burned area in California increased five-fold since the 1970s and over half of this increase has been linked to anthropogenic climate change (Abatzoglou and Williams 2016, Williams *et al* 2019). Future projections of climate change, population growth, and development predict that large wildfires (greater than 10 000 hectares) could occur 50% more often across the state by the end of the 21st century (Westerling 2018).

Wildfire emissions contribute to degraded air quality that is dangerous for public health (Balmes 2018). Global fire emissions have been linked to hundreds of thousands of deaths per year due to elevated smoke fine particulate matter ($PM_{2.5}$) concentrations (Johnston *et al* 2012, Roberts and Wooster 2021). Although $PM_{2.5}$ concentrations have been declining across most parts of the United States, wildfire-prone regions in the western U.S. have seen increasing

Table 1. Section 5141.1, *Protection from Wildfire Smoke*, including mean daily $PM_{2.5}$ thresholds, corresponding air quality index (AQI), safety estimates, and personal protection equipment (PPE) protection for agricultural workers (California Department of Industrial Relations 2019).

Mean daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	AQI	Levels of Health Concern	PPE Protection for Agricultural Workers
<12.0	0–50	Good	None
12.0–35.4	51–100	Moderate	None
35.5–55.4	101–150	Unhealthy for Sensitive Groups	None
55.5–150.4	151–200	Unhealthy	Employers are required to provide proper PPE for employees (N-95, N-99, N-100, etc, must be approved by the US National Institute for Occupational Safety and Health (NIOSH))
150.5–250.4	201–300	Very Unhealthy	Employers are required to provide proper PPE for employees (N-95, N-99, N-100, etc, must be approved by NIOSH)
250.5–500.4	301–500	Hazardous	AQI > 500, employees are required to wear a respirator

pollution (McClure and Jaffe 2018). Future projections point to substantial increases in the frequency and severity of high wildfire pollution events in the western U.S. by the mid to late 21st century (Liu *et al* 2016, Ford *et al* 2018, Li *et al* 2020). There is consistent evidence that smoke exposure contributes to general respiratory effects like asthma and chronic obstructive pulmonary disease (COPD), and growing evidence for its role in respiratory disease, all-cause mortality, and cardiovascular morbidity and mortality (Reid *et al* 2016, Chen *et al* 2020, Zhou *et al* 2021).

Agriculture is an important part of California's economy and employs more than 400 000 people per year, according to the California Employment Development Department (EDD) (State of California 2021). This is likely an underestimate due to undercounting of seasonal, part-time, and/or undocumented workers. California's Central Valley, one of the primary agricultural producing regions of the state, has some of the worst air quality in the country, which can be further degraded by regional fire activity (Schweizer and Cisneros 2017). In addition, many farmworkers have underlying health risks, low socioeconomic status, and reduced health care access that increases their vulnerability (Schenker *et al* 2015). In 2019, the California Division of Occupational Safety and Health (Cal/OSHA) implemented Emergency Regulation Section 5141.1, *Protection from Wildfire Smoke*, which is now permanent. Section 5141.1 provides thresholds and the associated worker protection measures required of employers to reduce worker exposure during wildfire events (table 1) (California Department of Industrial Relations 2019). This regulation requires employers to determine the $PM_{2.5}$ air quality index (AQI), either from local, state, or federal air monitoring sites, or by directly monitoring $PM_{2.5}$ at the worksite. When the AQI is above 150 ($PM_{2.5} \geq 55.5\ \mu g\ m^{-3}$), employers are required to lower exposures by providing NIOSH-approved personal protection equipment (PPE) such as N-95 respirators, shifting work to locations with filtered air, moving workers to lower AQI areas, reducing work time in unfiltered air, or reducing physical intensity of work. When the $PM_{2.5}$ AQI is above 500 ($PM_{2.5} \geqslant 500.5\ \mu g\ m^{-3}$), respirator use is required in accordance with Section 5144 which includes a fit test and medical evaluation (California Department of Industrial Relations 2012). Respirators such as N-95 masks can be effective at protecting lungs against wildfire smoke if worn properly (California Department of Industrial Relations 2019).

Many employers and workers in California's agricultural industry are not aware of the health hazards of wildfire smoke pollution or the measures that can be taken to protect health (Riden *et al* 2020). The AgriSafe Network found that respiratory health was considered a top health threat by participants, which could be related to multiple, often co-occurring, sources of pollution from machinery, dust, or smoke (Corrieri *et al* 2019). Surveys conducted in farming communities have also shown that some farmworkers feel economic pressure to continue working despite potential health risks, pointing to the need for direct employer protective actions (Riden *et al* 2020). For example, the California Heat Illness Prevention Study (CHIPS) found that strategies to reduce heat-related illness in farmworkers must consider situations that may encourage risk-taking during extreme heat and the effectiveness of training materials (Courville *et al* 2016). Outdoor agricultural workers can be exposed to overlapping climate hazards, such as extreme heat, which could limit the adoption and proper use of PPE such as N-95 respirators in efforts reduce smoke pollution exposure (Austin *et al* 2020, Xu *et al* 2020).

There is increasing recognition of the need to better understand vulnerable population exposure to smoke pollution (Cascio 2018). While existing work has examined the health risks of smoke exposure in California and other fire-prone regions around the world (Marlier *et al* 2019, Reddington *et al*

2015, 2021) to our knowledge, the potential exposure of outdoor agricultural workers to smoke pollution under future climate conditions has not yet been explored. Social surveys have highlighted this public health threat and the State has mandated worker protections, but there remains a critical gap in connecting wildfire smoke exposure metrics with potential agricultural worker exposure. Further, with wildfire frequency and severity expected to increase across the state with future climate change (Westerling 2018), analysis based solely on current conditions may misrepresent future health risks. In this paper, we address these gaps in the literature by using two complementary atmospheric modeling datasets to examine outdoor agricultural worker exposure to smoke pollution through the lens of existing worker protection measures. First, we isolate the climate change contribution to the shifting distribution of agricultural worker smoke pollution exposure at the county-level in California from the past (2004–09) to the future (2046–51). Using these counties as a guide, we then compare existing monitoring and modeling capabilities to monitor during the extreme 2020 fire season.

