AGU ADVANCING EARTH AND SPACE SCIENCES

GeoHealth

RESEARCH ARTICLE
10.1029/2024GH001033

Special Collection:
Geospatial data applications for environmental justice

Key Points:

- The Agricultural Pass program challenges the safety of migrant farmworkers during extreme wildfires
- Regional variabilities in air quality emphasize the importance of localized measurements
- The use of local low-cost sensor data with recommended filtering and smoke correction, enhances health and safety air quality monitoring

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
C. A. Chunga Pizarro,
cchungap@uci.edu

Citation:
Chunga Pizarro, C. A., Buchholz, R. R., Hornbrook, R. S., Christensen, K., & Méndez, M. (2024). Air quality monitoring and the safety of farmworkers in wildfire mandatory evacuation zones. *GeoHealth*, *8*, e2024GH001033. https://doi.org/10.1029/2024GH001033

Received 17 FEB 2024
Accepted 24 JUN 2024

Author Contributions:
Conceptualization: Carlo A. Chunga Pizarro, Kevin Christensen, Michael Méndez
Data curation: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook
Formal analysis: Rebecca R. Buchholz, Rebecca S. Hornbrook, Michael Méndez
Funding acquisition: Michael Méndez
Investigation: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca

Air Quality Monitoring and the Safety of Farmworkers in Wildfire Mandatory Evacuation Zones

Carlo A. Chunga Pizarro[1], Rebecca R. Buchholz[2], Rebecca S. Hornbrook[2], Kevin Christensen[3], and Michael Méndez[1]

[1]University of California Irvine, Irvine, CA, USA, [2]Atmospheric Chemistry Observations & Modeling Laboratory, NSF National Center for Atmospheric Research, Boulder, CO, USA, [3]Independent Researcher

Abstract The increasing frequency and severity of wildfires due to climate change pose health risks to migrant farm workers laboring in wildfire-prone regions. This study focuses on Sonoma County, California, investigating the effectiveness of air monitoring and safety protections for farmworkers. The analysis employs AirNow and PurpleAir $PM_{2.5}$ data acquired during the 2020 wildfire season, comparing spatial variability in air pollution. Results show significant differences between the single Sonoma County AirNow station data and the PurpleAir data in the regions directly impacted by wildfire smoke. Three distinct wildfire pollution episodes with elevated $PM_{2.5}$ levels are identified to examine the regional variations. This study also examines the system used to exempt farmworkers from wildfire mandatory evacuation orders, finding incomplete information, ad hoc decision-making, and scant enforcement. In response, we make policy recommendations that include stricter requirements for employers, real-time air quality monitoring, post-exposure health screenings, and hazard pay. Our findings underscore the need for significant consideration of localized air quality readings and the importance of equitable disaster policies for protecting the health of farmworkers (particularly those who are undocumented migrants) in the face of escalating wildfire risks.

Plain Language Summary In Sonoma County, California, wildfires and wildfire smoke are becoming more frequent and severe due to climate change. This study looks at how wildfire smoke could impact farmworkers, who often work outdoors. By comparing data from different air quality monitors during the 2020 Sonoma County wildfires, we found that farmworkers are exposed to high pollution levels, with some monitors showing more pollution than others. We also found that the system for deciding when farmworkers should labor during wildfires needs to be more consistent and adequately protect their health. Based on our findings, we recommend better air quality monitoring, improved policies to protect farmworkers during wildfires, and more support for those affected by the pollution. This research highlights the need to prioritize the health and safety of farmworkers, especially as wildfires become more common.

1. Introduction

Wildfire frequency and intensity, as well as the impacts of wildfire smoke, are predicted to increase with global warming and drier conditions in the future (O'Dell et al., 2019; Westerling & Bryant, 2008). The southwestern United States exemplifies this trend (Bedsworth et al., 2018; Ford et al., 2018; Williams et al., 2019). In 2020, California experienced an unprecedented number of wildfires, with 44% (22 fires) of the 50 largest fires in the U. S. occurring in the state (Albores et al., 2023; Keeley & Syphard, 2021; National Interagency Coordination Center, 2020). The disastrous wildfire season exposed more than half of California's population to the highest number of severe air pollution days in the state's recorded history (Safford et al., 2022). The California Fourth Climate Assessment report projects that the state's wildfire burn area may increase 77% by the end of the century (Bedsworth et al., 2018). The likelihood of numerous climate-related hazardous events, such as extreme heat, occurring simultaneously has increased in the state (Rosenthal et al., 2022). These conditions often lead to fire ignition, as high temperatures predispose fuels to burn (Goss et al., 2020). This not only exacerbates existing issues faced by marginalized populations but also creates new, disproportionate health effects (Phillips et al., 2020).

Extreme wildfire events and environmental justice concerns intersect in Northern California's Sonoma County. The county has experienced severe air pollution and loss of life and property from wildfires, particularly during periods of drought and extreme heat (Marlier et al., 2022). Moreover, Sonoma's economy heavily relies on livestock, agriculture, and the region's award-winning wine. The winegrape sector alone employs more than 70%

S. Hornbrook, Kevin Christensen, Michael Méndez
Methodology: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook, Kevin Christensen, Michael Méndez
Project administration: Carlo A. Chunga Pizarro
Resources: Rebecca R. Buchholz, Rebecca S. Hornbrook, Kevin Christensen, Michael Méndez
Software: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook
Supervision: Michael Méndez
Validation: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook, Michael Méndez
Visualization: Carlo A. Chunga Pizarro, Rebecca S. Hornbrook, Michael Méndez
Writing – original draft: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook, Michael Méndez
Writing – review & editing: Carlo A. Chunga Pizarro, Rebecca R. Buchholz, Rebecca S. Hornbrook, Michael Méndez

(or 8,500) of the laborers in the county (Smith, 2021). However, the total number of farmworkers may be significantly undercounted due to the large undocumented workforce, which often avoids interaction with governmental representatives for fear of deportation (Fazel-Zarandi et al., 2018).

Wildfires prompted Sonoma County's businesses and government to prioritize the wine industry by advocating for initiatives that may put farmworkers' lives at risk. In 2017, Sonoma County adopted an Ag (Agricultural) Pass program, issuing temporary permits allowing farmworkers to enter mandatory evacuation zones during wildfires, in conditions considered hazardous to the general population, to continue essential labor including harvesting crops. Note that permitted activities have been modified several times since 2017, but currently and in 2020, they include crop harvesting. A recent policy analysis estimated that hundreds of farmworkers, the majority of whom are undocumented migrants, entered hazardous zones with little governmental oversight (Méndez & Chunga Pizarro, 2022). Since their ad hoc adoption, Ag Pass permits have been used during various fire events, including the Glass Fire and LNU Lightning Complex fires in 2020. Given the program's lack of oversight, inconsistencies with state-level emergency protocols, and insufficient monitoring of hazardous air quality in the impacted regions, there is a need to further analyze the risks, health impacts, and structural inequalities the program imposes on farmworkers, in particular those who are undocumented (Méndez, 2022).

The effects of wildfire smoke on health include eye irritation, heart and respiratory conditions such as chest pain or excessive breathlessness often preceding cardiac events, and increased fatigue (Aguilera et al., 2021; Finlay et al., 2012; Youssouf et al., 2014). A significant component of wildfire smoke, $PM_{2.5}$ (particulate matter 2.5 μm and smaller in diameter) is strongly associated with acute respiratory effects, and long-term exposure is linked to higher mortality rates (Black et al., 2017; Hart et al., 2015; Henderson et al., 2011; Reid et al., 2016; Vos et al., 2020). Intensifying wildfires during harvest season poses a significant threat to outdoor agricultural workers' health, primarily due to exposure to $PM_{2.5}$. Many agricultural workers have underlying health risks, lower socioeconomic status, and reduced access to health care (Riden et al., 2020). Undocumented agricultural farmworkers often face a high risk of wildfire smoke exposure, and are particularly vulnerable to environmental hazards (Méndez et al., 2020; Smolski, 2019). Their pre-disaster marginalized status is influenced by an array of factors, including limited English proficiency, lack of health and unemployment insurance, racial discrimination, and labor exploitation (Fazel-Zarandi et al., 2018; Mollenkopf & Pastor, 2016; Nixon, 2011). In particular, Indigenous Mexican people in Sonoma County are culturally and linguistically isolated. Many are illiterate, and some speak neither Spanish nor English, but only their native languages, such as Mixteco, Triqui, Maya, and Chatino. These realities often impede their ability to negotiate with their employers to improve their work situation and exercise their basic civil rights (Méndez, 2022). Previous research has shown how undocumented Latino/a and Indigenous farmworkers are excluded from disaster planning and response (Méndez et al., 2020). Despite concern expressed by agricultural farmworkers about poor air quality from wildfire smoke, employers typically do not develop protocols to manage workers in these conditions (Riden et al., 2020). The increasing frequency and severity of wildfires, resulting from both climate change and human-caused factors (i.e., fires started intentionally or accidently), have exacerbated the dangers faced by farmworkers, raising their exposure to hazardous wildfire smoke, and heightening impacts on their health.

