HHS Public Access

Author manuscript

J Agromedicine. Author manuscript; available in PMC 2024 July 01.

Published in final edited form as:

J Agromedicine. 2023 July ; 28(3): 595–608. doi:10.1080/1059924X.2023.2213232.

Wildfire smoke monitoring for agricultural safety and health in rural Washington

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Abstract

Objectives: This study aimed to evaluate the performance of a low-cost smoke sampling platform relative to environmental and occupational exposure monitoring methods in a rural agricultural region in central Washington state.

Methods: We co-located the Thingy AQ sampling platform alongside cyclone-based gravimetric samplers, a nephelometer, and an environmental beta attenuation mass (E-BAM) monitor during August and September of 2020. Ambient particulate matter concentrations were collected during a smoke and non-smoke period and measurements were compared across sampling methods.

Results: We found reasonable agreement between observations from two particle sensors within the Thingy AQ platform and the nephelometer and E-BAM measurements throughout the study period, though the measurement range of the sensors was greater during the smoke period compared to the non-smoke period. Occupational gravimetric sampling methods did not correlate with $PM_{2.5}$ data collected during smoke periods, likely due to their capture of larger particle sizes than those typically measured by $PM_{2.5}$ ambient air quality instruments during wildfire events.

Conclusion: Data collected before and during an intense wildfire smoke episode in September 2020 indicated that the low-cost smoke sampling platform provides a strategy to increase access to real-time air quality information in rural areas where regulatory monitoring networks are sparse if sensor performance characteristics under wildfire smoke conditions are understood. Improving access to spatially resolved air quality information could help agricultural employers protect both worker and crop health as wildfire smoke exposure increases due to the impacts of climate change. Such information can also assist employers with meeting new workplace wildfire smoke health and safety rules.

Keywords

Wildfire smoke; agriculture; low-cost sensors; rural air pollution

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Disclosure statement: The authors confirm that there are no relevant financial or non-financial competing interests to report.

Introduction

Poor air quality from wildfires has become an important health issue in the Northwest.[1] Wildfire smoke exposure is of particular concern among outdoor workers in Washington's agricultural industry, which employs up to 140,000 workers during the growing season, spanning from June to October, during which the region also experiences peak wildfire season.[2–6] Location, time, and labor-intensive outdoor tasks can all increase smoke exposure for agricultural workers. Washington agricultural workers and their communities have experienced increased wildfire smoke,[7] though the magnitude of exposure and health burdens in these settings are not well characterized.

Wildfire emissions produce $PM_{2.5}$, PM_{10}, CO, CO_2, O_3, NO_2, VOCs, and PAHs, which can have a variety of health impacts on humans.[8] Smoke can cause eye, nose, and throat irritation among healthy workers in addition to shortness of breath, persistent cough, wheeze, chest tightness, and increased mucus production. Workers with pre-existing respiratory conditions, such as asthma, chronic obstructive pulmonary disease, or other respiratory diseases, may experience exacerbation of symptoms with smoke exposure.[9] While there have been limited studies of the health effects of wildfire smoke exposure in agricultural workers, studies of wildland fire fighters have shown that occupational exposures to wildfire smoke are associated with decreased lung function in the short term and may increase the risk of hypertension in the long-term.[9] Studies of wildfire smoke exposure among the general population have also reported associations with cardiovascular outcomes, low birthweight, and mental health outcomes.[8] Less is known about long-term health impacts of repeated smoke exposures, the effects of smoke on cognitive decline, and smoke-related health disparities.[8] Current smoke studies are typically retrospective, reliant on administrative health data, and unable to capture the total public health impact of hard to measure exposures and health effects, particularly in rural areas.[10,11] Additionally, smoke has an impact on the agricultural industry, as it can cause undesirable flavor characteristics, otherwise known as "smoke taint", in key Northwest commodities such as tree fruit, wine grapes, and hops.[12]

Rural communities recognize the value of local air monitoring,[13] especially for capturing the spatial heterogeneity of smoke levels from one valley's air drainage to the next during fire season. Regulatory air pollution monitors have far better coverage in urban centers than rural areas, so relatively less is known about smoke exposure levels at outdoor locations of agricultural workers. Moreover, measurement methods for compliance with the National Ambient Air Quality Standards (NAAQS) for ambient air pollution (i.e. $PM_{2.5}$ and PM_{10}) are significantly different from the standards applied in the workplace setting to protect workers from occupational sources of respirable dust, with the latter having a different median size, broader size cutoff and 8-hour averaging time for exposure. The Washington Air Monitoring Network (WAMN) consists of 81 sites that monitor for $PM_{2.5}$ most commonly, PM_{10}, O_3, NO_X, and SO_X occasionally, and CO and CO_2 rarely if ever. East of the Cascade Mountains, 35 WAMN sites cover a land area of approximately 45,000 mi^2 (116,550 km^2) (Figure 1). A higher-density network would allow growers to better anticipate and respond to local exposures to protect workers and crops.

Policy developments also highlight the importance of understanding occupational exposures to wildfire smoke. To supplement the occupational respirable dust standards, states have developed wildfire smoke-specific rules to better protect outdoor workers during the wildfire smoke season. In California, CalOSHA permanent regulations require employers to take various actions, including providing N95 masks, at different air pollution thresholds based not on occupational respirable dust concentrations but on ambient $PM_{2.5}$ concentrations, for employees exposed to wildfire smoke.[14,15] The California rule defines its $PM_{2.5}$ thresholds based on Environmental Protection Agency's Air Quality Index (AQI) values, which are categories based on $PM_{2.5}$ concentrations, intended to communicate air pollution information and public health risk. A similar permanent rule in Oregon and emergency rule in Washington were enacted in 2022, which rely on $PM_{2.5}$ concentration thresholds instead of AQI values.[16,17] In all three states, employers are given the option to use readings from the nearest regulatory air monitoring sites (e.g., by using information provided on government websites, such as airnow.gov) or to directly measure the ambient air concentration for $PM_{2.5}$ at work locations in accordance with air monitoring instrument manufacturer instructions. AQI thresholds and the required exposure control measures for each state are outlined in Table 1. In Washington, workers who believe their health has been impacted by wildfire smoke are now being encouraged to get a medical evaluation and, if appropriate, file a workers' compensation claim, which requires a determination of the likelihood of workers' exposure levels causing health effects.[18]

Agricultural workers often live and work in the same area, meaning the consideration of both occupational and non-occupational exposure may be important to understanding cumulative smoke exposure. Because regulatory air pollution monitoring networks are often sparse in rural areas, supplementing existing air monitoring networks with emerging low-cost sensor technology could provide an opportunity to better monitor both occupational and non-occupational exposures and protect worker health.