2. Data and methods

2.1. Past and future smoke pollution

We incorporate previously published estimates of wildfire-specific contributions to $PM_{2.5}$. Liu *et al* (2016) simulated wildfire contributions to daily $PM_{2.5}$ concentrations under past (2004–2009) and future (2046–2051) climate conditions using the GEOS-Chem chemical transport model v9-01-03 at $0.5^{\circ} \times 0.67^{\circ}$ resolution across North America. To estimate wildfire emissions, Liu *et al* (2016) applied a statistical fire prediction model that related wildfire burned area to meteorological variables, as well as ancillary factors such as elevation, population, fuels, and Santa Ana wind events in California (Yue *et al* 2013, 2014). These relationships were used to simulate past and future wildfire burned area under the A1B climate scenario. This scenario describes a future world with rapid economic growth, a peak in global population by mid-century, and balanced fossil fuel and non-fossil fuel energy sources that would result in mid-century global CO_2 concentrations of $\sim$530 ppm (IPCC 2001). GEOS-Chem simulations then estimated $PM_{2.5}$ for: (1) past: all sources (wildfires and all other sources such as transportation, power generation, or industry), (2) past: non-fires (excluding wildfires), and (3) future: all sources (future wildfires and all other sources). Non-fire sources are held constant to past levels in the future simulations, as emissions projections from non-fire activity are beyond the scope of this analysis. To calculate $PM_{2.5}$ transport and loss processes, the same meteorological fields were applied for the present-day and future scenarios. This approach allows us to isolate the impact of changing fire activity on smoke $PM_{2.5}$.

Simulated daily $PM_{2.5}$ is available at the county level across the western U.S. for six-year periods in the past (2004–09) and the future (2046–2051). We also analyze the 'smokewave' metric, developed as an analogous metric to a heatwave, to characterize sustained pollution exposure during wildfire events with at least two consecutive days of smoke $PM_{2.5}$ higher than the 98th quantile of wildfire $PM_{2.5}$ concentrations during 2004–2009. Monitoring data has been used in the original assessment of the Liu *et al* (2017) analysis for the past time period to correct biases in exposures simulated by GEOS-Chem 2017. For a more in-depth description of model set up, we refer the reader to Liu *et al* (2016).

2.2. Agricultural worker exposure

Our worker exposure analysis draws upon similar methodologies that assessed the burden of climate-related hazards for outdoor workers. Zuidema *et al* (2021) estimated the exposure of outdoor construction workers by county in Washington State by combining daily $PM_{2.5}$ concentrations during wildfire seasons with monthly worker totals. Austin *et al* (2020) used quarterly agricultural worker data to map exposure to coincident heat and $PM_{2.5}$ during recent wildfire events. Tigchelaar *et al* (2020) evaluated the exposure of agricultural workers in the U.S. to extreme heat under current and future climate change scenarios using county-level agricultural worker employment levels from the recent past.

For this study, we obtain county-level total monthly farm labor employment statistics for 2004–2009 and 2020 from the EDD Labor Market Information Division public databases (figure 1) (State of California 2021). Employment statistics are derived from the Current Employment Statistics dataset, which estimates the number of jobs located in each county, rather than by the residence of workers. Employment is estimated by number of full-time jobs but does not reflect the total number of hours worked or number of workers.

We quantify average worker exposure across the fire season (May–October) for 2004–2009 to match the GEOS-Chem dataset described previously. We estimate worker exposure to smokewave conditions and exceedances over Section 5141.1 air quality categories using a metric of person-day exposure, which sums the number of workers per county exposed to concentrations at or above a given threshold each day. We hereafter refer to this metric as 'worker smoke exposure day.' As in Tigchelaar *et al* (2020), for future exposures, we hold worker employment constant at past levels given the lack of spatially resolved estimates of future worker distributions. We test the sensitivity of this assumption by recalculating future smoke exposure with two alternatives: (1) county-level total

