



Camp Fire Air Quality Data Analysis





CARB's mission is to promote and protect public health, welfare, and ecological resources through effective reduction of air pollutants while recognizing and considering effects on the economy. CARB is the lead agency for climate change programs and oversees all air pollution control efforts in California to attain and maintain health-based air quality standards.

Contents

Executive Summary	vi
Background	viii
Monitoring and Air Quality	2
Monitoring	2
Air Quality	2
Data Comparison - Camp Fire and Summer Wildfires	5
Particulate Matter	5
Metals	6
Chemical Species	8
Health Impacts	11
Wildfire Smoke	11
Smoke from Structural Fires	11
Wildfire Ash	12
Specific Chemical Compounds	12
Fine Particulate Matter (PM2.5)	12
Metals, Organic Carbon, Ammonium Nitrate, and Ammonium Sulfate	13
Health Effects Summary	15
Going Forward	16
Health Effects Research	16
Complex mixtures of smoke:	16
High short-term exposures:	16
Repeated or long-term exposure to wildfires:	16
Chemical-biological analysis of smoke:	16
Modeling	17
Monitoring	17
Appendix A: Resources	18
California Air Resources Board	18
California Department of Public Health	18
U.S. Environmental Protection Agency	18
Appendix B: Satellite Imagery and PM2.5 AQI Values	19
Appendix C: Toxics Air Monitoring Sites	22



Executive Summary

The 2018 Camp Fire was the deadliest wildfire in California history. At least 85 people died as the catastrophic wildfire burned through Butte County, destroying nearly 19,000 buildings and most of the town of Paradise. The fire generated a large plume of heavy smoke that traveled thousands of miles. The smoke caused dangerously high levels of air pollution in the Sacramento Valley and Bay Area in particular, for a period of about two weeks.

Staff at the California Air Resources Board (CARB) compared air quality data from the Camp Fire with three other large wildfires in 2018 that burned mostly vegetation. When wildfires burn structures, they produce a range of harmful and toxic substances. CARB's analysis shows this was indeed the case during the Camp Fire, when elevated levels of lead and zinc were detected, as well as calcium, iron and manganese. Some of these metals traveled more than 150 miles, and were detected in the air as far away as San Jose and Modesto.

Particulate matter (PM) is typically the biggest health concern from wildfire smoke. Particles from smoke tend to be very small (with diameters of 2.5 micrometers [μm] and smaller), and can be inhaled into the deepest recesses of the lung. This size of particulate matter is often referred to as $\text{PM}_{2.5}$. The tiniest, ultrafine particles in $\text{PM}_{2.5}$ can pass directly into the bloodstream where they can affect the heart and other organs. During the 2018 Camp Fire, maximum $\text{PM}_{2.5}$ levels for the period from November 8 through November 22 were more than three times the average levels seen during the same time period from 2010 to 2017.

The Paradise Gardens community in Paradise, California, was devastated by the November 2018 Camp Fire.

The number of buildings burned during this fire was significant, and not something traditionally seen in California wildfires. The Carr Fire, which burned over 50 percent more acreage in the Shasta-Trinity National Forest in late July and August of 2018, destroyed about 1,600 buildings. The Mendocino Complex Fire, occurring during the same time period, burned almost three times the acreage of the Camp Fire, but destroyed only about 250 buildings. CARB staff used data from these wildfires, as well as that collected during the Ferguson Fire in Mariposa County, which burned mostly inaccessible wildland areas during the same basic time period (late summer 2018). The goal was to better understand the air quality differences that might occur between wildfires that burn primarily vegetation, such as the Ferguson Fire, and those that burn more structures. Staff also examined potential additional health impacts that could arise from structure-burning wildfires in more populated areas.

All four wildfires showed increases in $\text{PM}_{2.5}$ levels, with higher concentrations measured at sites closer to the fires. Data from all four fires showed increases in the metal composition of $\text{PM}_{2.5}$ as well. Only the Camp Fire, however, saw significant increases in both lead and zinc. Lead was highest in Chico, which was the closest available monitoring site to the Camp Fire, while zinc levels were slightly higher at the monitoring site in Modesto, roughly 150 miles away. It is unclear if sources other than the Camp Fire may have contributed to the zinc detected in Modesto. Other components, such as organic carbon and potassium ions, used as a way to chemically trace the presence of smoke, were elevated during all the wildfires, with the highest levels also occurring in Chico during the Camp Fire. Data collected during the four wildfires showed no significant differences in other chemical components of $\text{PM}_{2.5}$.