This paper addresses the following research questions: 1) how do low-cost particle sensor measurements compare to nephelometer particle measurements during a period with vs without wildfire smoke? 2) Are $PM_{2.5}$-based exposures as specified in new outdoor worker rules correlated with traditional respirable dust-based exposures during a wildfire smoke event? We discuss the findings for these questions in the context of the potential for improved information from new low-cost monitoring networks in rural areas for the protection of agricultural workers.

Methods

We established cross-sector partnerships to evaluate the performance of a low-cost smoke monitoring platform relative to occupational and environmental regulatory methods. We compared $PM_{2.5}$ and PM_4 measurements from the Thingy AQ monitoring platform to measurements obtained from cyclone-based gravimetric samplers, a nephelometer, and a Portable Beta Attenuation Mass Monitor (E-BAM) during a smoke and non-smoke period during summer 2020 in Wenatchee, WA.

Cross-sector partnerships

This study was made possible by a diverse team of academic researchers from the University of Washington and Washington State University, the Washington Department of Ecology, a wildfire smoke sensor developer from Thingy, LLC, and agricultural partners in the tree fruit, wine grape, and hops industries. The Washington State Department of Ecology and Washington State University provided access to air monitoring and weather monitoring sites, respectively, and shared their data portals and models to support timely, coordinated research about smoke resilience and provide insights about the viability of broad-scale air sensor networks and data quality. Thingy, LLC joined this effort to work directly with growers and agencies to test new smoke monitoring and networking solutions in agricultural settings. These partnerships have led to several new research initiatives, such as worker safety intervention testing and smoke taint studies led by growers and land grant institutions in Washington, Oregon, and California.

Study location and study period

Sensor co-locations were carried out in August and September 2020 at the WA Department of Ecology air monitoring site in Wenatchee, WA, an agricultural hub located in the central region of the state. NIOSH 0600 Method filter-based and E-BAM sampling began on 8/30/2020. The low-cost Thingy AQ sensors were deployed on 9/11/2020. The study period ended on 9/28/2020. The Thing AQ sensors, gravimetric samplers, and E-BAM, were placed at the same elevation and within 2 m of a Nephelometer.

Sampling equipment and procedures

Thingy AQ sensors—Two Thingy AQ Wildland Fire Real-time Smoke & Air Quality Monitoring and Telemetry System platforms were deployed during the study period.[19] The sampling platforms include electrochemical carbon monoxide (CO) and ozone (O_3) sensors, a non-dispersive infrared carbon dioxide (CO_2), and two laser scattering fine particulate matter ($PM_{2.5}$) concentration sensors, the Plantower PMS 5003 and the Sensirion SPS30.[20,21] The platform also includes temperature and humidity sensors. Each sensor collected a sample every 15 minutes throughout the study period. The focus of this paper is on the particle data from the Plantower and Sensirion sensors.

Gravimetric sampling—Cyclone-based gravimetric samplers were deployed following the NIOSH Method 0600 for 10-day sampling periods throughout the study period. [22] One 4-hour sample was also collected on 9/11/2020. PVC 37 mm filters in cassettes were attached to aluminum cyclones (SKC Aluminum Respirable Dust Cyclone #225–01-02) and personal sampling pumps (SKC Universal PCXR8) set to 2.5 L/m. Pumps were calibrated in the field before and after sampling using a calibration adaptor (SKC Calibration Adapter, for Aluminum Cyclone #225–01-03) and a primary calibrator (Bios DryCal Defender 520). Two sample media and one field blank were deployed during each 10-day sampling period. Filters were weighed using a UMT-2 microbalance before and after sampling after equilibrating for at least two hours in an environmentally controlled chamber. Concentrations of respirable particles were calculated using equation (1):

$$C = \frac{(W2 - W1) - (B2 - B1)}{V} \times 10^3 mg/m\ 3 \quad (1)$$

Portable beta attenuation mass monitor (E-BAM)—Particulate mass concentrations were also obtained by a Portable Beta Attenuation Mass Monitor (Met One Instruments E-BAM-9800) located next to the other samplers at a height of 1.5 m.[23] The monitor was fitted with a TSP (Total Suspended Particulate Matter) PM_{10} inlet that removes particles larger than 10 microns and with a second downstream $PM_{2.5}$ sampling inlet. It was configured for 1-hour sampling periods with 15-minute real time averages. The pump has a 16.7 L/min inlet volumetric flow rate and zero, span, and leak checks on the flow rates were performed at the beginning and end of the study.

Nephelometer—$PM_{2.5}$ concentrations were obtained from the Department of Ecology's Radiance Research M903 Nephelometer, which is deployed as part of the Washington Air Monitoring Network.[24,25] The Department of Ecology previously calibrated their nephelometer instruments to co-located Federal Equivalent Method (FEM) instrument measures. For this study, we refer to the nephelometer measurements as acceptable $PM_{2.5}$ AQI and speciation mass measurements per the U.S. Environmental Protection Agency and consider them to be our best estimate of $PM_{2.5}$ concentrations. [26] The nephelometer records hourly scattering coefficient (Bscat), which is converted to a mass concentration using the Department of Ecology's calibration equation (2):

$$\mathrm{NPM}_{25} = 20.3^{*}\mathrm{bscat} + 2.20 \quad (2)$$

Meteorology—Hourly temperature data were obtained from the Department of Ecology monitoring site and hourly relative humidity data were obtained from the E-BAM.