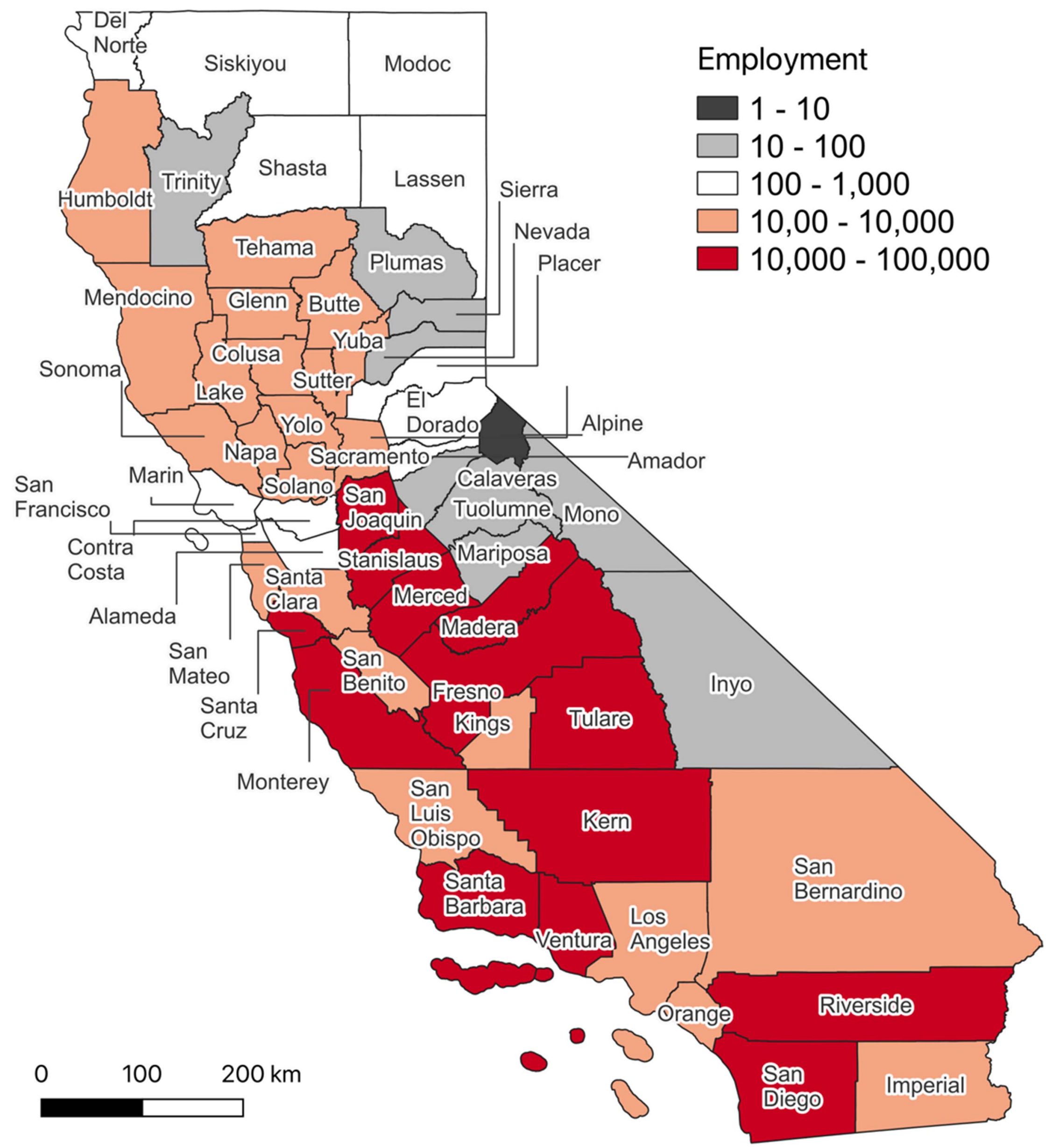

Figure 1. Average agricultural worker distribution by county for the May–October wildfire season from 2004 to 2009 (State of California 2021).

monthly farm labor in 2020 (State of California 2021), which may be closer to mid-century worker profiles compared to 2004–2009, and (2) alternative work schedules that assume workers are exposed five days per week with access to clean air indoors for the other two days per week. These sensitivity tests hold the smoke exposure levels constant but alter the distribution of workers and number of days exposed, respectively.

2.3. Case study for 2020 extreme wildfire season

The GEOS-Chem county-level analysis of long-term climate changes (section 2.2) isolates the contribution of future climate to smoke $PM_{2.5}$ exposures. Estimates of smoke $PM_{2.5}$ at higher spatial resolution are available for recent extreme fire seasons in California such as 2020 (but not for future climate projections), and these can provide additional insight into data availability for current and proposed worker protection policies. For example, the NOAA High Resolution Rapid Response (HRRR-Smoke) model provides hourly forecasts of surface-level smoke $PM_{2.5}$ across the U.S. at 3 km spatial resolution (Ahmadov *et al* 2017). Based on the Weather Research and Forecasting model coupled to Chemistry (WRF-Chem) model, HRRR-Smoke estimates smoke $PM_{2.5}$ in near real-time. Fire emissions are calculated from fire radiative power (FRP) observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi National Polar-orbiting Partnership satellite. This is used to initialize 48 h forecasts of smoke $PM_{2.5}$ (available at: https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/). We convert hourly forecasted smoke $PM_{2.5}$ for June – November 2020 from the HRRR-Smoke model to 24 h average concentrations prioritizing the 00Z (midnight) initialization time, with the 12Z initialization used to fill in missing values.

$PM_{2.5}$ concentrations vary greatly over space, and the air quality at the closest monitoring station may not be representative of that at an agricultural site. We compare surface-level HRRR-Smoke estimates to station measurements from the EPA's Air Quality System (AQS) from stations used in air quality decision making (available at: https://aqs.epa.gov/aqsweb/airdata/download_files.html). We estimate exceedances over the 'Unhealthy' air quality threshold (defined in table 1) measured by monitoring stations and estimated by the HRRR-Smoke model. We use this to evaluate: (a) the variability of smoke $PM_{2.5}$ across agricultural counties, and (b) the ability of existing monitors to capture this variability. Since the HRRR-Smoke dataset does not incorporate background sources of pollution, we expect station monitors to report higher concentrations in urban areas with more non-fire sources of $PM_{2.5}$ such as transportation, industry, or dust.

3. Results

3.1. Smokewave exposure

Smoke $PM_{2.5}$ concentrations during smokewave events are highest in northern California (figure 2, top row). Future projections show the largest increases across central and northern coastal counties, with stable and/or smaller increases in the Central Valley. However, the duration of smokewave conditions during each six-year period shows slightly different spatial patterns. Future increases in duration of up to 18 d are calculated in several counties located in the Central Coast and Central Valley (figure 2, middle row). This suggests that although smoke $PM_{2.5}$ concentrations during smokewave events intensify in northern California under future climate conditions, several counties in central California with large numbers of agricultural workers will experience an increase in the frequency of smokewave conditions. Finally, when coupled with the number of agricultural workers per county, counties in central California are more vulnerable (figure 2, bottom row). For example, Tulare, Monterey, and Fresno counties have an increase in 230 000, 470 000, and 490 000 agricultural worker smoke exposure days, respectively, characterized by smokewave conditions over each six-year period. Please refer to figure S1 for a named map of all counties in California.