The health impacts of air pollutants produced by wildfires can be significant. While the elevated levels of lead detected in Chico during the Camp Fire only lasted for about a day, these numbers are still concerning, since lead is considered a toxic air contaminant and any increased exposure can be harmful. Lead exposure has been linked to high blood pressure, reproductive effects and cancer in adults. Infants and young children are especially sensitive to low levels of lead that are known to cause behavioral changes and learning deficits.

The short-term spikes in particulate matter from the Camp Fire and other wildfires included in this analysis were comparable to industrial and mobile source pollution levels seen in countries like China and India. Both countries show subsequent increases in respiratory diseases and infections, and chronic heart and lung disease, resulting in increased medical visits, hospital admissions, and risk of death.

In general, short-term exposure (days or weeks) to $PM_{2.5}$ and wildfire smoke has been strongly linked to increasing severity of asthma; other respiratory disease, such as chronic obstructive pulmonary disease (COPD); inflammation or infections, including bronchitis and pneumonia; emergency department visits; and hospital admissions. Long-term exposure to $PM_{2.5}$ is linked to a wide range of human health effects, such as respiratory and heart-related illnesses and hospitalizations, adverse brain effects, depression, memory loss, learning disorders, reduced lung function growth in children and premature death.

CARB is sponsoring several studies that will provide additional insight into both the short-term and long-term health impacts of wildfire smoke. CARB-funded investigators are currently studying the associations between short-term exposure to wildfire $PM_{2.5}$ and loss of work days and increases in asthma attacks. CARB is also funding a long-term health effects study in which primates were naturally exposed during infancy to wildfires and continue to be monitored throughout adulthood. Additionally, CARB is pursuing future research to examine the effects of repeated short-term exposures to $PM_{2.5}$ that are becoming more common with large wildfires and longer wildfire seasons in California.

Increased monitoring of wildfire pollution, particularly during fires with higher incidences of structures burning, is paramount to understand the impacts these different types of fires have on air quality as well as the health of California's citizens. Partly as a result of this analysis, and the recent severity and scale of wildfires in California, CARB is proposing an expansion of monitoring efforts, including an increased response with portable samplers for both particulate matter and air toxics. In addition, CARB will modify sampling frequencies and durations as needed and increase its cooperation with CalOES to better understand the components of each type of wildfire smoke, while also providing the public with more detailed information about smoke impacts.



Background

The Camp Fire burned more than 150,000 acres, including most of the town of Paradise, from November 8 until November 25, 2018, when it was considered fully contained. Eighty-five people died as a direct result of the fire, which also destroyed almost 19,000 structures (14,000 of them residences).¹ Recovery efforts continue to this day, with rebuilding ongoing for both residents and businesses in the community.

Smoke from the fire began impacting communities almost immediately. Thick smoke plumes initially spread due west, migrating toward the coast (see Figure 1 and images in Appendix B) and eventually impacting areas both to the south and the north. There was some impact in the mountains to the east, but prevailing winds kept those impacts minimal. Smoke advisories were issued by various local air districts almost immediately. With the first initial impacts recorded on November 8, the highest levels of particulate matter (PM) were recorded between November 13 and November 16, and concentrations finally returned to normal conditions, below current state and federal PM ambient air quality standards (standards), by November 22.

This document brings together an understanding of the monitoring efforts in place at the time of the Camp Fire, analysis of the air quality data collected, and an overview of the impacts on public health. Proposed additional research efforts on the impacts of short- and long-term smoke exposure, and increased monitoring plans and needs are also discussed.

¹ www.fire.ca.gov/incidents/2018/11/8/camp-fire/, accessed 4/13/2020.