Smoke and non-smoke period definitions—For one week during the study period, there were multiple active fires contributing to high smoke concentrations in the region. This was followed by a period without smoke, which allowed us to examine sensor performance across both periods. We defined a smoke day as one when $PM_{2.5}$ concentrations from the nephelometer exceeded 20.4 μg/m^3, following a smoke day classification method previously developed for a study of wildfire smoke exposures in Washington state.[27] Non-smoke days were classified as those when $PM_{2.5}$ measurements were below the 20.4 μg/m^3 threshold. Doubleday et al. applied additional criteria to days that fell within 9–20.4 μg/m^3; however, $PM_{2.5}$ concentrations dropped rapidly after the smoke cleared from the study area and baseline concentrations were consistently below 9 μg/m^3. We defined the smoke period for this study as 9/11/2020–9/18/2020. The non-smoke period spanned 9/20/2020–9/28/2020.

Data analysis

Mean and standard deviation concentrations from the nephelometer and E-BAM monitors and the two Thingy AQ sensors were calculated for each of the NIOSH 0600 method sampling time periods to compare concentrations across monitoring methods. We calculated the relative differences between filter-based samples and the Sensirion PM_4 average concentrations, as well as between $PM_{2.5}$ measurements from the nephelometer and each Thingy AQ sensor. We also generated box plots to visualize the distribution of $PM_{2.5}$ measurements from each of the monitoring methods during the different NIOSH 0600 method sampling periods.

We used Bland-Altman plots to analyze the agreement between the two Thingy AQ sensors and the E-BAM and the nephelometer. The Bland-Altman method evaluates the bias between two sampling methods by calculating the average difference in measurements as well as the limits of agreement at a 95% confidence interval.

Mean and standard deviation $PM_{2.5}$ concentrations along with coefficients of variation (CV) were calculated for each Thingy AQ sensor and the nephelometer and E-BAM during the smoke and non-smoke period. Multivariable linear regression was used to evaluate the correlation between hourly observations from both Thingy AQ sensors and the nephelometer measurements, controlling for hourly temperature and relative humidity, across the entire study period as well as the smoke and non-smoke periods, separately.

Results

During the sampling period, multiple wildfires in the surrounding region resulted in a multi-day smoke event. During that smoke event, $PM_{2.5}$ concentrations averaged 105.81 μg/m^3 and reached as high as 290.27 μg/m^3, based on measurements from the nephelometer. After the smoke had cleared from the study area in the week following the major smoke event, $PM_{2.5}$ concentrations decreased to an average of 3.47 μg/m^3, with a maximum concentration of 15.32 μg/m^3 (Table 3).

The NIOSH 0600 filter-based sampling method was used to evaluate Thingy AQ sensor performance relative to occupational standard monitoring methods. The NIOSH 0600 method is intended for sampling up to 8 hours during the workday; however, we also deployed the filters over multiple days because of the relatively low baseline concentration ambient $PM_{2.5}$ concentrations in the area. We also deployed one filter during a 4-hour period during the smoke event. During the wildfire smoke event, the filter-based measurements did not appear to capture the high concentrations measured by the $PM_{2.5}$ monitoring methods, except for during the 4-hour sampling period, which fell within the suggested sampling time of NIOSH 0600 protocol (Table 2, Figure 2).

Figure 3 shows a series of Bland-Altman plots comparing measurements from the two Thingy AQ sensors and the nephelometer. Both sensors showed large errors relative to the nephelometer at very low concentrations. The magnitude of error decreased in both the Plantower and Sensirion sensor but remained consistently negative as concentrations increased.

Time series of $PM_{2.5}$ concentrations during the smoke and non-smoke period from the Plantower, Sensirion, E-BAM, and nephelometer are shown in Figure 4. For both Thingy AQ sensors, relative variability was greater during the smoke period ($CV_{Plantower}$=61.48 and $CV_{Sensirion}$= 77.16) compared to the non-smoke period ($CV_{Plantower}$=42.40 and

$CV_{Sensirion}$=64.61) (Table 3). Across the full study period, the multivariable linear regression showed a strong correlation between both Thingy AQ sensors and the nephelometer, with better performance for the Sensirion, after controlling for temperature and relative humidity ($R^2_{Sensirion}$= 0.82, $R^2_{Plantower}$= 0.82). R-squared values observed during the smoke period ($R^2_{Sensirion}$= 0.71, $R^2_{Plantower}$= 0.70) were similarly strong, but worsened during the non-smoke period, particularly for the Plantower ($R^2_{Sensirion}$= 0.27, $R^2_{Plantower}$= 0.07) (Table 4).

Discussion

This study was designed to pilot test two low-cost wildfire smoke sensors built into the Thingy AQ sampling platform within the context of existing occupational and environmental regulatory frameworks and monitoring methods. We co-located the Plantower and Sensirion sensors alongside a nephelometer and E-BAM, as well as gravimetric samplers deployed under the NIOSH 0600 protocol for respirable particles. A major wildfire smoke event during the study period allowed us to compare sensor performance during a period with elevated smoke concentrations and a period with particulate matter levels closer to baseline. Overall, both sensors performed well relative to the nephelometer and E-BAM during the smoke period but declined in performance during the non-smoke period. The concentrations derived from the gravimetric sampler measurements collected during the multi-day sampling periods with lower ambient $PM_{2.5}$ concentrations were more similar to those obtained through other monitoring methods. The gravimetric sampler measurements collected during the higher concentration smoke periods were consistently lower than those obtained from other methods, except for the sample collected during the 4-hour sampling period, which fell within the recommended sampling time of the NIOSH 0600 protocol. The negative bias of the filter-based measurements during high concentration periods could be the result of extending the deployment of filters beyond what is recommended by the NIOSH 0600 protocol and potentially masking the high amount of mass collected when averaged over a long sampling period.