3.2. Section 5141.1 standard exceedance days

We next calculate the number of days with $PM_{2.5}$ concentrations exceeding Section 5141.1 thresholds (table 1). We calculate total $PM_{2.5}$ exceedances (considering ambient and wildfire contributions together) because of the sensitivity of threshold exceedances to background concentrations. However, we also track the fractional contributions of wildfire smoke to total $PM_{2.5}$ at these different concentration thresholds. The average number of exceedances refers to the total number of exceedances in all counties divided by the number of counties. Across all counties in California, the average number of exceedances $\geq$12.0 μg m^{-3} (the limit for 'Good' daily air quality) increases from 40.6 to 42.6 d summed over each six-year period in past and future climate conditions, respectively (table 2). Wildfire smoke contributes 58% and 63% of daily concentrations in this category in the past and future. Since ambient (non-fire) contributions are held constant, this isolates the role of climate change-induced future wildfire activity.

Wildfires have a larger influence on exceedances over more extreme thresholds. The average number of daily exceedances across all counties summed over each six-year period increases from 5.0 to 8.5 for concentrations $\geq$35.5 μg m^{-3}, the threshold for air designated as 'Unhealthy for Sensitive Groups' in Section 5141.1 (table 2, figure 3). In Fresno and Monterey Counties, which have the highest absolute increase of worker smoke exposure days, wildfire smoke contributes 91% and 93% of concentrations during future exceedance days over this threshold.

The top three counties for total average agricultural worker employment from 2004–2009 are Monterey, Kern, and Fresno Counties, which each average more than 50 000 summer outdoor full-time equivalent jobs. These counties see no exceedances of the 35.5 μg m^{-3} threshold in the past period, but five, one, and two exceedance days, respectively, summed over the future six-year period (figure 3). This suggests that certain counties which have not previously faced high smoke $PM_{2.5}$ concentrations may need to prepare for increasing exposure in the future. Monterey County also sees exceedances $\geq$55.5 μg m^{-3}, the threshold designated for 'Unhealthy' air quality. Sonoma County, with an average of 6500 agricultural workers, is the county with the most intense air pollution due to wildfires in past climate conditions. This exposure may intensify in the future, including concentrations at 'Hazardous' levels (>250.5 μg m^{-3}). These hazardous levels of smoke $PM_{2.5}$ are not seen under past climate conditions but occur in nine counties in future climate conditions. This corresponds to 1500 worker smoke exposure days of exposure to the hazardous category over the six-year simulated period in the future.

This analysis also estimates the potential change in N-95 respirators to protect workers, with larger relative increases at more extreme smoke $PM_{2.5}$ concentrations. If Section 5141.1 remains unchanged for