FIGURE 1: CAMP FIRE SMOKE IMPACTS – NOVEMBER 16, 2018²

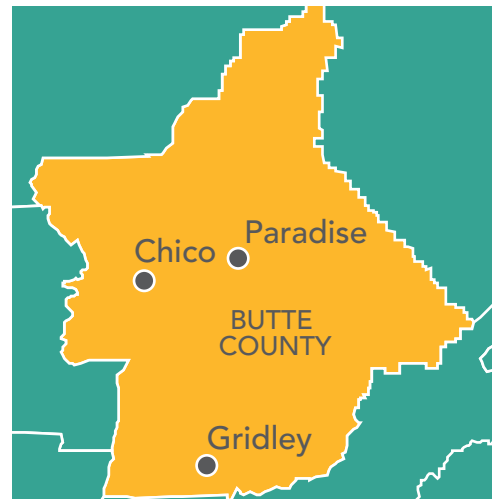
² MODIS Aqua Corrected Reflectance (True Color) Satellite Image, NASA Worldview, worldview.earthdata.nasa.gov, downloaded 10/7/20

Monitoring and Air Quality

Monitoring

During the 2018 Camp Fire in Paradise, California, all of the Butte County ambient air monitoring sites were in operation. The California Air Resources Board (CARB) operates monitoring stations in Chico (carbon monoxide [CO], nitrogen dioxide [NO₂], ozone, particulate matter [PM₁₀ and PM_{2.5}], and toxics), Gridley (PM_{2.5}), and Paradise (ozone and PM_{2.5}).

Two monitoring sites located in Paradise did not collect data during the Camp Fire; the ozone monitor at the Paradise-Airport site and the PM monitor at the Paradise-Theater site ceased operations when Pacific Gas and Electric Company (PG&E) cut power to the area on November 8. A filter-based monitor at the Chico site, 15 miles away from the Camp Fire, continued to operate, collecting samples on November 10, 2018, and November 16, 2018, (on an every 6th day collection schedule). The Chico site also collected data using a specialized speciation sampler, which uses filters to collect samples of particulate matter. The filters are later processed in a laboratory to determine the chemical composition of the particulate matter. Among other details, speciation helps quantify PM_{2.5} mass, trace elements, wood smoke tracers, carbon, and ions.³