The Occupational Safety and Health Administration (OSHA) has set a permissible exposure limit (PEL) for respirable particles of 5 mg/m^3 based on an 8-hour work day.[28] No concentrations recorded by any monitor used in this study exceeded the current occupational standard; however, concentrations did exceed the 24-hour regulatory standard set by the Environmental Protection Agency (EPA) of 35 μg/m^3 on multiple days throughout the study period.[29] This discrepancy highlights the limitations of the current OSHA respirable particle standard and suggests that outdoor workers may indeed be exposed to unsafe levels of respirable particles during wildfire smoke events. Rule making efforts in both Washington and Oregon have implemented $PM_{2.5}$ standards for wildfire smoke events in outdoor working populations.[16,30] This is following similar standards put into place in California, which require employers to take actions to reduce outdoor worker exposures when the AQI for $PM_{2.5}$ reaches 151 or higher during wildfire smoke events.[31] In Oregon, a permanent rule takes effect when the $PM_{2.5}$ concentration is 35 μg/m^3 or higher.[16] In Washington, a 2022 emergency wildfire smoke rule, effective June 15–September 29, applied at $PM_{2.5}$ concentrations 20.5 μg/m^3 or higher.[17] A permanent rulemaking process is currently underway in Washington.[32] Our work informed policy efforts by highlighting air quality monitoring coverage gaps in rural areas and provides supporting information to employers who want more localized air quality data or plan to follow the direct reading options outlined in the rules.

This pilot study was limited by only sampling at one monitoring location. Wildfire smoke concentrations can vary greatly depending on factors such as topography and meteorological conditions, the latter of which can also impact low-cost sensor performance. Future studies should deploy sensors at multiple monitoring locations, alongside occupational and environmental regulatory monitors, to evaluate sensor performance across a heterogeneous meteorological and topographical landscape. As noted above, we were also limited in our ability to evaluate sensor performance relative to occupational monitoring methods because the standard NIOSH 0600 method is not designed for monitoring ambient smoke concentrations over multi-day periods. This limitation may suggest a need to explore other methods for monitoring occupational exposures during wildfire smoke events and points to the potential utility of low-cost sensors for this purpose.

Despite these limitations, this study demonstrated the potential of low-cost sensors embedded within the Thingy AQ sampling platform to monitor wildfire smoke conditions and provide occupationally-relevant air quality information in real time. Case studies from recent wildfire seasons have shown that existing monitoring networks do not provide adequate sampling of $PM_{2.5}$ in many at-risk regions with large numbers of agricultural workers.[33–35] Furthermore, as demonstrated in California projection analyses, agriculturally intensive areas may have disproportionate increases in wildfire smoke exposure due to the number of agricultural workers and the climate-related increases in wildfires.[34] One of the greatest benefits of emerging low-cost sensor technologies is their ability to supplement existing regulatory monitoring networks that are often sparsely distributed in rural areas, where high wildfire smoke exposures often occur. This technology represents a climate adaptation measure that can be placed in the hands of people who can quickly act on real-time information to protect workers, especially as wildfire smoke is perceived as a growing risk and safety concern among employers and workers in western agricultural production. Some employers have voiced that workers could take individual responsibility to keep themselves safe at the workplace.[36] However, the ability to assess wildfire risk has been variable among agricultural workers, a group that has indicated employer and supervisor attitude toward safety substantially affects the implementation of workplace safety measures related to wildfire smoke.[37] This technology has the potential to reduce disparities in access to local information by providing more spatiotemporally resolved information to those who are disproportionally impacted as well as employers and others, who must make decisions and comply with regulations.[38,39]

This technological solution can be integrated into "precision agriculture", a framework that growers have embraced to improve the efficiency and accuracy of farm management decisions with time-sensitive information. Precision agriculture was defined as "a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production."[40] Future applications of the Thingy AQ sampling platform will include further integration with Washington State University's (WSU) AgWeatherNet (AWN) system, which provides near real-time weather data for 201 meteorological stations distributed across Washington's agricultural region through its online portal.[41,42] AWN has approximately 13,000 registered users and its website averages 50,000 hits per day during the growing season. Collected variables include air temperature, relative humidity, dew point, soil temperature, rainfall, wind speed, wind direction, solar radiation, and leaf wetness. Data from this network drive insect, disease, disorder, and horticultural models such as the Decision Aid System. AWN has also been involved in health applications, such as a heat awareness system intended to protect workers, in addition to crop health.[43–45] By adding sensors such as Thingy AQ sampling boxes to the existing AWN monitoring network, real time air quality information will soon be available to growers on a data platform that they are already familiar with, which can be used to make decisions about worker and crop health as they continue to face worsening wildfire smoke events during the growing season. Beyond real-time monitoring to inform near-term decision making, low-cost sensors may also generate data that can be used to validate and improve existing air quality, smoke plume, and exposure modeling efforts. For example, the Thingy AQ sampling platform could be used to evaluate the WSU Air Information Report for Public Access and Community Tracking (AIRPACT) system, which predicts air quality for O_3, NO_X, and CO gasses and $PM_{2.5}$ and PM_{10}. The platform could also be used to evaluate the US Forest Service's BlueSky system, which simulates cumulative smoke impacts from prescribed, wildland, and agricultural fires across different regions and has been utilized by regulators and incident command teams for decision making.[46]

Conclusion

Wildfires and subsequent smoke events are expected to worsen in the coming years.[47,48] Wildfire season often aligns with peak growing season in Washington's agricultural regions, meaning outdoor workers are likely at increased risk for exposure to hazardous smoke levels. Existing regulatory ground monitoring networks are sparsely distributed in rural areas, making it difficult to accurately assess worker exposures, particularly in topographically heterogeneous landscapes, such as agricultural areas in Washington. We evaluated the Plantower and the Sensirion low-cost sensors within the Thingy AQ sampling platform relative environmental and occupational regulatory monitoring methods as a means to supplement the existing air quality monitoring network in central Washington. Future work is needed to assess sensor performance across a wider geographical area; however, the Thingy AQ sampling platform may provide one mechanism through which to increase the density of air quality monitors in rural agricultural regions to provide real time data that employers can use to protect worker and crop health.