Through advocacy by migrant and labor rights groups, in 2019 the California Occupational Safety and Health Standards Board (Cal/OSHA) adopted an emergency regulation (CCR § 5141.1) requiring employers of outdoor workers to provide respiratory masks when the Air Quality Index (AQI) due to $PM_{2.5}$ exceeds 150 (i.e., $PM_{2.5} > 55.5$ μg m^{-3}) for more than 1 hr (Department of Industrial Relations, State of California, 2019). It is important to note that the Sonoma Board of Supervisors staff reports that Cal/OSHA regulations, like Smoke Rule 5141.1, govern workers protections in Sonoma County (Sonoma County Board of Supervisors Ad Hoc Committee on Evacuation Zone Access, 2022). An AQI level greater than 150 corresponds to the United States Environmental Protection Agency (US EPA) health hazard level "Unhealthy" (US EPA, 1999). Research has shown the need for improvement and standardization in these systems: the requirement for N95 masks is implemented and enforced unevenly, employers who request Ag Passes are not required to establish emergency disaster plans, and air quality monitoring is inadequate (Méndez, 2022; Cal/OSHA, 2019). Employers, moreover, are advised to monitor the AQI for $PM_{2.5}$ using websites that rely almost entirely on the EPA network of AirNow monitors (U.S. Environmental Protection Agency, n.d.). In Sonoma County, the sole AirNow $PM_{2.5}$ monitor is in Sebastopol, where conditions may not be representative of the air quality at individual job sites throughout the county. For these reasons, we explore the use of the low-cost PurpleAir monitor network, which collects and shares $PM_{2.5}$ data for public use. The number of PurpleAir monitors brought online in wildfire-prone regions has increased rapidly in recent years, likely as a direct result of residents' growing concern over worsening air quality (Liang et al., 2021). California and the Sonoma County region have the highest adoption of the technology in the country (Liang et al., 2021). In this study, we compare $PM_{2.5}$ data from the network of PurpleAir monitors and data from the EPA AirNow monitor in Sonoma County during the 2020 wildfire season. We focus our analysis on two specific wildfire events, the Glass Fire and the LNU Lightning Complex fires. We also point out the safety implications of poor record-keeping and haphazard decision-making in the Ag Pass system and offer policy recommendations based on our findings and related best practices.

2. Materials and Methods

2.1. Agricultural Pass Records

We filed a public records request, administered and authorized by the Sonoma County Department of Agriculture/Weights & Measures, and received Ag Pass permit applications issued for 2020. We acquired both electronic copies of original applications and Excel spreadsheet versions of the permits.

After reviewing the permits, we exclusively mapped permits whose original application was consistent with information in the Excel database. We excluded permits lacking a hardcopy application that were not endorsed by the Sonoma County Agricultural Board of Supervisors. The lack of complete worksite locations in the Excel database introduced spatial inaccuracies during the data cleaning and mapping analysis. In assessing inaccuracies, we employed a perfect match yield score as a metric, flagging any score falling below 85 (Ratcliffe, 2004). A subsequent review session was conducted to determine the presence of inaccuracies in the addresses. We used the ArcGIS Geocode tool to visualize worksites to precise coordinates for mapping purposes. For the LNU Lightning Complex fires, a total of 370 permits were mapped, yielding 590 distinct worksites and 1,603 workers. The Glass Fire yielded 96 applications, 120 worksites, and 633 workers. Additionally, it is important to note that the actual number of workers for each permit is unreliable because of mismatches between permits and the absence of worker counts on some permits (Méndez & Chunga Pizarro, 2022).

2.2. AirNow $PM_{2.5}$ Data

The Sebastopol EPA AirNow station employs a Met One BAM-1020 mass monitor with VSCC - Beta Attenuation for $PM_{2.5}$ measurement. We downloaded hourly $PM_{2.5}$ observations from the Sebastopol AirNow site for the time period 31 July–6 November 2020 from [https://aqs.epa.gov/data/api]. We calculated daily average $PM_{2.5}$ values, 24-hr $PM_{2.5}$, filtering for data with sufficient daily data coverage (i.e., ≥90% or at least 22 out of 24 possible data points available for each PST calendar day.)

2.3. PurpleAir $PM_{2.5}$ Data

We downloaded raw (2-min) PurpleAir data for the time period 31 July–6 November 2020 for all monitors located within Sonoma County for free using the ThingSpeak API interface [https://api.thingspeak.com, downloaded July 2022]. We note that the API access for PurpleAir data changed dramatically in January 2023 and now requires using the site https://api.purpleair.com for data older than 72 hr.

Each PurpleAir monitor has two sensors: sensor A and sensor B. Every 2 minutes, active PurpleAir monitors connected to the database record and report several parameters including relative humidity (RH), and two internally calculated ambient $PM_{2.5}$ values for each sensor, $PM_{2.5,cf=1}$_A, $PM_{2.5,cf=1}$_B, in μg m^{-3}, referred to now as $PM_{2.5}$_A and $PM_{2.5}$_B. We filtered these raw 2-min data for adequate hourly data coverage, that is, ≥90% coverage or at least 27 out of 30 possible data points available for each hour. We then determined hourly averages of $PM_{2.5}$_A, $PM_{2.5}$_ B = hourly $PM_{2.5}$_A and hourly $PM_{2.5}$_B, respectively, as well as hourly averaged RH. Note that instrument down time combined with filtering 2-min data for ≥90% coverage resulted in a loss of 20% of the potential raw hourly data.

Next, we filtered the PurpleAir data to remove hourly $PM_{2.5}$ values for which the agreement between the A and B sensors was poor, as this indicated unreliable or erroneous data. Specifically, hourly $PM_{2.5}$ data were removed where the following were both true:

$$|\text{hourly } PM_{2.5}\_A - \text{hourly } PM_{2.5}\_B| > 5\ \mu g\ m^{-3} \quad (1)$$

$$|\text{hourly PM}_{2.5}\text{\_A} - \text{hourly PM}_{2.5}\text{\_B}| / \left[\left(\text{hourly PM}_{2.5}\text{\_A} + \text{hourly PM}_{2.5}\text{\_B}\right)/2\right] > 0.7. \quad (2)$$

Equation 1 requires the absolute difference between the hourly averages from each sensor to be more than 5 μg m^{-3} and Equation 2 requires the absolute difference between the hourly averages divided by the mean of the hourly averages to be greater than 70%. For hours when both Equation 1 and Equation 2 are true, the hourly data were removed from the data set. This filtering step resulted in an additional loss of 2.7% of the available hourly data. Next, we applied the EPA-recommended smoke correction (Barkjohn et al., 2022) to the mean of the hourly averages using the following:

$$\text{PM}_{2.5,\text{corr}} = 0.534 \times \left(\left[\left(\text{hourly PM}_{2.5}\text{\_A} + \text{hourly PM}_{2.5}\text{\_B}\right)/2\right]\right) - 0.0844 \times \text{RH} + 5.604, \quad (3)$$

where $PM_{2.5,corr}$ is the corrected hourly $PM_{2.5}$ in μg m^{-3} for a given PurpleAir monitor with hourly averaged RH (i.e., the hourly RH in % with values between 0 and 100). Finally, we calculated 24-hr $PM_{2.5}$, filtering for data with sufficient daily data coverage (i.e., ≥90% or at least 22 out of 24 possible data points available for each PST calendar day). This final filtering step resulted in a further 9.8% loss of the hourly data. Using the above criteria, we retrieved and corrected $PM_{2.5}$ data from 359 PurpleAir monitors in Sonoma County during the study period with sufficient hourly and 24-hr data coverage.