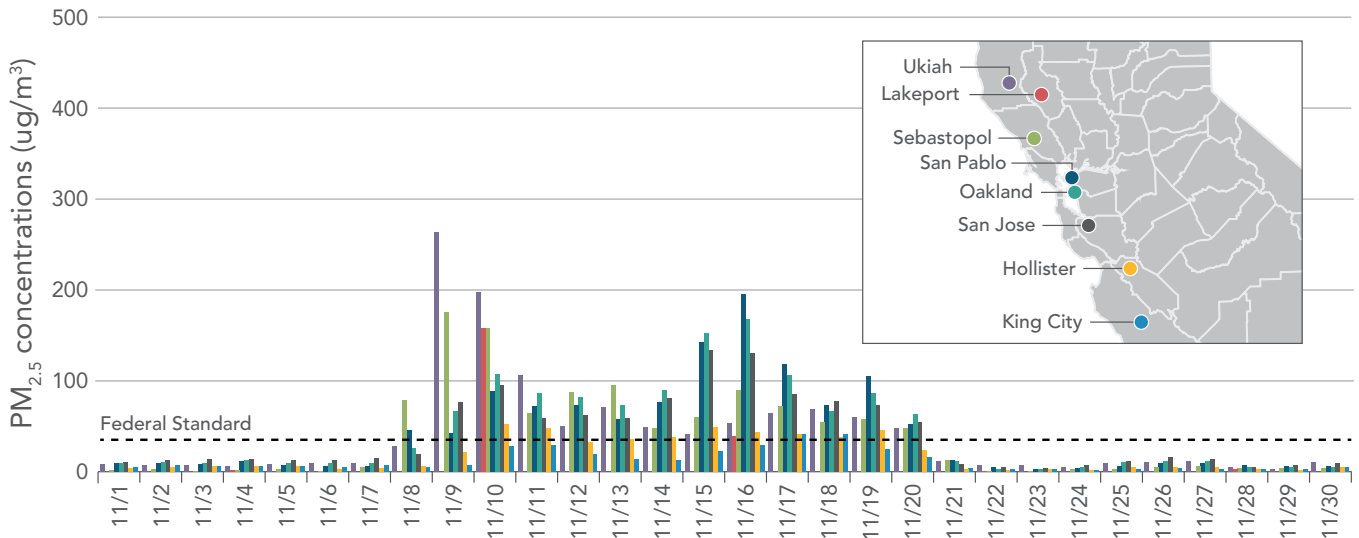
Air Quality

Particulate matter increased at most sites in Northern California west and south of the Camp Fire (Figure 2). The highest PM concentrations were recorded in Chico, the closest monitoring site to the Camp Fire and in the direct path of the smoke plumes (Figure 3). The average PM concentrations at selected monitoring sites showed significant increases when compared to both historical (2010 to 2017) November averages and to the period in which the Camp Fire occurred (Figure 3; Tables 2 and 3). From November 8 to November 22, PM_{2.5} increased by more than 300 percent from historical averages.

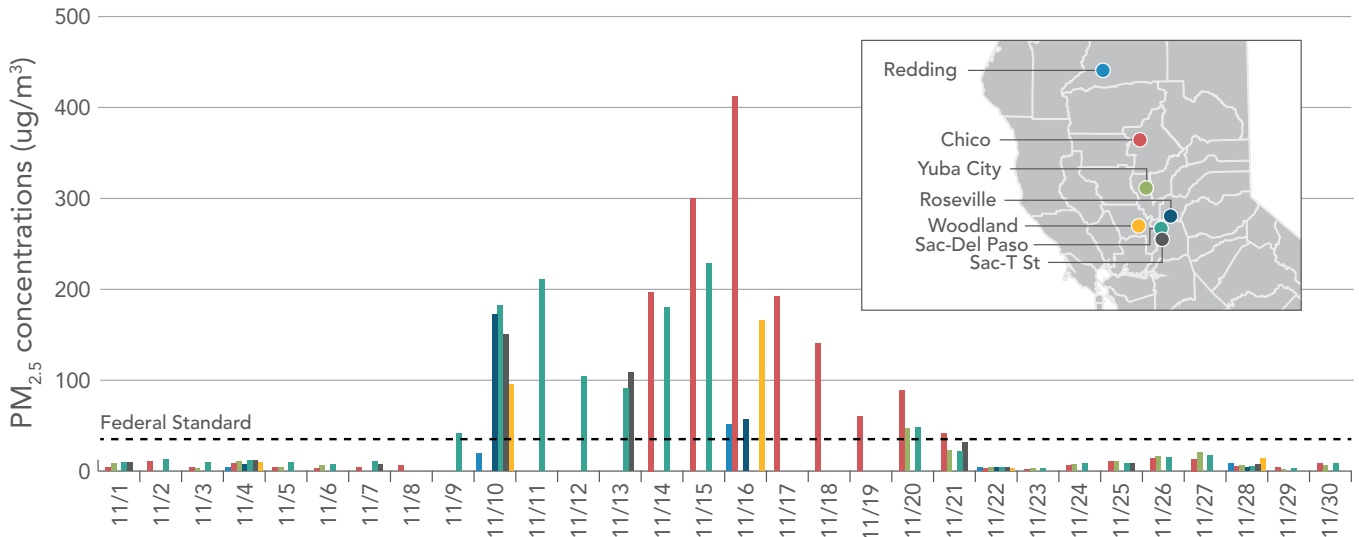
³ The Chico speciation sampler shut down as designed to protect the equipment on two occasions due to particulate loading from the smoke that exceeded designated safety limits. As a result, the sampling durations on November 10 and November 16 were less than 24 hours, as required by USEPA for submission to the Air Quality System (AQS) database. However, the speciation sampler was able to maintain the required flow rates for more than 17 hours on November 10 and more than 13 hours on November 16. While that data could not be formally reported to AQS, it was sufficient for CARB staff to analyze. All laboratory quality control criteria, as specified in CARB's standard operating procedures (SOP), were determined to be within acceptable limits. All other valid data collected from the Butte County air monitoring sites has been reported to AQS.