Acknowledgements

David Brown and Lav Khot from Washington State University's AgWeatherNet program. Sean Lundblad, James Laing, and Jill Schulte from the Washington State Department of Ecology. Timothy Gould from the University of Washington. Andrew Smallridge of Thingy, LLC. Funding for this project was provided by the U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health through Cooperative Agreement #5 U54 OH007544 with the Pacific Northwest Agricultural Safety and Health (PNASH) Center.

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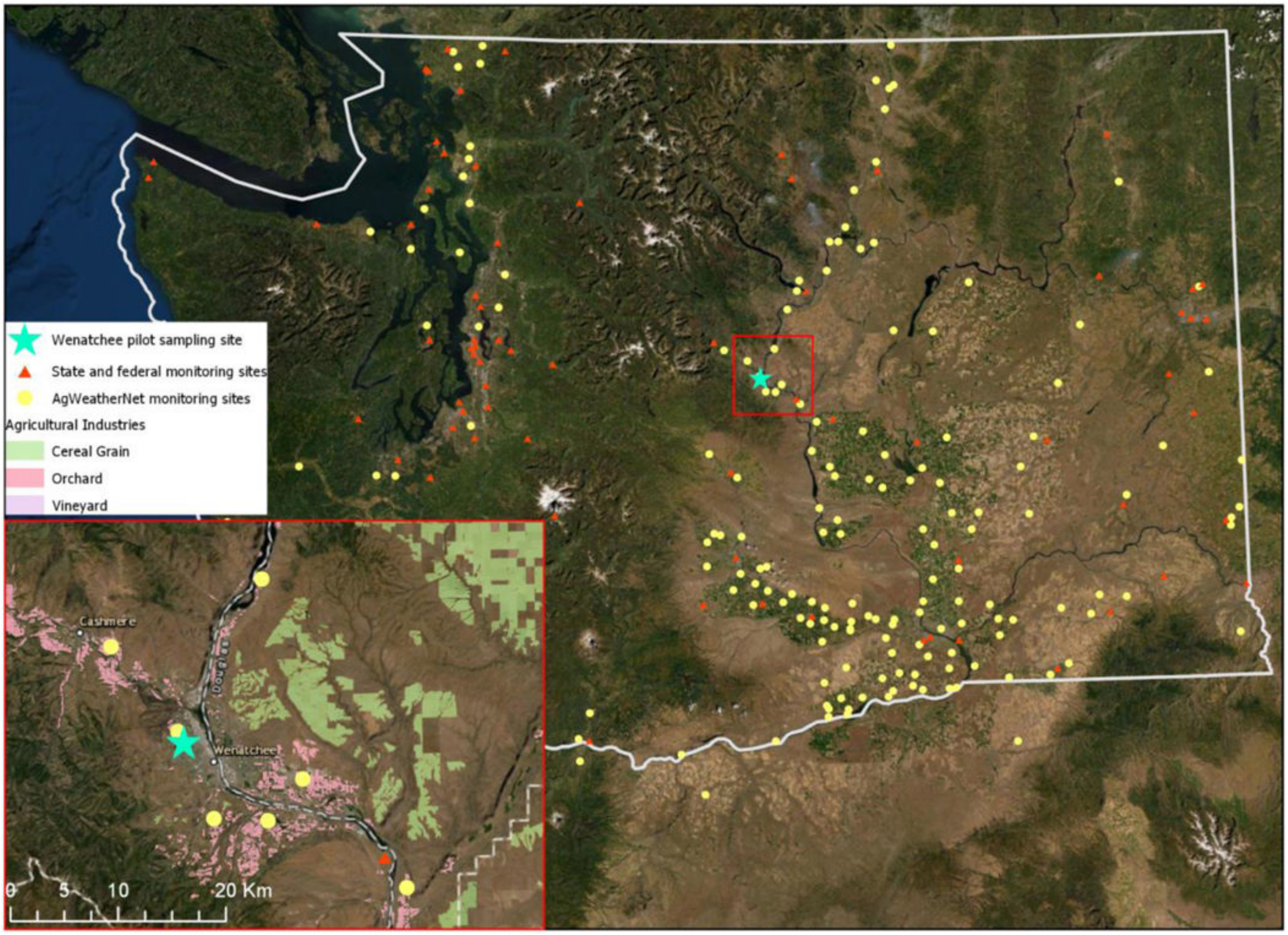

Figure 1.
Map of the state and federal air quality monitoring network, the AgWeatherNet monitoring network, and the location of the Wenatchee pilot sampling site. The inset map also shows the prominent crop types in the surrounding area.