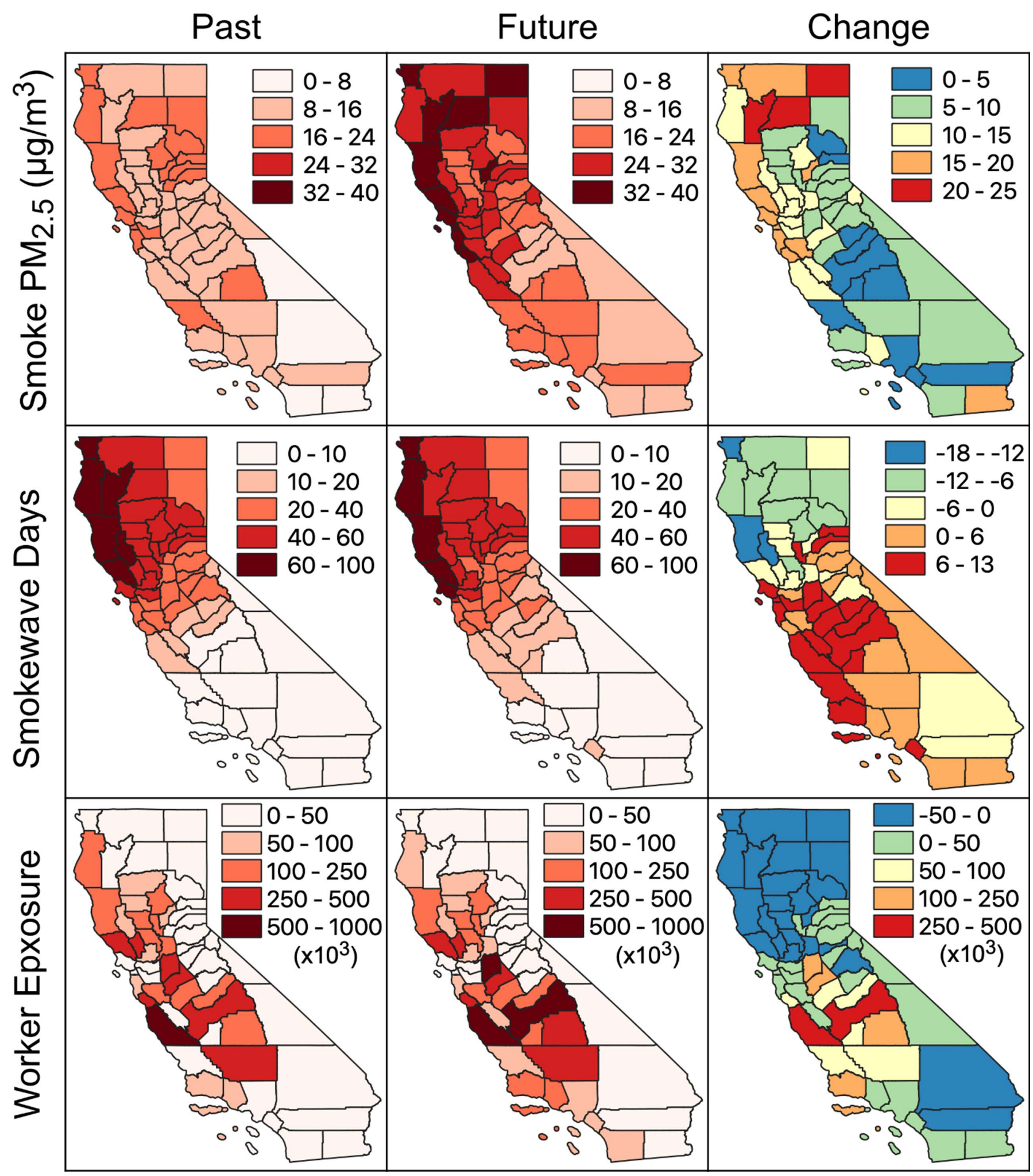

Figure 2. Top Row: Smoke $PM_{2.5}$ concentrations during smokewave events for the past (2004–2009, left), future (2046–2051, middle) and change (future minus past, right) (top row). Middle Row: Total number of days in smokewaves (⩾2 d at 98th percentile of wildfire $PM_{2.5}$ from 2004–2009) summed over each six-year period. Bottom Row: Agricultural worker exposure to smokewaves (in worker smoke exposure days), summed over the six-year period.

the AQI for $PM_{2.5}$ exceeding 500 (e.g. 'Hazardous'), 15 000 respirators would be needed in the future over a typical six-year period versus none in the past. The future supply needed to provide respirators to workers for voluntary use when the air quality is 'Very Unhealthy' or 'Unhealthy' could increase 491% and 214%, respectively, over a typical six-year period. If Section 5141.1 were to be strengthened to require that respirators be provided to workers when the air quality becomes 'Unhealthy for Sensitive Groups,' there is an expected 192% increase. These estimates may be conservative (figure 4), with additional increases in future worker smoke exposure days if we use the 2020 level of agricultural workers or if we consider the need for replacement respirators if they become wet or visibly dirty. However, if we reduce exposure to a 5 d work week only, exposure would be reduced.

3.3. 2020 case study

There were 120 AQS monitoring stations operating in California during the 2020 wildfire season (figure 5). Some stations reported data more frequently than others, with an average of 139 d of data per station out of 183 d total. We co-sampled with available HRRR-Smoke estimates for a maximum of 180 d over this period with data from both sources. The number of exceedances over 'Unhealthy' air quality calculated by observations and HRRR-Smoke compared

Table 2. Distribution of the number of daily exceedances for $PM_{2.5}$ exposures above $PM_{2.5}$ thresholds from Section 5141.1, summed over each period and then averaged across counties. The sum of ambient and wildfire contributions is considered in calculating exceedances, with number of counties (out of 58 total) exceeding the threshold in parentheses. Also shown are the fraction of total $PM_{2.5}$ contributed by smoke, and agricultural worker exposure in 10^3 worker smoke exposure days.

	Past (2004–2009)			Future (2046–2051)		
Mean daily $PM_{2.5}$ (μg m^{-3})	Daily Exceedances	Smoke Contribution (%)	Exposure (10^3 Worker smoke exposure days)	Daily Exceedances	Smoke Contribution (%)	Exposure (10^3 Worker smoke exposure days)
⩾12.0	40.6 (58)	58	11 100	42.6 (58)	63	13 000
⩾35.5	5.0 (45)	86	646	8.5 (55)	87	1890
⩾55.5	2.7 (36)	91	244	5.6 (45)	91	767
⩾150.5	1.0 (6)	98	16	1.9 (26)	98	96
⩾250.5	—	—	—	1.4 (9)	99	15