FIGURE 2: DAILY PM_{2.5} CONCENTRATIONS – NOVEMBER 2018

Coastal



Sacramento Valley



San Joaquin Valley

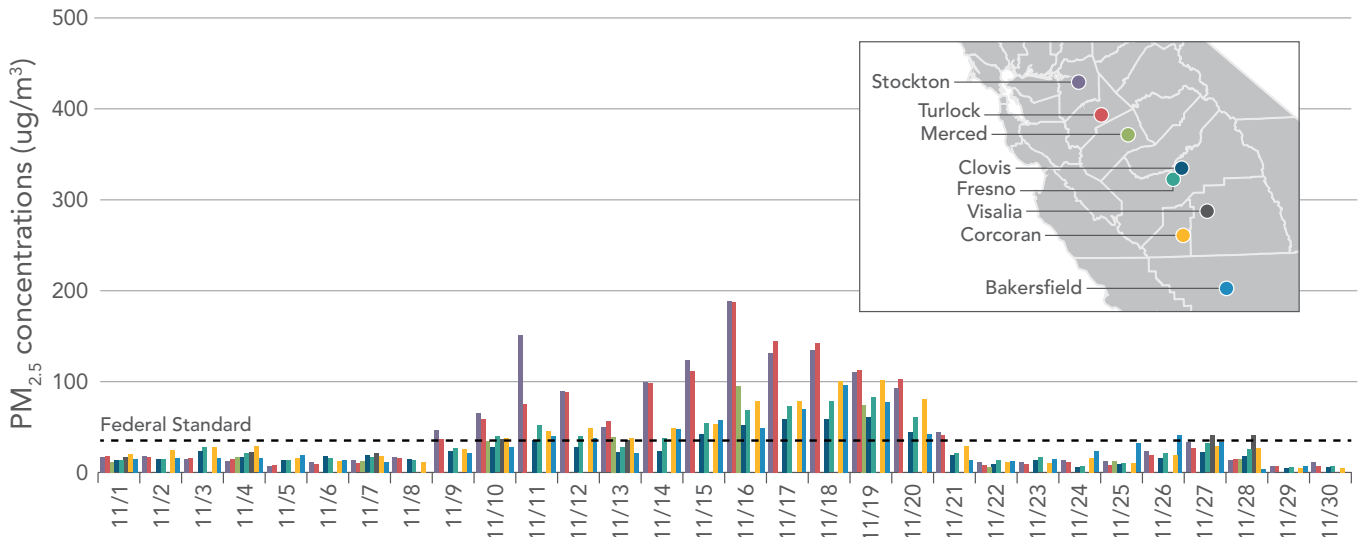
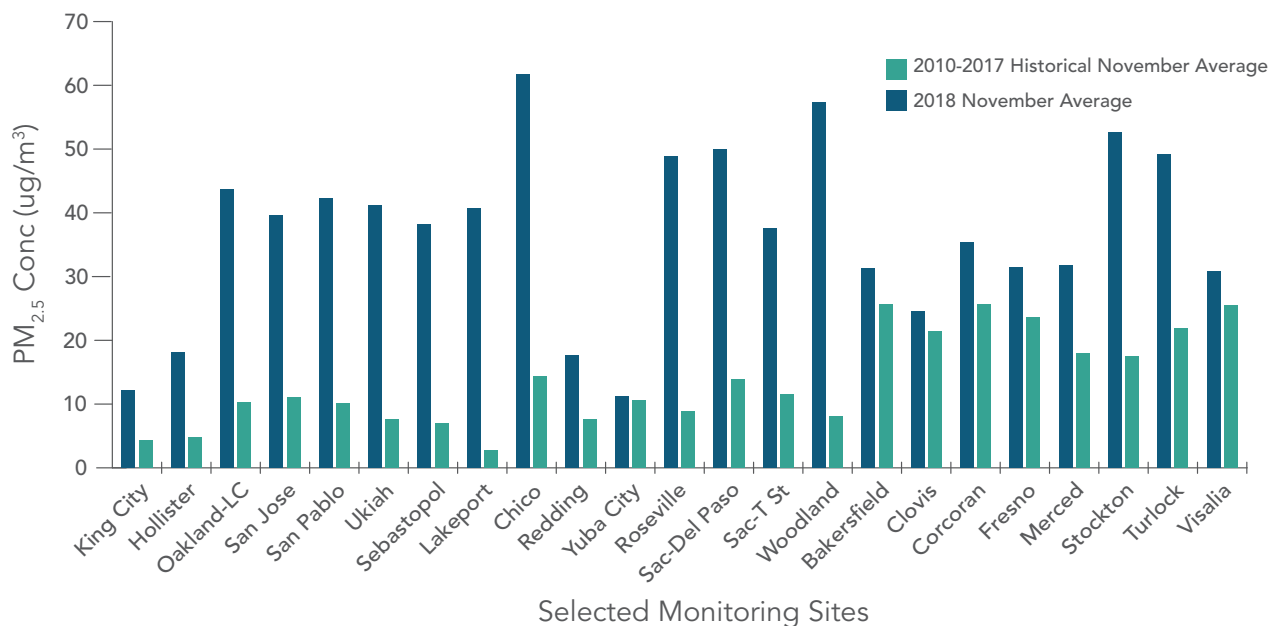