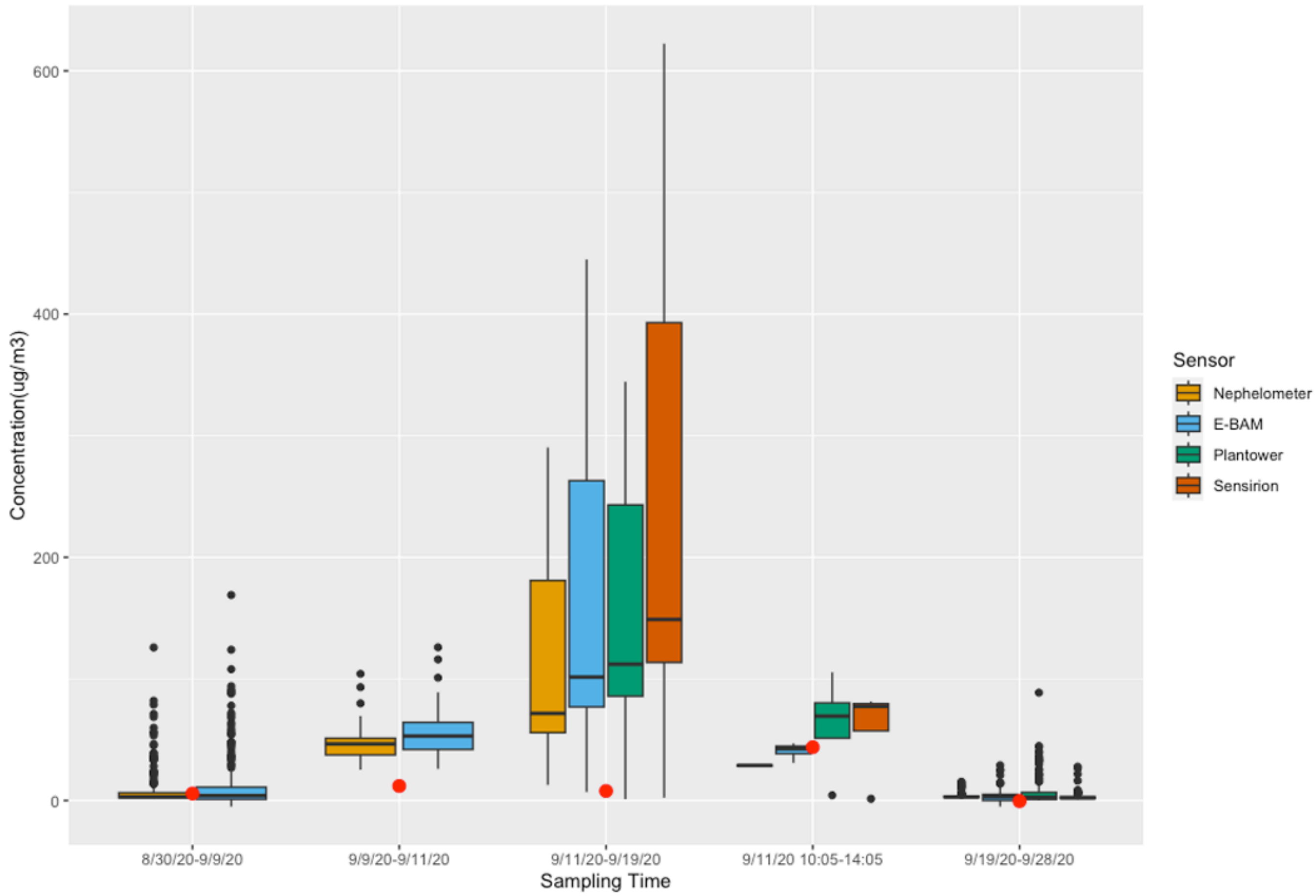

Figure 2.

Distribution of Plantower, Sensirion, and nephelometer PM2.5 measurements during the three filter-based sampling periods. The red dots represent the NIOSH 0600 Method filter sample concentrations from each sampling period.