2.4. Wildfire Pollution Episodes

We identified three wildfire pollution event periods in the Sonoma County $PM_{2.5}$ data, (a) LNU1 (0:00 PST 19 August to 23:59 PST 31 August), (b) LNU2 (00:00 PST 8 September to 23:59 PST 15 September), and (c) GLASS (00:00 PST 27 September to 23:59 PST 5 October). The time periods were selected using the criteria that they contained consecutive calendar days in which either the AirNow $PM_{2.5}$ data or the regional PA_{LNU} or PA_{GLA} $PM_{2.5}$ + standard deviation is ≥30 μg m^{-3}, which is double the WMO guideline for daily $PM_{2.5}$ levels and is sufficiently above the background levels of $PM_{2.5}$ for the county, while still capturing the edges of the events. We show a zoomed-in view of the hourly $\mathbf{PM_{2.5}}$ for these time periods in Figure S1 in Supporting Information S1. For each of the wildfire pollution episodes, we determined daytime maximum hourly $\mathbf{PM_{2.5}}$ for the times 08:00–19:59 (PST), and nighttime maximum hourly $\mathbf{PM_{2.5}}$ for the times between 20:00–07:59 (PST +1 day), requiring at least 10 out of 12 possible data points for each time period using the data from the AirNow monitor and the aggregated PurpleAir data for different regions in Sonoma County. The mean and standard deviations of the daytime and nighttime maximum hourly $\mathbf{PM_{2.5}}$ data for each of the three wildfire pollution events are listed in Tables S1 and S2 in Supporting Information S1, respectively.

3. Results and Discussion

3.1. Sonoma County $PM_{2.5}$ During the 2020 Fire Season

We investigate the 2020 wildland fire season in Sonoma County using $PM_{2.5}$ data from the AirNow monitor in Sebastopol, CA (38.4038°N, 122.8183°W), and smoke-corrected $PM_{2.5}$ data from aggregated PurpleAir monitors in Sonoma County (PA_{SON}) during the same time period. It has been shown previously that raw PurpleAir $PM_{2.5}$ data are biased high in comparison to AirNow $PM_{2.5}$ in wildfire smoke (Barkjohn et al., 2022). We use the correction recommended by the EPA in Barkjohn et al. for our smoke-impacted data. Details on the smoke correction and data coverage criteria for hourly $PM_{2.5}$ and 24-hr $PM_{2.5}$ averages are described in Section 2.

During our study period from 31 July–6 November 2020, Sebastopol was the sole operational AirNow station within Sonoma County monitoring $PM_{2.5}$. During the same period, there were 359 PurpleAir monitors reporting $PM_{2.5}$ in the county (Figure 1, Table 1). Figure 1 shows a map of Sonoma County with the location of the EPA AirNow monitor at Sebastopol, the locations of the active PurpleAir monitors that we used in this study, and the fire perimeters of the LNU Complex and Glass Fire. Figure 1 also includes the perimeters for the aggregated PurpleAir monitors in the Sebastopol region (PA_{SEB}), LNU Complex Ag Pass region (PA_{LNU}), and Glass Fire Ag Pass region (PA_{GLA}). Note that the latter two aggregation regions were identified to encompass locations where the majority of the Ag Passes were issued for each fire. The intent was not to generate an ideal data set, but rather to define general regions that are representative of the Ag Pass area to compare to the PA data obtained close to the regulatory monitor. Figure 2 shows the temporal evolution of the 24-hr average $PM_{2.5}$ values measured at

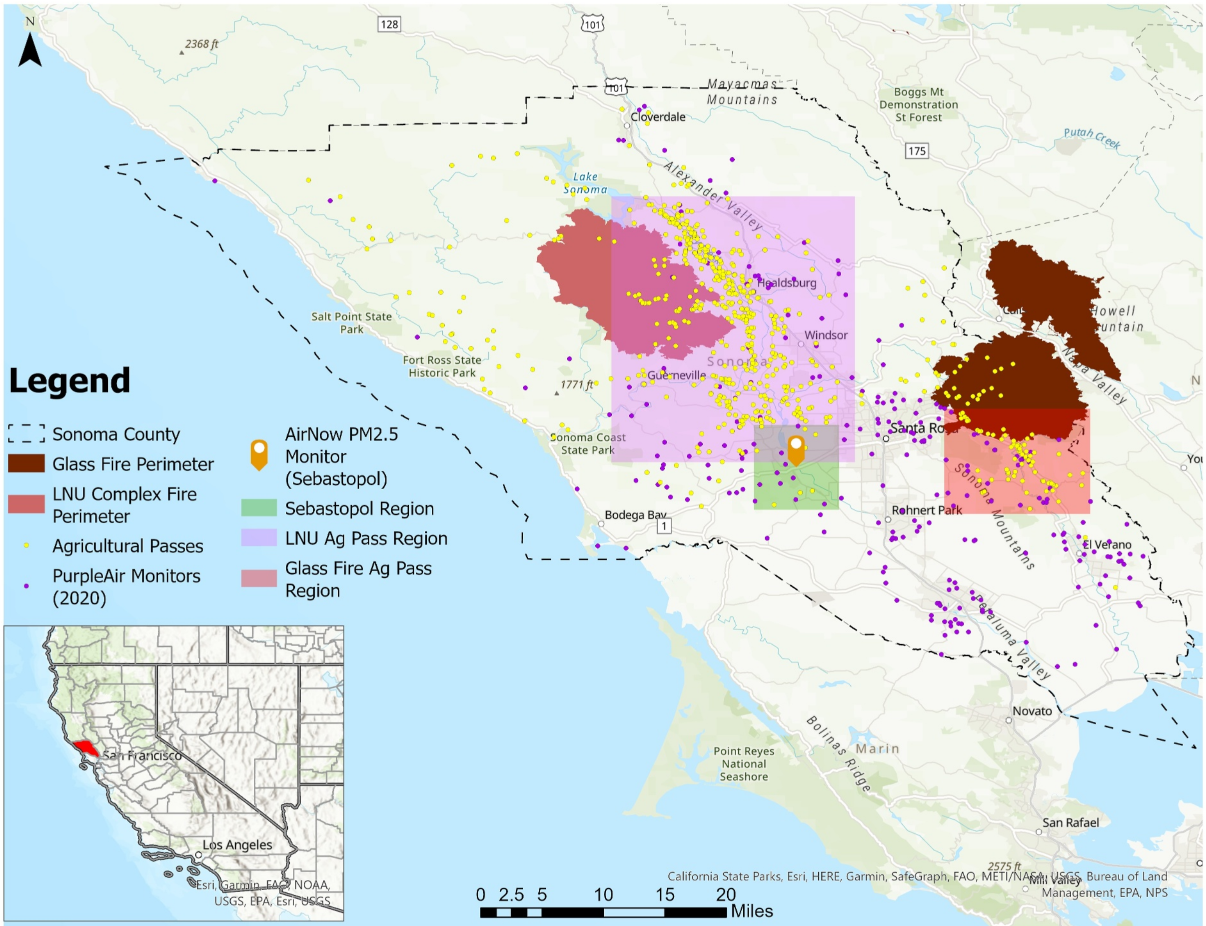

Figure 1. Map of the Sonoma County region, showing the perimeter of the county, the location of the EPA AirNow monitor at Sebastopol, PurpleAir monitors, the LNU Complex and Glass Fire perimeters, and the locations of the Agricultural Passes issued in response to the LNU Complex and Glass Fires. The three shaded boxes show the regions in which PurpleAir monitors are included in the statistics for the LNU Complex Agricultural Pass region (purple), the Glass Fire Agricultural Pass Region (red), and the Sebastopol Region (green). The inset shows the location of Sonoma County in California.

Sebastopol by the AirNow monitor and the county-wide averaged PurpleAir $PM_{2.5}$ data during the study period. Table 1 defines the study regions and summarizes the $PM_{2.5}$ statistics for the AirNow and the aggregated county-wide and regional PurpleAir data for the regions shown in Figure 1 for the entire study period.

During the study period, 24-hr $PM_{2.5}$ values exceeded the World Health Organization (WHO) health guideline (i.e., >15 μg m^{-3}) (World Health Organization, 2021) on 18 days according to the AirNow data, and on 34 days according to the aggregated county-wide PurpleAir data. The hourly $PM_{2.5}$ values exceeded the EPA thresholds for Unhealthy for Sensitive Groups (>35.5 μg m^{-3}) and Unhealthy (>55.5 μg m^{-3}) on 21 and 13 calendar days, respectively, using the AirNow data, and on 27 and 16 calendar days, respectively, using the county-wide average PurpleAir monitors.