FIGURE 3: NOVEMBER MONTHLY AVERAGE CONCENTRATIONS AT SELECTED SITES – NOVEMBER 2018 COMPARED TO AVERAGE OF NOVEMBERS 2010-2017



The following tables highlight the significant increase in PM_{2.5} concentrations recorded at selected sites in the path of the smoke plume and compares them to average concentrations from the previous eight years (2010-2017).

TABLE 1: MAXIMUM PM CONCENTRATIONS AT FOUR SELECTED SITES

Site	PM _{2.5}	
	Concentration (ug/m ³)	Date
Chico	412	11/16/18
Modesto	190	11/16/18
Sacramento-Del Paso	228	11/15/18
San Jose	134	11/15/18

TABLE 2: COMPARISON OF PM CONCENTRATIONS AT SELECTED SITES TO HISTORICAL AVERAGES

Average Concentrations at Selected Sites (ug/m ³)	PM _{2.5}	
	2010-2017	2018
November 1 - 30	16	37
November 8 - 22	15	64

TABLE 3: INCREASE IN PM CONCENTRATIONS AND PERCENTAGES FROM HISTORICAL AVERAGES

2018 Increase from Historical (2010-2017) Average	PM _{2.5}	
	Concentration Increase (ug/m ³)	Percent Increase (%)
November 1 - 30	21	137
November 8 - 22	49	315

Data Comparison - Camp Fire and Summer Wildfires

Data from the Camp Fire was compared with data collected during the Carr, Mendocino Complex, and Ferguson fires in the summer of 2018 (Table 4). The Camp Fire, with almost 19,000 structures burned, showed characteristics not seen in the other, more traditional wildfires that burned mostly vegetation.

TABLE 4: SELECTED WILDFIRES IN CALIFORNIA IN 2018 FOR DATA COMPARISON

Wildfire	Location (Counties)	Time Frame (ignition-containment)	Acreage Burned (appx)	Structures Destroyed (appx)
Camp Fire	Butte	11/8/18-11/25/18	150,000	18,800
Carr Fire	Shasta, Trinity	7/23/18-8/30/18	230,000	1,600
Mendocino Complex (Ranch and River Fires)	Colusa, Glenn, Lake, Mendocino	7/27/18-9/18/18	460,000	~250
Ferguson Fire	Mariposa	7/13/18-8/19/18	97,000	<10

During the 2018 summer wildfires and the Camp Fire, Chico showed the highest concentrations of $PM_{2.5}$ of the four selected speciation monitoring sites. This is likely due to the fact that Chico was the closest of the speciation monitors to three of the four fires evaluated in this report. In Chico, the $PM_{2.5}$ concentration increased by nine times above the average during the summer wildfires, and almost 100 times above the average during the Camp Fire.