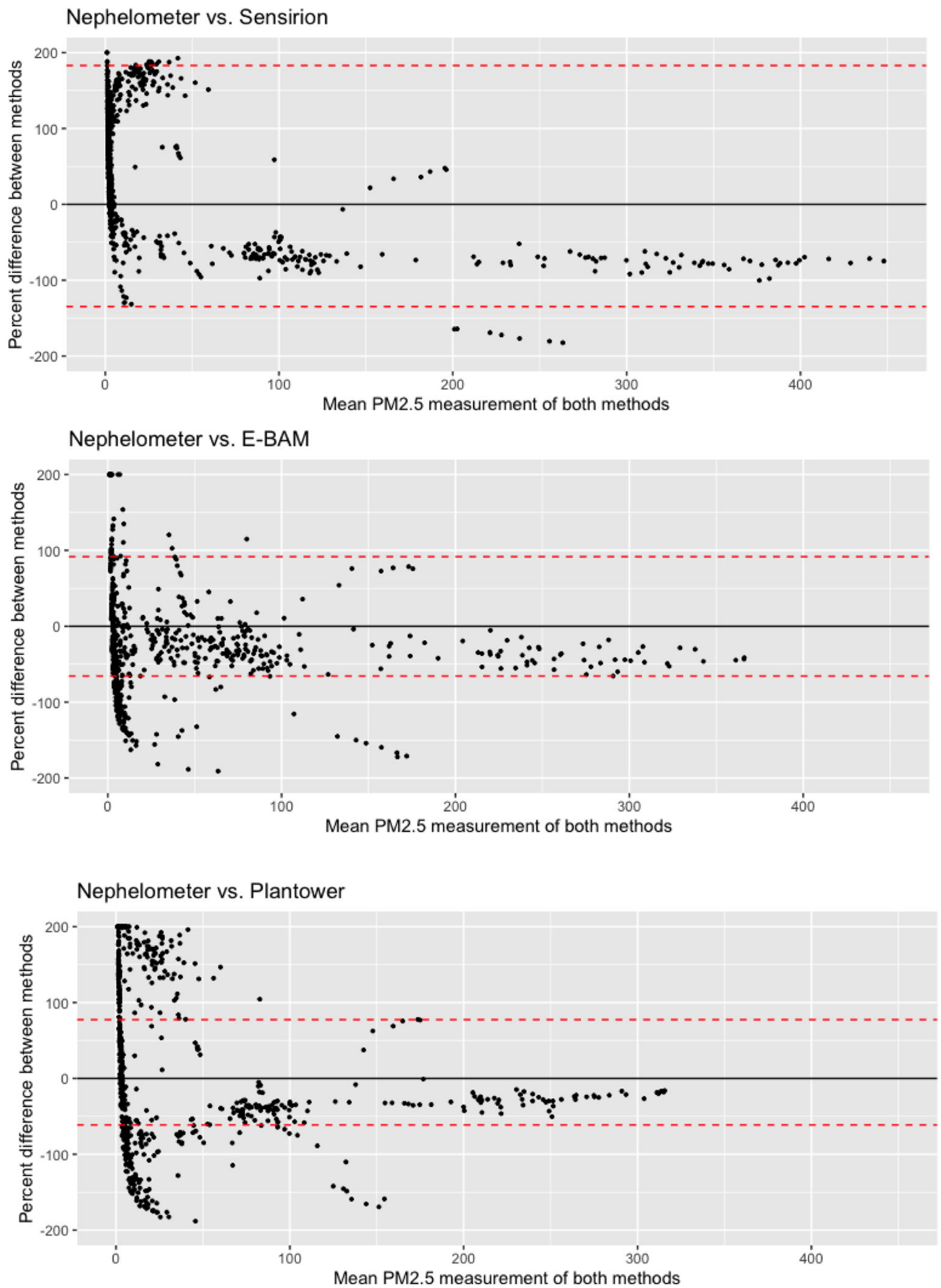

Figure 3.

Bland Altman plots comparing the percent difference in $PM_{2.5}$ measurements to the mean $PM_{2.5}$ measurements between the Sensirion and the nephelometer; the Plantower and the nephelometer; the nephelometer and the E-BAM.

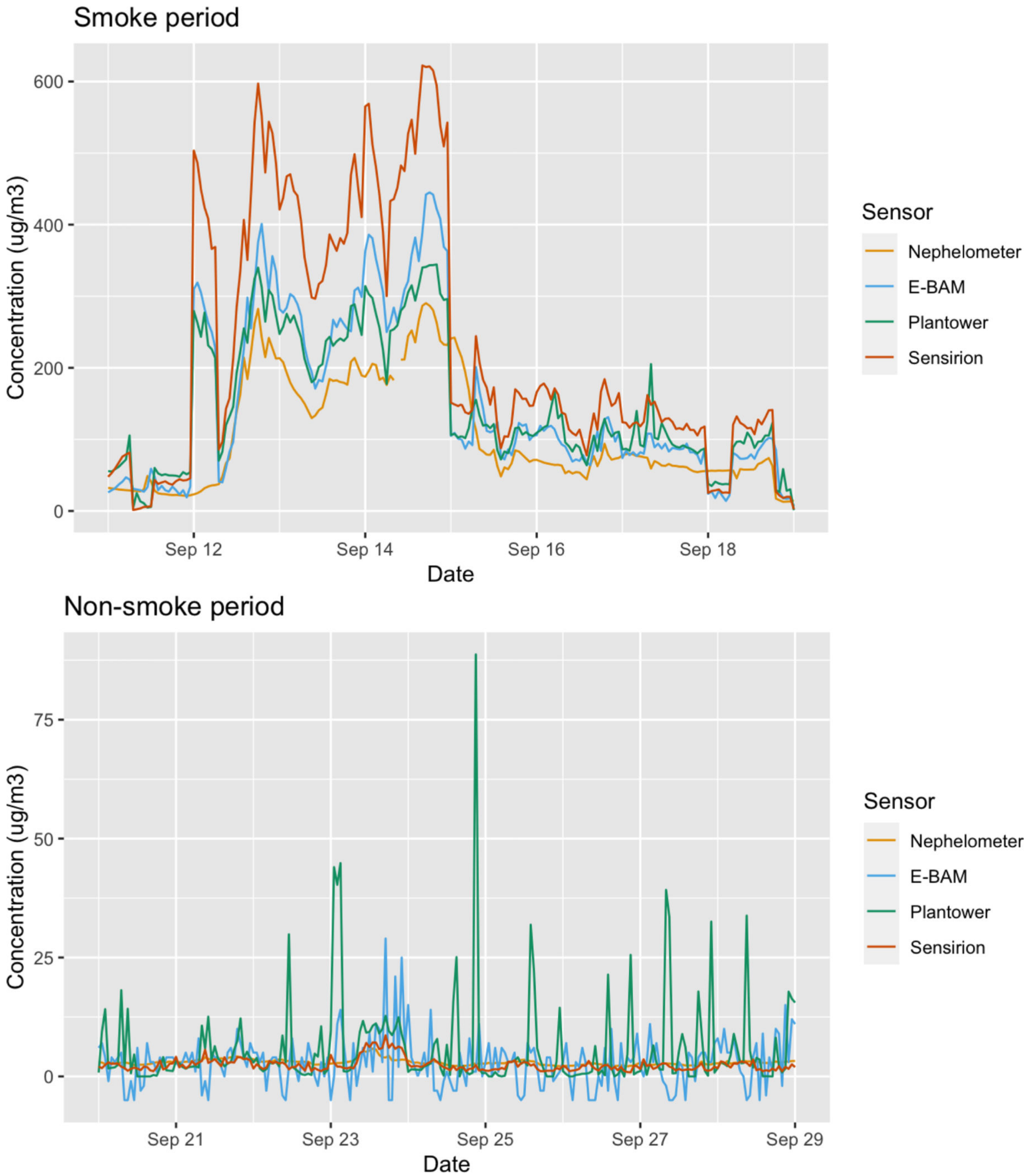

Figure 4.

Time series of PM2.5 measurements from the two low-cost sensors, the nephelometer, and the E-BAM during the smoke period (top) and the non-smoke period (bottom).

Table 1.

Wildfire smoke occupational exposure control requirements outlined in the permanent smoke rules from California and Oregon and the emergency smoke rule effective in Washington from June 15, 2022 – September 29, 2022. Note that $PM_{2.5}$ thresholds are reported in concentrations for Oregon and Washington and AQI for California, based on the rules for each state.