To determine whether the differences between the AirNow and county-wide averaged PurpleAir $PM_{2.5}$ statistics are due to differences generated by the smoke-correction or are caused by regional air quality differences within the county, we evaluate the PurpleAir monitors in the vicinity of the AirNow monitor (i.e., PA_{SEB}). We compare hourly $PM_{2.5}$ from the AirNow monitor with hourly averaged smoke-corrected $PM_{2.5}$ data from 11 PurpleAir monitors located near the AirNow monitor, defined as within ±0.05° latitude and longitude of the Sebastopol station, shown by the green shaded box in Figure 1. The colocation boundaries were chosen as a compromise between sufficient PurpleAir data for robust statistical analysis, and the representation of equivalent air mass sampling. Figure 3 shows a time series of the AirNow hourly $PM_{2.5}$ and PA_{SEB} hourly $PM_{2.5}$ for our study period, as well as a correlation plot for the two data sets. The standard deviation in the PA_{SEB} hourly $PM_{2.5}$ data, shown as

Table 1
Study Regions and $PM_{2.5}$ Statistics During the Study Period 31 July–6 November 2020

	AirNow[a]	PurpleAir[b]			
Location/Region	Sebastopol	Sonoma County	Sebastopol Region	LNU AgPass Region	Glass AgPass Region
Bounds (Latitude, Longitude)	38.404°N, 122.818°W	N/A[c]	38.354–38.454°N, 122.868–122.768°W	38.410–38.723°N, 122.036–122.749°W	38.349–38.473°N, 122.472–122.644°W
No. of $PM_{2.5}$ monitors	1	359	11	52	28
Mean 24-hr $PM_{2.5}$, μg m^{-3}	14.5	15.4	12.7	14.1	18.9
24-hr $PM_{2.5}$ 98th percentile, μg m^{-3}	86.1	83.5	64.1	60.5	108.9
No. of days 24-hr[d] $PM_{2.5} > 15$ μg m^{-3}	18	34	21	29	34
No. of days 24-hr $PM_{2.5} > 35.5$ μg m^{-3}	7	7	7	7	13
No. of days 24-hr $PM_{2.5} > 55.5$ μg m^{-3}	6	5	3	3	7
No. of days hourly $PM_{2.5}$ exceeded 35.5 μg m^{-3}	21	27	14	22	28
No. of days hourly $PM_{2.5}$ exceeded 55.5 μg m^{-3}	13	16	10	16	18

[a]AirNow monitor information is in italics. [b]PurpleAir data that has been filtered and smoke-corrected, as described in Section 2.3. [c]Sonoma County is bounded by the county borders, not by latitude and longitude. [d]24-hr $PM_{2.5}$ is the mean of hourly average $PM_{2.5}$ as described in Section 2.3.

green shading in Figure 3a, demonstrates that the agreement between the PurpleAir monitors within the Sebastopol colocation region is excellent with the (up to) 11 monitors measuring relatively consistent $PM_{2.5}$ values, even during the wildfire events. The average standard deviation of the PA_{SEB} hourly $PM_{2.5}$ values over the

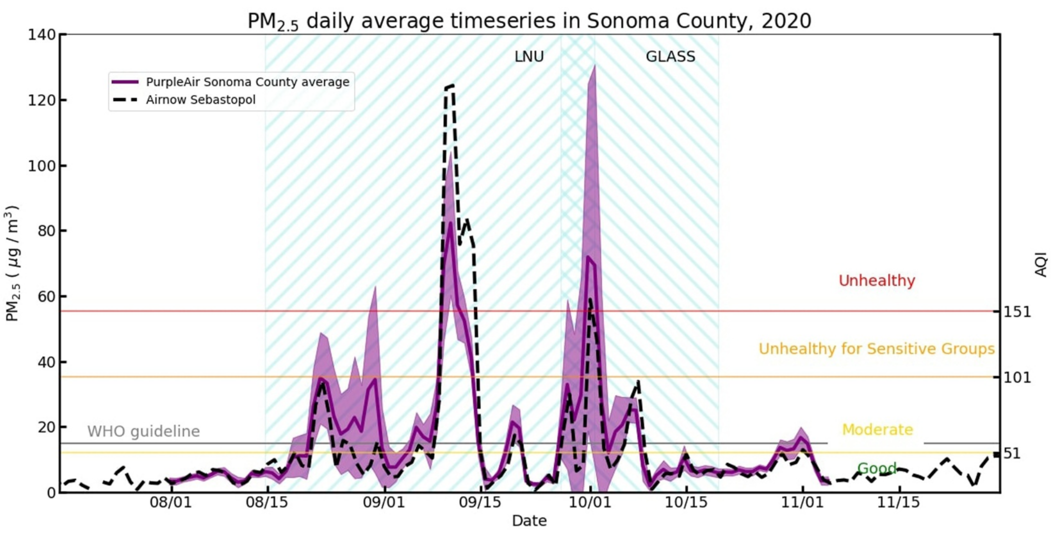

Figure 2. Time series of 24-hr $PM_{2.5}$ values from the Sebastopol AirNow monitor (black, dashed), and the 24-hr county-wide average of smoke-corrected PurpleAir $PM_{2.5}$ in the Sonoma County region (purple), with spatial standard deviation (shaded purple). The World Health Organization (WHO) 24-hr air quality guideline level for $PM_{2.5}$ for minimizing the global burden of disease associated with air pollution, 15 μg m^{-3} (World Health Organization, 2021) and the EPA thresholds for health impacts (US EPA, 1999) are shown as horizontal lines. Time periods of the two largest fire complexes (LNU and Glass) are denoted in light blue hatched shading.

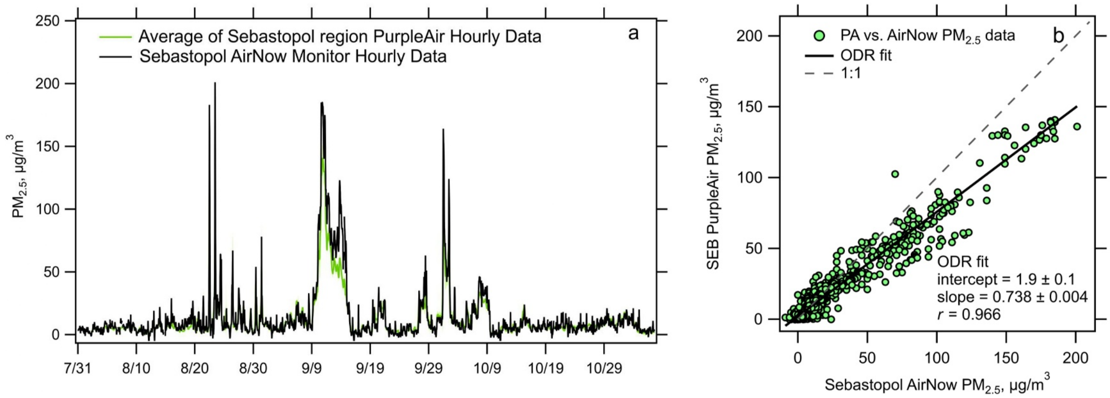

Figure 3. (a) Time series for the 31 July–6 November 2020 wildland fire season hourly $PM_{2.5}$ data from the Sebastopol AirNow station (black) and hourly averaged measurements averaged from 11 PurpleAir monitors located within ±0.05° latitude and longitude of Sebastopol (SEB; green), with the standard deviation of the PurpleAir monitors shown in green shading, and (b) a correlation plot of the average PurpleAir hourly $PM_{2.5}$ data against the SEB hourly $PM_{2.5}$ data, showing orthogonal distance regression (ODR; solid black line), 1:1 line (dashed line), and Pearson correlation coefficient ($r = 0.966$). Note that in panel (a), where the agreement is very good, the PurpleAir average hourly data (green) is not visible behind the Sebastopol AirNow data (black).

study period is 2.2 μg m^{-3}, and the average relative standard deviation for PA_{SEB} hourly $PM_{2.5}$ values greater than 5 μg m^{-3} is 18%.