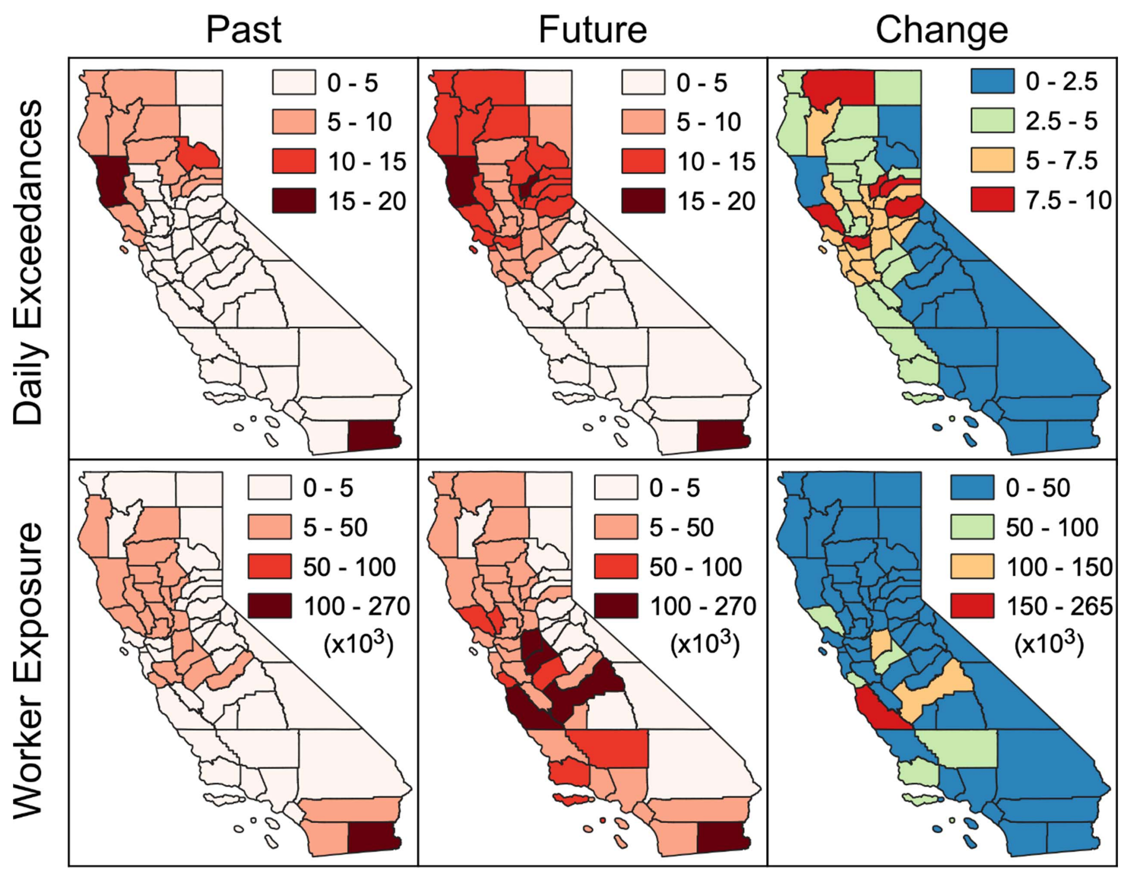

Figure 3. Total number of daily exceedances (top row) and worker smoke exposure days (bottom row) over the 'Unhealthy for Sensitive Groups' air quality threshold (⩾35.5 μg m^{-3}) according to Section 5141.1, summed over each six-year period.

well (figure S2), despite stations reporting total $PM_{2.5}$ and HRRR-Smoke estimating smoke $PM_{2.5}$ only.

We next assigned county-averages of HRRR-Smoke grid cells as well as all stations within a county (figure 5). This is a simplification of representing air pollution within a county, but employers are not required to conduct spatial interpolations of monitoring data. Many counties have no stations available. In addition, there are currently only 3, 5, and 6 $PM_{2.5}$ monitors in Monterey, Kern and Fresno counties, respectively, which our long-range analysis highlights as the most vulnerable counties for agricultural workers. We find exceedances in northern California and the Central Valley during the 2020 wildfire season, although of higher absolute magnitude than future climate projections due to the extreme nature of the 2020 fire season. In 2020, Fresno and Tulare counties may have required more than 500 000 N-95 respirators to comply with Section 5141.1 guidance according to the HRRR-Smoke forecasted smoke $PM_{2.5}$; station

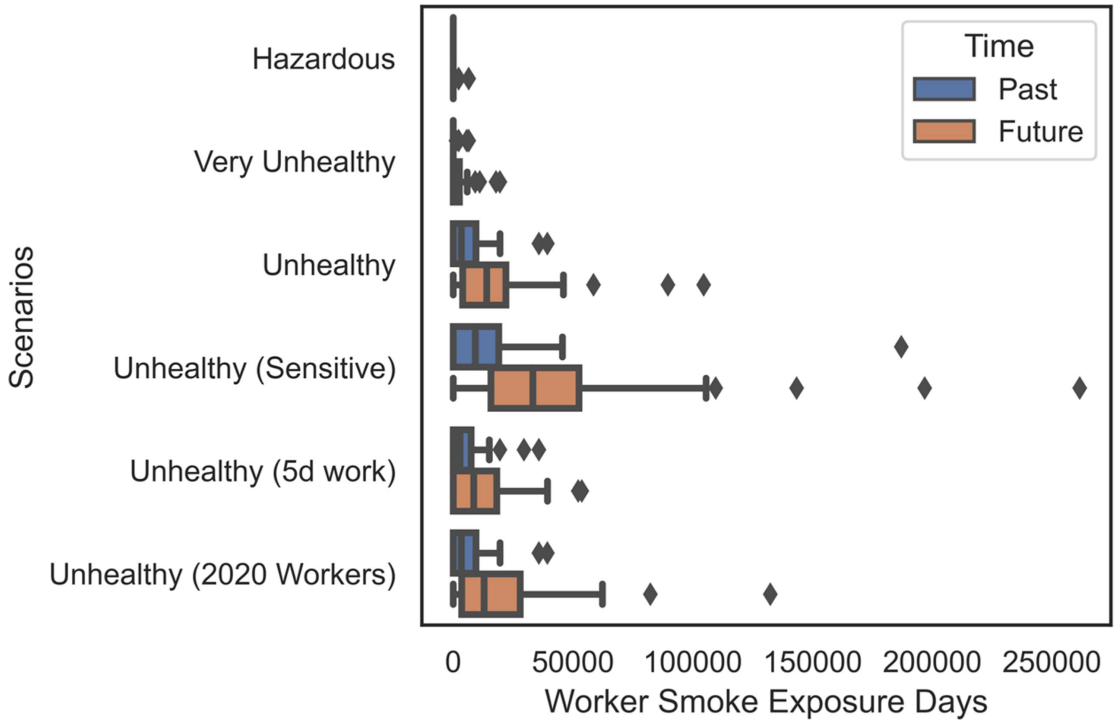

Figure 4. Distribution of worker smoke exposure days at the county scale for the past and future. Estimates only include counties with a minimum of 1000 agricultural workers during the wildfire season. The first four rows correspond with Section 5141.1 categories. 'Unhealthy (5d work)' estimates exposure assuming 5 versus 7 d. 'Unhealthy (2020 Workers)' estimates exposure with the future worker distribution shifted to 2020.