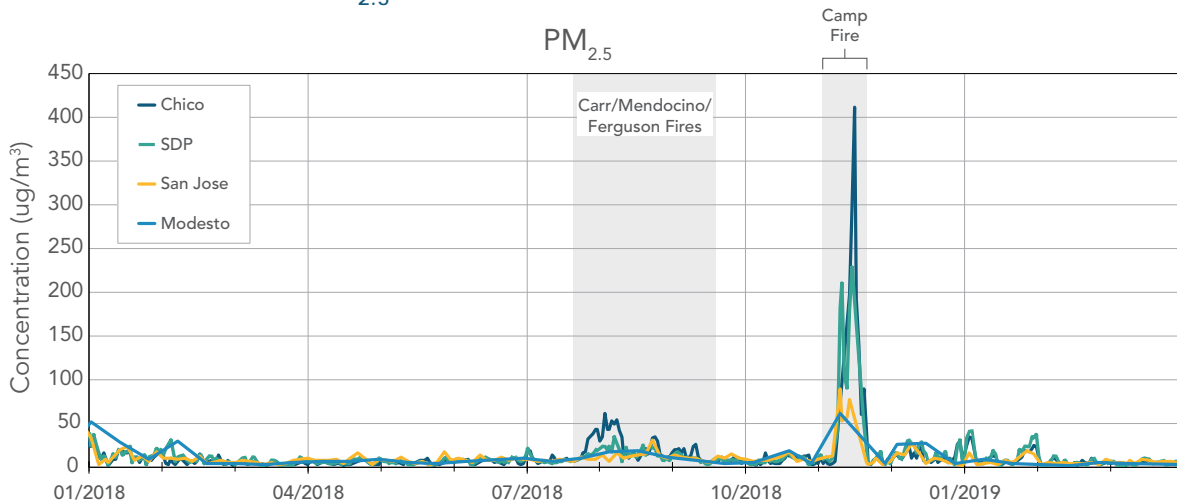
Particulate Matter

Particulate matter is the principal pollutant of concern with wildfire smoke, particularly $PM_{2.5}$ (with diameters of 2.5 micrometers, far smaller than the diameter of a human hair), which can be inhaled into the lungs. $PM_{2.5}$ is a complex mixture of solids and aerosols that can contain a myriad of chemical compounds, including metals, organic and elemental carbon, potassium, organic matter and geologic material, and potentially ammonium nitrate and ammonium sulfate.

During the 2018 summer wildfires and the Camp Fire, Chico showed the highest concentrations of $PM_{2.5}$ of the four selected speciation monitoring sites. In Chico, the $PM_{2.5}$ concentration increased by nine times above the average during the summer wildfires, and almost 100 times above the average during the Camp Fire.

$PM_{2.5}$ contributed by the summer wildfires continued until the end of September 2018. The $PM_{2.5}$ contributed by the Camp Fire continued until the end of November 2018. The slightly elevated $PM_{2.5}$ seen in December 2018 and early January 2019 could be from lingering smoke and ash from the Camp Fire, the high PM levels typical of that time of year (due to woodstove use), or both.

FIGURE 4: COMPARISONS OF $PM_{2.5}$ CONCENTRATIONS



Metals

Metal concentrations were higher during the Camp Fire, particularly lead (Pb) and zinc (Zn), which increased dramatically (Figure 5). Other metals including calcium (Ca), iron (Fe), and manganese (Mn) were elevated during all the wildfires studied. The metal contributions to $PM_{2.5}$ speciation data from the Camp Fire continued until the end of November 2018.