During the study period, the PA_{SEB} is in good agreement with the Sebastopol AirNow data, with the PA_{SEB} hourly $PM_{2.5}$, on average, within 4.4 ± 7.6 μg m^{-3} (absolute difference mean ± standard deviation) of the AirNow hourly $PM_{2.5}$, with an average percent difference, that is, $[PA_{SEB} - \text{AirNow}]/[\text{AirNow}] \times 100\% = 28 \pm 22\%$ for AirNow $PM_{2.5}$ values > 5 μg m^{-3}. The correlation plot of PA_{SEB} hourly $PM_{2.5}$ versus hourly AirNow $PM_{2.5}$ (Figure 3b) indicates good correlation across the range of values observed, with a Pearson correlation coefficient $r = 0.966$. The correlation in Figure 3b has a slope of 0.738 ± 0.004, indicating that the EPA-recommended smoke correction applied to the raw PurpleAir data resulted in overcorrected values when compared to the Sebastopol AirNow monitor. Consequently, we determine that our conclusions drawn with aggregated PurpleAir $PM_{2.5}$ data are likely an underestimate of the true $PM_{2.5}$ concentrations. Despite this overcorrection, the comparison of the PurpleAir monitors closest to the Sebastopol $PM_{2.5}$ monitor supports the fact that standard deviation in the county-wide average PurpleAir data in Figure 2 reflects the true spatial variability in $PM_{2.5}$ values within Sonoma County during the study period. Our evaluation of the PurpleAir $PM_{2.5}$ data in the Sebastopol colocation region confirms that we can confidently use aggregated data from local PurpleAir monitors to investigate $PM_{2.5}$ and air quality associated with wildfire smoke in Sonoma County with the consideration that the PurpleAir $PM_{2.5}$ values are, on average, approximately 28% lower than the EPA-calibrated monitor.

3.2. Regional Air Quality Impacts of Sonoma County Wildfire Smoke on Farmworkers

To further understand the local impact of the 2020 wildland fires on farmworkers in Sonoma County, we refine our investigation to the regions where farmworkers were actively working, namely the agricultural pass exception regions. Records of permits and associated applications provided the locations of worksites for specific passes, as well as the names and number of people associated with each pass, the date, time, access point, address of the location of the critical agricultural function, and type of agricultural activity conducted during the wildfire. Our examination of these records revealed an ad hoc approval process, lacking established protocols or clearly defined standards as described in the application form. A number of discrepancies within individual applications were also identified. Specifically, an Excel database containing permit records listed supplementary worksite addresses that were absent in the original documents. The approval status of the additional addresses is uncertain, as the reasons for their inclusion are unknown. A number of applications listed multiple worksites (ranging from 2 to 50) but failed to provide the corresponding number of workers at each site. Moreover, applications with multiple addresses did not clarify whether workers were dispersed across each worksite or assigned to specific sites. The application form requested detailed worksite locations, but many applications only provided a street name and/or a city name without further elaboration. Our approach to mapping, given this incomplete information, is described in Section 2.1.

10.1029/2024GH001033

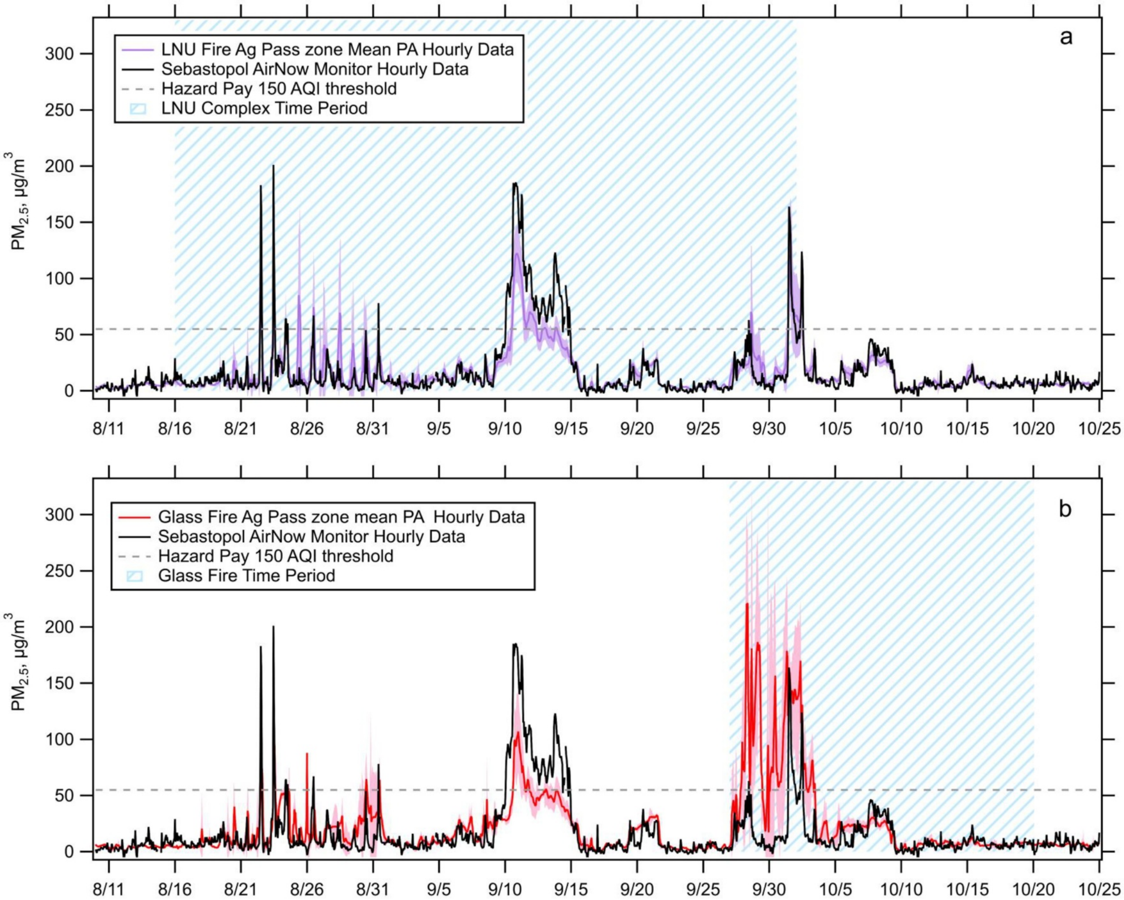

Figure 4. Time series of hourly $PM_{2.5}$ observed at the AirNow station at Sebastopol (black) and mean hourly $PM_{2.5}$ data from the PurpleAir monitors within the areas that agricultural workers received exceptions to work during (a) the LNU Fire (purple) and (b) the Glass Fire (red), using the regions shown in Figure 1 and defined in Table 1. The shading on the PurpleAir data shows the standard deviation in the data from the PurpleAir sensors within each region.

The locations of the Ag Passes issued during the LNU Complex and the Glass Fire are shown in Figure 1. These Ag Passes are clustered in two regions, for which we identify latitude and longitude boundaries (listed in Table 1), namely the LNU Complex region and the Glass Fire region. During our study period, 52 PurpleAir monitors reported data in the LNU Complex region (PA_{LNU}), and 28 PurpleAir monitors reported data in the Glass Fire region (PA_{GLA}). Figure 4 shows the hourly AirNow $PM_{2.5}$ observed at Sebastopol compared to the mean of the hourly PurpleAir $PM_{2.5}$ within the two Ag Pass regions. While there are many correlations between the data sets, there are some key differences between the AirNow $PM_{2.5}$ and the local aggregates of PurpleAir $PM_{2.5}$ data in the vicinity of the Ag Passes. Specifically, in Figure 4a, which shows the mean hourly PurpleAir data from the LNU Complex Ag Pass region, between 19 August and 1 September 2020, the mean hourly PurpleAir data in the region, PA_{LNU}, exceeded the 55.5 μg m^{-3} (AQI 150) threshold on 25 and 28 August, while the hourly AirNow data remained well below 30 μg m^{-3}. As well, the LNU region PurpleAir data demonstrated significantly more variability with the hourly mean +standard deviation (purple shading) reaching the 55 μg m^{-3} threshold every day between 21 August and 30 August 2020. Likewise, in Figure 4b, which shows the comparison of the mean hourly PurpleAir PM2.5 in the Glass Fire region and the AirNow hourly data, we see significant variability in the 28 PurpleAir monitors (red shading) during the Glass Fire time period from 27 September through 3 October. During this time the mean hourly PurpleAir $PM_{2.5}$ from the Glass Fire Ag Pass region far exceeds that from the AirNow station in Sebastopol.