State	$PM_{2.5}$ Threshold	Exposure controls
California [15]	AQI 151	*Engineering controls:* provide enclosed space with filtered air. *Administrative controls:* change work schedules, reduce work intensity, or provide additional rest periods. *PPE:* provide NIOSH-approved particulate respirators for voluntary use and training on the regulations, health effects of smoke exposure, and proper use of respirators.
	AQI 500	*PPE:* required use of particulate respirators
Oregon [16]	35.5 µg/m3	*Engineering controls:* provide enclosed buildings or vehicles with filtered air. *Administrative controls:* Provide and document employee training. relocate to another outdoor work location or change work schedules. Monitor exposure levels periodically throughout the shift. *PPE:* provide NIOSH-approved filtering facepiece respirators for voluntary use.
	200.9 µg/m3	*PPE:* provide NIOSH-approved filtering facepiece respirators for mandatory use.
	500.4 µg/m3	*PPE:* provide NIOSH-approved particulate respirators for mandatory use.
Washington [17]	20.5 µg/m3	*Administrative controls:* have a written wildfire smoke response plan. Provide employee and supervisor training. Monitor exposure levels periodically throughout the shift. *PPE:* employer is encouraged to provide NIOSH-approved particulate respirators for voluntary use.
	35.5 µg/m3	*Engineering controls:* provide enclosed building, structure, or vehicle with filtered air *Administrative controls:* change work location, change work schedules, reduce work intensity, or provide additional rest periods. *PPE:* employer is required to provide NIOSH-approved particulate respirators for voluntary use.

Table 2.

NIOSH 0600 Method filter sample concentrations and mean and standard deviation PM concentrations from the nephelometer, the Plantower, and the Sensirion sensors for the three filter sampling periods along with summaries of temperature and relative humidity (RH) during each period. Relative differences between the filter concentrations and the Sensirion PM_4 measurements and between the nephelometer and $PM_{2.5}$ measurements from both sensors.

	Mean (SD)								Relative Differences		
Date	Temp (°C)	RH (%)	Nephelometer (ug/m3)	E-BAM (ug/m3)	Plantower PM2.5 (ug/m3)	Sensirion PM4 (ug/m3)	Sensirion PM2.5 (ug/m3)	Filter Sample (ug/m3)	Filter vs. Sensirion PM4	Neph vs. Plantower PM2.5	Neph vs. Sensirion PM2.5
8/30/20–9/9/20	24.3 (5.88)	34.4 (13.4)	9.13 (15.85)	12.77 (24.03)	-	-	-	5.77	-	-	-
9/9/20–9/11/20	19.8 (7.37)	39.3 (16.8)	47.52 (15.52)	57.20 (19.86)	-	-	-	11.93	-	-	-
9/11/20 10:05–14:05	13.7 (0.49)	64.8 (2.23)	28.81 (0.63)	41.88 (12.83)	10.32 (18.33)	5.79 (2.46)	7.89 (13.10)	43.85	0.87	−1.14	−1.05
9/11/20–9/19/20	16.9 (4.56)	55.0 (16.7)	107.85 (77.05)	156.10 (117.70)	152.73 (93.42)	263.32 (208.32)	192.80 (147.70)	7.86	−32.5	−0.72	−1.39
9/19/20–9/28/20	11.51 (4.69)	61.5 (19.1)	3.45 (2.12)	2.80 (5.26)	5.99 (14.12)	3.24 (3.27)	4.42 (10.34)	−0.51	7.35	−0.90	0.18

Table 3.

Mean and standard deviation $PM_{2.5}$ concentrations from the two low-cost sensors, the nephelometer, and the E-BAM during the smoke period (9/11/20–9/18/20) and the non-smoke period (9/20/20–9/28/20).

	Mean (SD)				Relative Differences		Lin's concordance correlation coeff.	
	Nephelometer (ug/m3)	**E-BAM (ug/m3)**	**Plantower (ug/m3)**	**Sensirion (ug/m3)**	**Neph vs. Plantower PM2.5**	**Neph vs. Sensirion PM2.5**	**Neph vs. Plantower PM2.5**	**Neph vs. Sensirion PM2.5**
Smoke Period	105.81 (77.05)	157.44 (117.39)	152.04 (93.47)	234.83 (181.21)	−0.73	−1.37	0.73	0.44
Non-Smoke Period	3.47 (2.20)	2.55 (5.08)	5.16 (12.17)	2.43 (1.57)	−0.89	0.20	0.07	0.48

Table 4.

Multivariable linear regression models for comparing the Sensirion and Plantower sensor performance relative to the nephelometer.

	Full study period		Smoke period		Non-smoke period	
	Sensirion	**Plantower**	**Sensirion**	**Plantower**	**Sensirion**	**Plantower**
Thingy AQ Sensor	0.405***	0.685***	0.364***	0.689***	0.374***	0.031**
	(−0.007)	(−0.012)	(−0.017)	(−0.033)	(−0.044)	(−0.014)
RH	−0.149***	−0.226***	−0.558	−0.478	0.004	0.049***
	(−0.047)	(−0.048)	(−0.626)	(−0.634)	(−0.015)	(−0.016)
Temperature	−0.019	−0.036	−1.019	−0.771	0.031	0.196***
	(−0.128)	(−0.129)	(−2.182)	(−2.211)	(−0.061)	(−0.065)
Constant	17.236***	16.498***	69.139	41.01	1.806	-1.956
	(−3.643)	(−3.654)	(−65.889)	(−67.037)	(−1.558)	(−1.682)
Observations	793	793	192	192	241	241
R2/Adjusted R2	0.818/0.817	0.816/0.816	0.71/0.705	0.703/0.698	0.271/0.262	0.069/0.057
Residual Std. Error	24.716 (df = 789)	24.791 (df = 789)	41.829 (df = 188)	42.331 (df = 188)	1.886 (df = 237)	2.132 (df = 237)
F Statistic	1,178.142*** (df = 3; 789)	1,169.405*** (df = 3; 789)	153.378*** (df = 3; 188)	148.281*** (df = 3; 188)	29.386*** (df = 3; 237)	5.853*** (df = 3; 237)