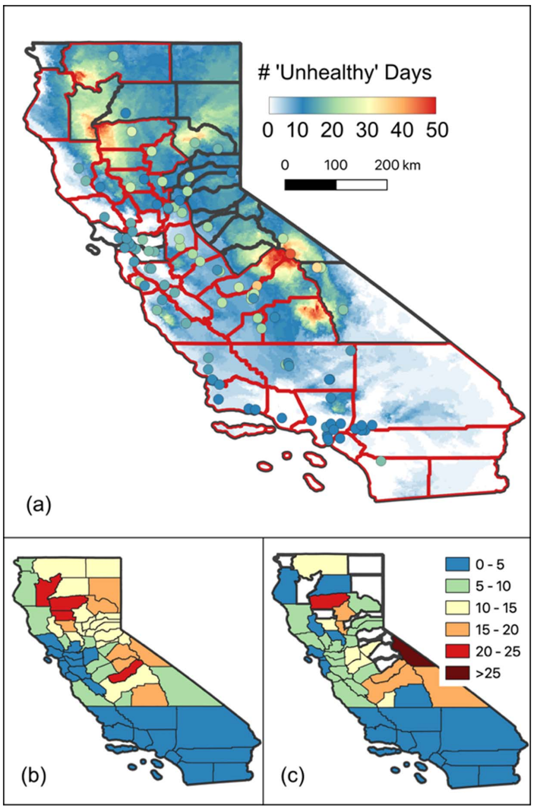

Figure 5. Number of daily exceedances over the 'Unhealthy' air quality threshold ($\geq$55.5 μg m^{-3}) from June to November 2020 (a). Ground monitoring data are represented by circles, overlaid on the HRRR-Smoke smoke-specific $PM_{2.5}$ simulations. Counties with more than 1000 agricultural workers are outlined in red. County averages of 'Unhealthy' air quality exceedances calculated by HRRR-Smoke smoke $PM_{2.5}$ (b) and EPA station total $PM_{2.5}$ (c). Counties with no station availability are shown in white.

monitors suggest Monterey County also required this level of respirators (figure S3).

4. Discussion

4.1. Summary of results

California's agricultural workers who spend most of their time working outdoors can be exposed to unhealthy to hazardous levels of smoke $PM_{2.5}$ pollution. We find that although the largest absolute increases in smoke $PM_{2.5}$ concentrations are in the northern part of the state, the Central Coast and Central Valley are highly vulnerable to future smoke exposure due to a combination of the number of agricultural workers and the climate-related increases in wildfires. Under future climate conditions, counties that have not experienced severe smoke pollution in the past may start to experience unhealthy to hazardous smoke pollution episodes, with wildfire smoke contributing 90% or more of pollution at these high pollution levels. Our case study of the 2020 fire season suggests that long-range climate projections of wildfire changes are already being experienced in agricultural regions in California.

4.2. Limitations and future work

There are several sources of uncertainty in this study that suggest areas for future work. First, we use county-level pollution estimates for past and future climate conditions. This assigns a single exposure value to the entire county, while we expect variability in smoke $PM_{2.5}$ concentrations within the counties, as demonstrated by our 2020 case study. Future work can use these modeling results to prioritize locations to install additional local air quality monitors. In addition, the statistical model used to predict future wildfire emissions under changing climate conditions does not consider recent severe wildfire seasons in the western U.S. and may therefore provide conservative estimates of future wildfire emissions.

An additional source of uncertainty relates to our estimates of the agricultural worker distribution. We do not differentiate between different types of agriculture or variations in the number of hours worked, as the available data are reported for total farm labor at the monthly scale. Therefore, our estimates are likely conservative given underreporting of seasonal, part-time, and/or undocumented workers in the California EDD statistics. It is likely that this affects all counties across the State. At the same time, if workers are exposed only five days per week and remain at home with reduced exposure for two days, our total estimates would be reduced (figure 4). There are also uncertainties regarding future mechanization trends, a potential shift towards less labor-intensive crops, and a possible increase in imported crops (Rutledge and Taylor 2019). Changes in climate that are expected to influence wildfire trends may also alter agricultural production through changes in water availability, heatwaves, crop planting and harvesting schedules, crop suitability shifts, and pests (Pathak *et al* 2018).

Finally, our study examines the potential wildfire smoke exposure and associated demand for N-95 respirators, weighted by the current distribution of agricultural workers in California. We do not, however, model agricultural labor modifications that employers and/or workers could make in response to wildfire smoke exposure. This could influence our results in several ways. First, agricultural labor can vary in response to $PM_{2.5}$ exposure (Graff Zivin and Neidell 2013). Workers could reduce their labor supply when pollution is high, or employers could shift labor allocation to lower pollution exposures. Recent surveys suggest, however, that air pollution is not currently considered to be a leading environmental health threat by agricultural workers when compared to extreme heat, for example (Wadsworth *et al* 2022) and many agricultural workers may feel the economic pressure to keep working regardless of pollution levels (Courville *et al* 2016). California's Central Valley, for example, already has some of highest baseline pollution in the country (Schweizer and Cisneros 2017), making additional smoke contributions from distant and/or less severe fires less noticeable. Less visible smoke plumes that enhance regional pollution levels could reduce the likelihood of taking protective actions. Even low to moderate levels of pollution are associated with negative health outcomes (Vodonos *et al* 2018), particularly for sensitive groups like agricultural workers. Agricultural workers also report varied knowledge of appropriate safety precautions during smoke $PM_{2.5}$ exposure events, such as considering that cloth masks provide appropriate protection (Riden *et al* 2020). Second, while we focus on potential demand for PPE in response to Section 5141.1 regulations, employers could also respond by changing worker hiring and allocation decisions. Many agricultural employers may view safety practices for smoke protection as a concern for employees themselves to address and/or express a lack of knowledge about responding appropriately (Wadsworth *et al* 2022). Future labor modifications may alter worker and employer responses in additional unanticipated ways. These are important areas for future work.