Figures 2–4 show three significant wildfire pollution episodes with elevated $PM_{2.5}$ in Sonoma County. We defined the beginning and end dates and times for these three periods of interest in Section 2.4 (LNU1, LNU2 and GLASS), and evaluate the AirNow and PurpleAir $PM_{2.5}$ data statistics within each study region. For each wildfire

Table 2

Mean ± Standard Deviation of Hourly $PM_{2.5}$ During the Three Wildfire Pollution Episodes From the Sebastopol AirNow Monitor and the Aggregated PurpleAir Data for Different Study Regions in Sonoma County

	EPA	PurpleAir			
Time period	AirNow, μg m^{-3}	Sonoma county, μg m^{-3}	Sebastopol region, μg m^{-3}	LNU AgPass region, μg m^{-3}	Glass AgPass region, μg m^{-3}
1 LNU1 0:00 19 Aug–23:59 31 Aug	14.5 ± 22.7	22.1 ± 14.5 (N = 123)[a]	13.6 ± 17.6 (N = 5)	19.4 ± 19.0 (N = 20)	21.8 ± 17.4 (N = 11)
2 LNU2 0:00 8 Sep–23:59 15 Sep	66.7 ± 48.3	45.1 ± 27.3 (N = 173)	48.8 ± 35.7 (N = 6)	43.0 ± 28.6 (N = 26)	41.4 ± 21.4 (N = 19)
3 GLASS 0:00 27 Sep–23:59 5 Oct	22.0 ± 27.9	33.5 ± 24.0 (N = 263)	20.3 ± 20.4 (N = 8)	26.0 ± 23.2 (N = 43)	73.0 ± 55.2 (N = 23)

[a]N is the number of PurpleAir monitors with data included in reported mean.

pollution event, we determine the mean hourly $PM_{2.5}$, the mean daytime and nighttime maximum hourly $PM_{2.5}$ values, and the number of days where hourly $PM_{2.5}$ levels exceeded Unhealthy levels of 55.5 μg m^{-3} (or $55.5 \times 0.738 = 41.0$ μg m^{-3} for PurpleAir measurements, to account for the overcorrection of the PurpleAir data). These statistics are collected in Tables 2 and 3, Tables S1 and S2 in Supporting Information S1. Interestingly, we note that for all aggregates, the numbers of active PurpleAir monitors reporting data increased during each subsequent wildfire pollution event, which demonstrates the community's collective growing interest in monitoring local pollution conditions over this period of intense wildfire impact.

In Table 2 we see good agreement between the AirNow and mean PA_{SEB} $PM_{2.5}$ during the LNU1 pollution event, and slightly higher but not statistically different means for PA data from the entire county, PA_{LNU}, and PA_{GLA}. For the LNU2 event, the mean $PM_{2.5}$ from all four PA aggregates is lower than the AirNow $PM_{2.5}$ mean of 66.7 μg m^{-3}. Factoring in the PA data overcorrection gives a closer comparison to the AirNow data. In contrast, during the GLASS smoke event, the local PA_{GLA} aggregate mean $PM_{2.5}$ of 73.0 μg m^{-3} was more than a factor of three higher than the AirNow mean $PM_{2.5}$. This demonstrates that the AirNow station was not able to represent the local air quality impacts of the Glass Fire, and would have classed the air quality as "Moderate" instead of "Unhealthy."

The overnight hours are preferable for winegrape harvesting, and so we explore the differences in daytime and nighttime air quality during these three wildfire pollution events. The analysis includes daytime and nighttime maximum $PM_{2.5}$ values (Tables S1 and S2 in Supporting Information S1). During the LNU1 event, we see large day to night differences in the mean maximum $PM_{2.5}$, with maximum $PM_{2.5}$ concentrations higher during the day than overnight by factors of 3 and 4 from the PA_{LNU} and AirNow data, respectively, generally in good agreement. The LNU2 pollution event differs strongly from LNU1, with no significant day to night difference seen in any metric. As well, similar to Table 2, we note that higher mean maximum $PM_{2.5}$ values were observed at the AirNow station during LNU2 than from any of the regionally aggregated PurpleAir monitors. During the GLASS

Table 3

Number of Days With Hourly $PM_{2.5}$ Above Hazard Pay Threshold (55.5 μg m^{-3}) at Sebastopol During Three Main Wildfire Pollution Episodes, Compared With PurpleAir Monitors in Different Regions of Sonoma County (In Parentheses, the Number of Days the Maximum Hourly PurpleAir Exceeded 41 μg m^{-3} to Account for the PurpleAir Overcorrection)

	EPA	PurpleAir			
Time period	AirNow	Sonoma county	Sebastopol region	LNU AgPass region	Glass AgPass region
1 LNU1 0:00 19 Aug–23:59 31 Aug	6 days	5 (5) days	4 (6) days	6 (8) days	6 (6) days
2 LNU2 0:00 8 Sep–23:59 15 Sep	5 days	4 (5) days	5 (5) days	4 (5) days	3 (6) days
3 GLASS 0:00 27 Sep–23:59 5 Oct	3 days	2 (4) days	2 (3) days	3 (3) days	7 (7) days

wildfire pollution event, the day versus night differences between the AirNow station and the PA_{GLA} are also pronounced. While the AirNow station reported higher mean daytime maximum hourly $PM_{2.5}$, the aggregated PA_{GLA} nighttime mean maximum hourly $PM_{2.5}$ 136.5 μg m^{-3} exceeded the daytime mean maximum hourly $PM_{2.5}$ (117.9 μg m^{-3}) and was a factor of 3.8 higher than that of the AirNow station (35.5 μg m^{-3}). The GLASS event data demonstrates that for some pollution events the AirNow station at Sebastopol is not sufficient for monitoring the air quality in all regions of Sonoma County.

Finally, for each of the three wildfire pollution episodes we plot the mean 24-hr $PM_{2.5}$ diel profiles for the AirNow data and the regionally aggregated PurpleAir data (Figure 5). The diel cycle plots indicate that the three periods of high smoke impact from wildfire in Sonoma County resulted in very different spatial patterns of pollution. The first time period (LNU1) showed a clear 24-hr pollution pattern for all regions, with highest $PM_{2.5}$ values occurring around noon local time and dropping overnight. This follows the well-known pattern of increasing fire activity during the day, followed by a decrease overnight. The Glass Ag Pass region peaked a little later in the day than either Sebastopol or LNU Ag Pass regions, likely because its location farther from the wildfire during this time period resulted in a delay in smoke impact via atmospheric transport. Time period two (LNU2) possessed no clear 24-hr pattern, with extremely high average $PM_{2.5}$ over the whole 24-hr period for all regions, indicating widespread regional smoke impact. Sebastopol measured the highest $PM_{2.5}$ during this period, always above the EPA Unhealthy threshold. The lower PurpleAir measurements are likely a reflection of the low bias of corrected $PM_{2.5}$ values by PurpleAir monitors as shown in Figure 3b. The LNU2 time period is characterized by low wind speeds and meteorological conditions that encourage atmospheric stagnation and the build-up of smoke pollution in the boundary layer (Albores et al., 2023). Time period three (GLASS) showed 24-hr patterns in $PM_{2.5}$ values, but large heterogeneity between regions. Specifically, the Glass Ag Pass region, where the fires were occurring, experienced increases in pollution overnight and into the morning, while other regions showed the expected decrease overnight. Additionally, the Glass Ag Pass region was always well above the WHO guideline and above the Unhealthy EPA threshold overnight, while Sebastopol indicated conditions below the WHO guideline overnight. The GLASS time period is an example where data from different monitors would support very different conclusions about the impact of smoke on working conditions.

4. Policy Implications

The Ag Pass program is intended to safeguard agricultural interests but has generated significant health concerns among farmworkers. Our analysis underscores those concerns. We recommend that state and local governments take the following actions before, during and after wildfires to protect the health and safety of farmworkers in mandatory evacuation zones. These proposed policies are based on our analysis of the Ag Pass program and $PM_{2.5}$ monitors in Sonoma County, and on current best practices around these issues. The impact of the Ag Pass program will likely increase with the frequency and severity of wildfires; further research and monitoring of its effects on farmworkers will be needed in the future.

4.1. Mandatory Employer Emergency Plans and Emergency Training

Employers should be required to create comprehensive emergency plans to protect outdoor agricultural employees. Collaborative protocols should be developed with emergency response agencies and farmworker rights groups, to ensure efficient evacuation of outdoor workers. Training on disaster awareness, health and safety issues, entrapment avoidance, incident organization, fire behavior, and collaboration with emergency personnel should be offered to employees in multiple languages.

4.2. Clear Protocols on Identifying Workers and Locations

Accurate documentation of the number of workers entering worksites and the location of each site is paramount for safety. In all Ag Pass applications, complete addresses should be supplemented with geographical coordinates and accompanied by a comprehensive list of activities and stored materials. This documentation should be readily accessible to emergency personnel. Regular visits to previously accepted permit locations should be conducted to keep information up to date.

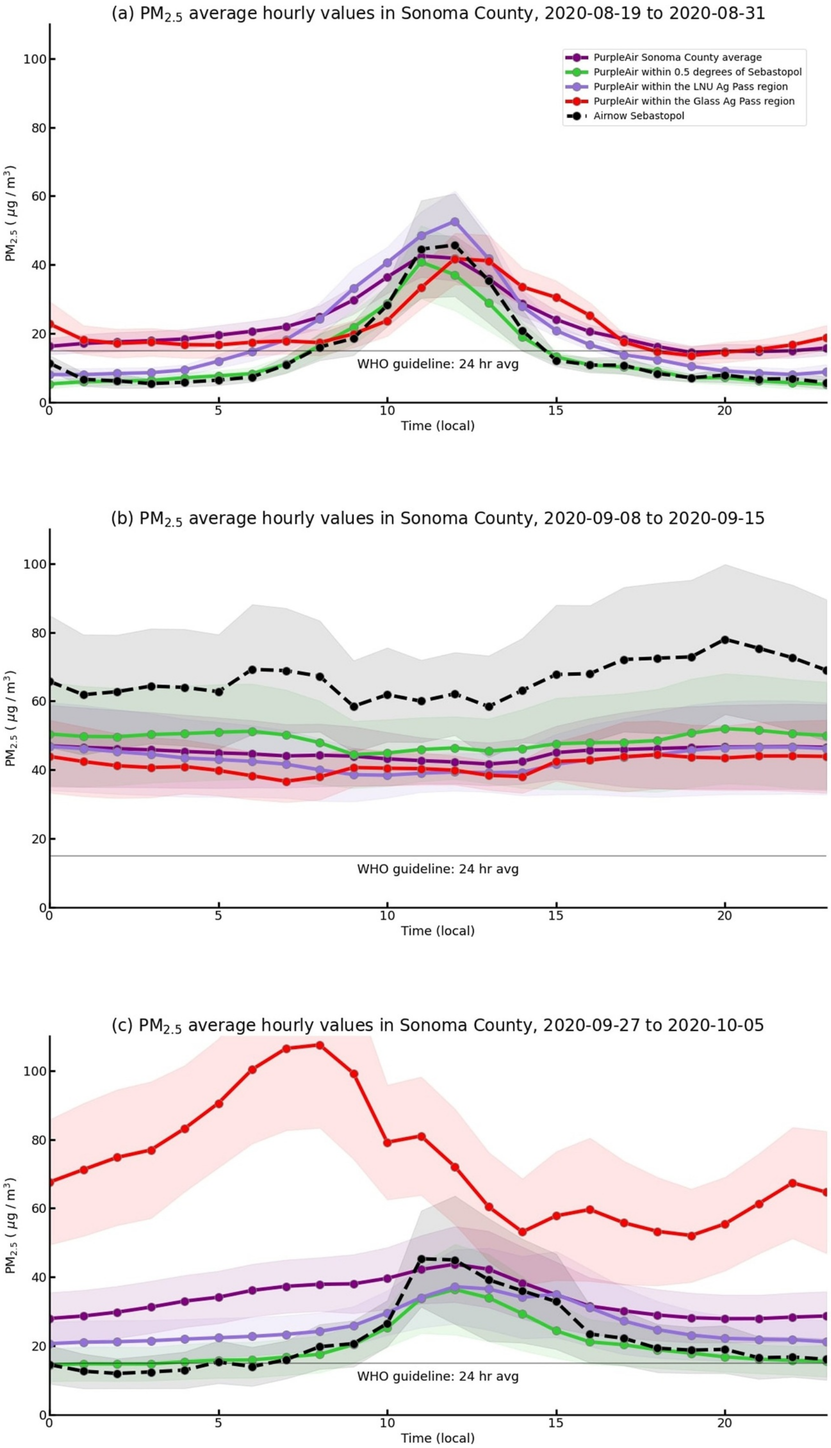

Figure 5. Diel cycles of AirNow and regionally aggregated PurpleAir mean hourly $PM_{2.5}$ for the three wildfire pollution episodes (a) 1 LNU1, (b) 2 LNU2, and (c) 3 GLASS. Shading shows standard error.

4.3. Real-Time Monitoring of Air Quality

Local real-time air quality monitors should be placed within worksites to provide farmworkers, employers, and government officials with more accurate and timely information on air quality. This will enable informed decisions regarding the use of Ag Pass permits and access to mandatory evacuation zones, in particular when these local air quality monitors indicate pollution events that are not reflected in the nearest regulatory monitor data.

4.4. Hazard Pay

In recognition of the risks that the Ag Pass system poses to agricultural workers, employers should provide time-and-a-half hazard pay for a complete 6-hr shift if the AQI is above 150 at any point within the previous 24 hr, a level considered unhealthy for everyone. Notably, three wineries in Sonoma and Napa counties have agreed to such terms in recent labor contracts (Barber, 2023; Quackenbush, 2022).

4.5. Post-Exposure Health Screenings

State and County governments and employers should provide funding to workers for post-exposure healthcare and well-being monitoring. These screenings should include initial health assessments, ongoing medical check-ups, and specialized tests focused on respiratory functions and potential toxicological effects of smoke inhalation. Additionally, regular health check-ups and mental health evaluations are essential to detecting early signs of smoke-related illnesses and addressing mental health impacts. Thus, defining wildfire smoke exposure, based on intensity and duration, would ensure targeted and effective health interventions. This recommendation promotes long-term responsibility, health history, and could ultimately reduce long-term healthcare costs.

4.6. Post-Incident Accountability and Data Accuracy

Following wildfire events during which Ag Passes are issued, the county should thoroughly evaluate the accuracy and effectiveness of the program. This analysis is critical for ensuring compliance and assessing risks associated with the program's implementation. To enhance transparency and enable future research, the resulting data and analysis should be publicly accessible.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The AirNow Sebastopol hourly $PM_{2.5}$ values and raw and processed hourly PurpleAir measurements of $PM_{2.5}$ within Sonoma County used in this study are available from https://doi.org/10.5065/xq6t-v944. Code developed for this project includes algorithms to download $PM_{2.5}$ data from the AirNow Sebastopol Station, download PurpleAir Sonoma County $PM_{2.5}$, correct and aggregate PurpleAir 2-min data into hourly averages, plot time series and diel cycles. The code is available on a GitHub Repository (Chunga Pizarro et al., 2024).

Acknowledgments

This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977. The project upon which this article is based was funded through the NSF NCAR Early Career Faculty Innovator Program under the same Cooperative Agreement and the Andrew Carnegie Corporation grant.

References

Aguilera, R., Corringham, T., Gershunov, A., & Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications*, *12*(1), 1493. https://doi.org/10.1038/s41467-021-21708-0

Albores, I. S., Buchholz, R. R., Ortega, I., Emmons, L. K., Hannigan, J. W., Lacey, F., et al. (2023). Continental-scale atmospheric impacts of the 2020 Western U.S. Wildfires. *Atmospheric Environment*, *294*, 119436. https://doi.org/10.1016/j.atmosenv.2022.119436

Barber, P. (2023). *Boeschen Vineyards in Napa Valley becomes 1st to provide vineyard workers hazard pay and disaster insurance*. The Press Democrat. Retrieved from https://www.pressdemocrat.com/article/news/boeschen-vineyards-in-napa-valley-becomes-1st-to-provide-vineyard-workers-h/

Barkjohn, K. K., Holder, A. L., Frederick, S. G., & Clements, A. L. (2022). Correction and accuracy of PurpleAir $PM_{2.5}$ measurements for extreme wildfire smoke. *Sensors*, *22*(24), 9669. https://doi.org/10.3390/s22249669

Bedsworth, L., Canyan, D., Franco, G., Fisher, L., & Ziaja, S. (2018). California's fourth climate change assessment [Statewide Summary Report: SUMCCCA4-2018-013]. https://climateassessment.ca.gov/

Black, C., Tesfaigzi, Y., Bassein, J. A., & Miller, L. A. (2017). Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. *Environmental Toxicology and Pharmacology*, *55*, 186–195. https://doi.org/10.1016/j.etap.2017.08.022

Cal/OSHA. (2019). Cal/OSHA reminds employers to protect workers if the air quality is unhealthy due to wildfire smoke. *California Department of Industrial Relations*. Retrieved from https://www.dir.ca.gov/DIRNews/2019/2019-81.html