4.3. Policy implications

According to Section 5141.1, employers must communicate to workers the health effects of wildfire smoke, the right to obtain medical treatment without fear of reprisal, and how to obtain the current AQI. Employers can use one of the listed governmental websites or use their own monitor if it does not underestimate worker exposure, measures $PM_{2.5}$ concentrations, and is properly calibrated and maintained. The maximum $PM_{2.5}$ concentrations allowed by Section 5141.1, as in this study, are 24 h averages and do not reflect the peak sub-daily concentrations. The inclusion of low-cost sensors could help to increase the spatial coverage and sub-daily information. This may help to capture extreme air quality exceedances not observed by existing government monitoring stations due to limited coverage (Seto *et al* 2019). Monitoring stations, however, do not differentiate between source contributions specific from wildfires. This can create ambiguity regarding when these regulations, which apply only to smoke exposure, should go into effect, such as when a distant wildfire contributes to regional air pollution enhancements.

Even with reliable air quality monitoring information, certain strategies to reduce exposure are more challenging for agricultural workers than other members of the public. Guidance to stay indoors and avoid outdoor, strenuous activity is impractical for outdoor workers (Xu *et al* 2020). California agricultural workers who spend most of their time working outdoors are exposed to unhealthy to hazardous levels of smoke $PM_{2.5}$ pollution, often for extended time periods. More than half of these workers are undocumented and work at least 40 h work weeks (Hernandez and Gabbard 2018, National Agricultural Statistics Service 2020).

One of the responses to Section 5141.1 is the voluntary or required use of PPE such as N-95 masks (California Department of Industrial Relations 2019). The efficacy of N-95 masks for outdoor use has mixed results since mask performance in real-world conditions does not always achieve expected exposure reduction (Cherrie *et al* 2018). With proper use, N-95 respirators can reduce exposure by a factor of 14 during wildfire events (Kodros *et al* 2021), but combustion-related particles may penetrate N-95 masks more efficiently than other particle types (Gao *et al* 2015). Several of the counties highlighted in our analysis are at risk of extreme heat (Tigchelaar *et al* 2020), which could also reduce proper PPE use (Riden *et al* 2020). Finally, even if workers are able to stay home in response to extreme pollution levels, they may not be protected from substantial pollution exposure. Indoor $PM_{2.5}$ exposures can exceed air quality guidelines during wildfire events, particularly in older buildings, those without air conditioning or filtration systems, and/or areas of high socioeconomic vulnerability (Burke *et al* 2021, Liang *et al* 2021, O'Dell *et al* 2022). In addition to PPE, Section 5141.1 also provides different options for employers to reduce worker exposure, including moving work activities to structures with filtered air or lower AQI exposures, reducing time working in unfiltered air, increasing rest time or frequency, or reducing the physical intensity of work. Additional research is needed to quantify the effect of each of these actions on reducing personal exposure.

Our research suggests several potential strategies that could better protect agricultural worker health in the coming decades. First, we find several counties with many agricultural workers are at high risk of a future increase in potential smoke pollution exposure. These future projections can be used to guide targeted interventions, such as the distribution of additional air quality monitors to employers and community-based organizations. Second, to supplement spatial gaps in ground monitoring systems, counties could incorporate modeling-based forecasts of smoke pollution, such as HRRR-Smoke, to provide advance warning to workers of extreme pollution events and plan short-term adjustments in operations to better protect worker health. Third, counties could expand local alert systems to warn farmworkers of unhealthy air quality due to wildfire smoke. The Ventura County Air Pollution Control District, for example, piloted one of the first of these systems in summer 2021 (Carlson 2021). This alert system provides English and Spanish alerts to farmworkers and supervisors when the AQI reaches unhealthy levels and additional warnings if the AQI reaches hazardous levels and mask use is mandatory.

5. Conclusions

Our manuscript provides, for the first time, an examination of the potential for agricultural worker exposure to wildfire smoke with climate change. Wildfires associated with future climate change in California will increase the number of days exceeding unhealthy air quality levels. Wildfires contribute more to exceedances at extreme levels of pollution. Despite underlying vulnerabilities of outdoor agricultural workers, existing regulations go into effect only at extreme concentration thresholds but do not at moderate levels of pollution. As wildfire smoke exposure patterns shift with climate change, these protections may need to be strengthened to better protect agricultural worker health. Additional capacity to monitor $PM_{2.5}$ during wildfire events will provide workers and employers with more accurate information to guide decision-making.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We thank June Spector, Allysa Miller, Elena Austin, Edward Kasner, and Amir Jina for helpful discussions regarding this work. This publication was supported by the Pilot Project Research Training Program of the Southern California NIOSH Education and Research Center (SCERC), Grant Agreement Number T42 OH008412 from the Centers for Disease Control and Prevention (CDC). Its contents are solely the responsibility of the authors and do not necessarily represent the official view of CDC. This project was also supported by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (CDC-NIOSH) Cooperative Agreement #U54 OH007550. Finally, we acknowledge support from Assistance Agreement 83587201 awarded by the U.S. Environmental Protection Agency (EPA). The paper has not been formally reviewed by the EPA. The views expressed in this paper are solely those of the authors and do not necessarily reflect those of the EPA.

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