Chunga Pizarro, C. A., Buchholz, R., Hornbrook, S. B., Christensen, K., & Méndez, M. (2024). *AirNow and low cost sensor PM2.5 during extreme wildfires in Sonoma County, 2020. Version 1.0*. UCAR/NCAR - GDEX. https://doi.org/10.5065/xq6t-v944

Department of Industrial Relations, State of California. (2019). Protecting outdoor workers exposed to smoke from wildfires. Retrieved from https://www.dir.ca.gov/title8/5141_1.html

Fazel-Zarandi, M. M., Feinstein, J. S., & Kaplan, E. H. (2018). The number of undocumented immigrants in the United States: Estimates based on demographic modeling with data from 1990 to 2016. *PLoS One*, *13*(9), e0201193. https://doi.org/10.1371/journal.pone.0201193

Finlay, S. E., Moffat, A., Gazzard, R., Baker, D., & Murray, V. (2012). Health impacts of wildfires. *PLoS Currents*, *4*. https://doi.org/10.1371/4f959951cce2c

Ford, B., Van Martin, M., Zelasky, S. E., Fischer, E. V., Anenberg, S. C., Heald, C. L., & Pierce, J. R. (2018). Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. *GeoHealth*, *2*(8), 229–247. https://doi.org/10.1029/2018GH000144

Goss, M., Swain, D. L., Abatzoglou, J. T., Sarhadi, A., Kolden, C. A., Williams, A. P., & Diffenbaugh, N. S. (2020). Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, *15*(9), 094016. https://doi.org/10.1088/1748-9326/ab83a7

Hart, J. E., Liao, X., Hong, B., Puett, R. C., Yanosky, J. D., Suh, H., et al. (2015). The association of long-term exposure to $PM_{2.5}$ on all-cause mortality in the Nurses' Health Study and the impact of measurement-error correction. *Environmental Health*, *14*(1), 38. https://doi.org/10.1186/s12940-015-0027-6

Henderson, S. B., Brauer, M., MacNab, Y. C., & Kennedy, S. M. (2011). Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. *Environmental Health Perspectives*, *119*(9), 1266–1271. https://doi.org/10.1289/ehp.1002288

Keeley, J. E., & Syphard, A. D. (2021). Large California wildfires: 2020 fires in historical context. *Fire Ecology*, *17*(1), 22. https://doi.org/10.1186/s42408-021-00110-7

Liang, Y., Sengupta, D., Campmier, M. J., Apte, J. S., & Goldstein, A. H. (2021). Wildfire smoke impacts on indoor air quality assessed using crowdsourced data in California. *Proceedings of the National Academy of Sciences*, *118*(36), e2106478118. https://doi.org/10.1073/pnas.2106478118

Marlier, M. E., Brenner, K. I., Liu, J. C., Mickley, L. J., Raby, S., James, E., et al. (2022). Exposure of agricultural workers in California to wildfire smoke under past and future climate conditions. *Environmental Research Letters*, *17*(9), 094045. https://doi.org/10.1088/1748-9326/ac8c58

Méndez, M. (2022). Behind the Bougainvillea Curtain: Wildfires and inequality. *Issues in Science & Technology*. https://www.jstor.org/stable/27161908

Méndez, M., & Chunga Pizarro, C. (2022). *Addressing disparities in Sonoma County's agriculture pass program*. University of California - Irvine School of Social Ecology. Retrieved from https://socialecology.uci.edu/sites/default/files/users/mkcruz/sonoma_policybrief_final_5.18.22_ccformat-4.pdf

Méndez, M., Flores-Haro, G., & Zucker, L. (2020). The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum*, *116*, 50–62. https://doi.org/10.1016/j.geoforum.2020.07.007

Mollenkopf, J., & Pastor, M. (2016). *Unsettled Americans: Metropolitan context and civic leadership for immigrant integration*. Cornell University Press.

National Interagency Coordination Center. (2020). Wildland fire summary and statistics annual report 2020. Retrieved from https://www.nifc.gov/fire-information/statistics

Nixon, R. (2011). *Slow violence and the environmentalism of the poor*. Harvard University Press.

O'Dell, K., Ford, B., Fischer, E. V., & Pierce, J. R. (2019). Contribution of wildland-fire smoke to US $PM_{2.5}$ and its influence on recent trends. *Environmental Science & Technology*, *53*(4), 1797–1804. https://doi.org/10.1021/acs.est.8b05430

Phillips, C. A., Caldas, A., Cleetus, R., Dahl, K. A., Declet-Barreto, J., Licker, R., et al. (2020). Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, *10*(7), 586–588. https://doi.org/10.1038/s41558-020-0804-2

Quackenbush, J. (2022). *Sonoma County vintner offers farmworkers 'hazard pay' during smoky days*. North Bay Business Journal. Retrieved from https://www.northbaybusinessjournal.com/article/industrynews/sonoma-county-vintner-offers-farmworkers-hazard-pay-during-smoky-days/

Ratcliffe, J. H. (2004). Geocoding crime and a first estimate of a minimum acceptable hit rate. *International Journal of Geographical Information Science*, *18*(1), 61–72. https://doi.org/10.1080/13658810310001596076

Reid, C. E., Brauer, M., Johnston, F. H., Balmes, J. R., & Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, *124*(9), 1334–1343. https://doi.org/10.1289/ehp.1409277

Riden, H. E., Giacinto, R., Wadsworth, G., Rainwater, J., Andrews, T., & Pinkerton, K. E. (2020). Wildfire smoke exposure: Awareness and safety responses in the agricultural workplace. *Journal of Agromedicine*, *25*(3), 330–338. https://doi.org/10.1080/1059924X.2020.1725699

Rosenthal, N., Benmarhnia, T., Ahmadov, R., James, E., & Marlier, M. E. (2022). Population co-exposure to extreme heat and wildfire smoke pollution in California during 2020. *Environmental Research: Climate*, *1*(2), 025004. https://doi.org/10.1088/2752-5295/ac860e

Safford, H. D., Paulson, A. K., Steel, Z. L., Young, D. J. N., & Wayman, R. B. (2022). The 2020 California fire season: A year like no other, a return to the past or a harbinger of the future? *Global Ecology and Biogeography*, *31*(10), 2005–2025. https://doi.org/10.1111/geb.13498

Smith, A. F. (2021). *2020 Sonoma County crop report*. Sonoma County Department of Agriculture/Weights & Measures. Retrieved from https://sonomacounty.ca.gov/Main%20County%20Site/Natural%20Resources/Agricultural%2C%20Weights%20%26%20Measures/Documents/Crop%20Reports/2020%20Sonoma%20County%20Crop%20Report%20FINAL%20%281%29.pdf

Smolski, A. R. (2019). Stemming the exploitation of immigrant farm labor. *Contexts*, *18*(2), 70–71. https://doi.org/10.1177/1536504219854727

Sonoma County Board of Supervisors Ad Hoc Committee on Evacuation Zone Access. (2022). Staff report: Evacuation zone access for agriculture and livestock producers. Sonoma County Board of Supervisors.

U.S. Environmental Protection Agency. (n.d.). About AirNow. Retrieved from https://www.airnow.gov/about-airnow/

US EPA. (1999). Air Quality Index Reporting; Final Rule, Federal Register, 64. Retrieved from https://www.airnow.gov/sites/default/files/2018-06/air-quality-index-reporting-final-rule.pdf

Vos, T., Lim, S. S., Abbafati, C., Abbas, K. M., Abbasi, M., Abbasifard, M., et al. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, *396*(10258), 1204–1222. https://doi.org/10.1016/S0140-6736(20)30925-9

Westerling, A. L., & Bryant, B. P. (2008). Climate change and wildfire in California. *Climatic Change*, *87*(S1), 231–249. https://doi.org/10.1007/s10584-007-9363-z

Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman-Morales, J., Bishop, D. A., Balch, J. K., & Lettenmaier, D. P. (2019). Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, *7*(8), 892–910. https://doi.org/10.1029/2019EF001210

World Health Organization. (2021). What are the WHO Air quality guidelines? Retrieved from https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines

Youssouf, H., Liousse, C., Roblou, L., Assamoi, E.-M., Salonen, R. O., Maesano, C., et al. (2014). Non-accidental health impacts of wildfire smoke. *International Journal of Environmental Research and Public Health*, *11*(11), 11772–11804. https://doi.org/10.3390/ijerph111111772