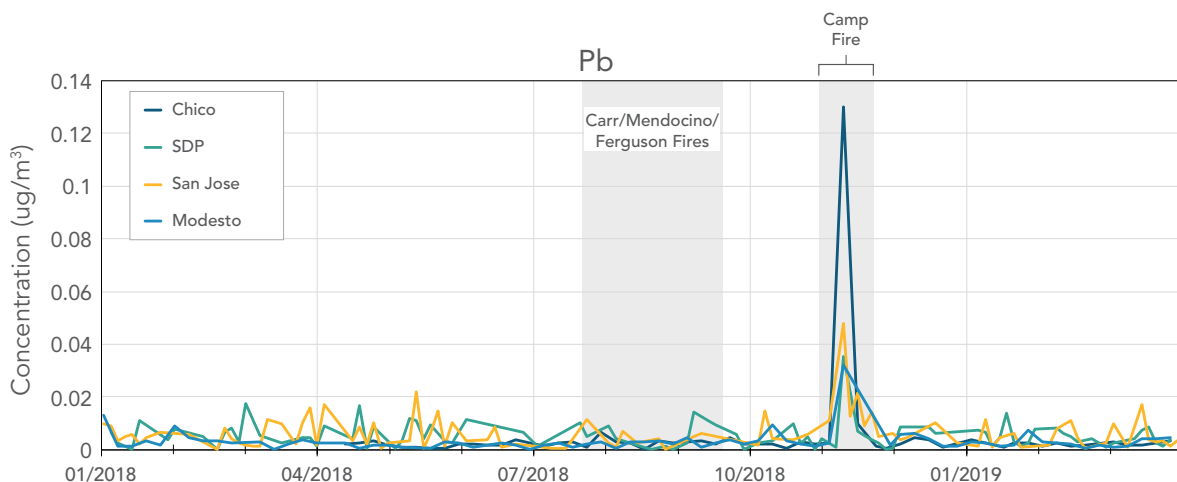
Among the key findings:

- The San Jose monitoring site showed the highest concentrations of both calcium and iron during the Camp Fire; concentrations of the two metals increased to about twice the levels seen in the days prior to the event.
- Manganese and lead were highest at the Chico monitoring site; concentrations increased by more than four times and 50 times above the average, respectively.
- Zinc was highest at the Modesto site, which already had slightly higher zinc concentrations; concentrations increased by more than 20 times the average at Modesto and 33 times the average at Chico.

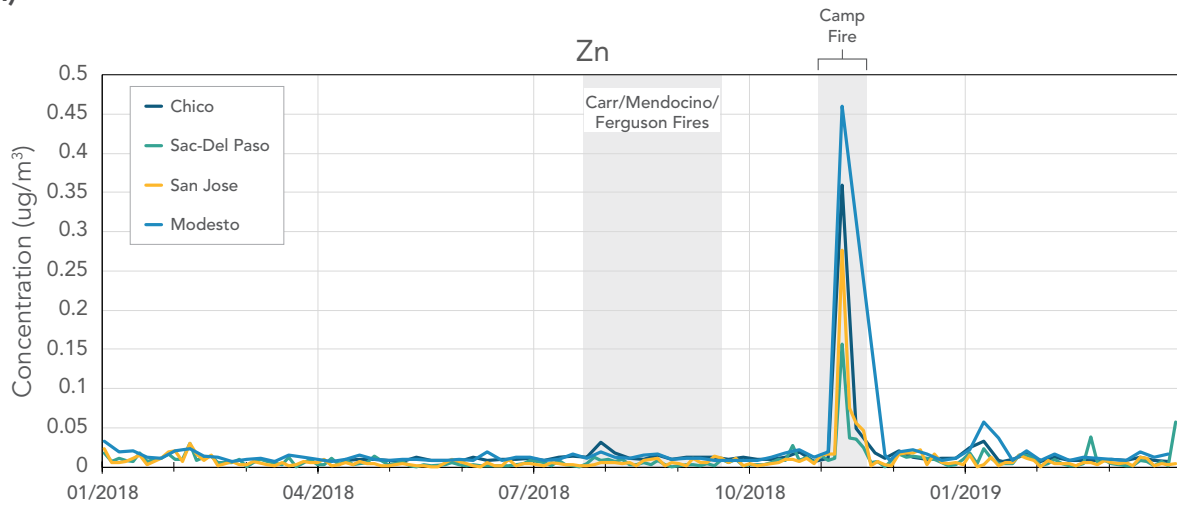
Potential effects of these elevated levels are discussed in the Health Impacts section of this report.

FIGURE 5: CONCENTRATION OF METALS IN $PM_{2.5}$ BETWEEN JANUARY 2018 AND MARCH 2019

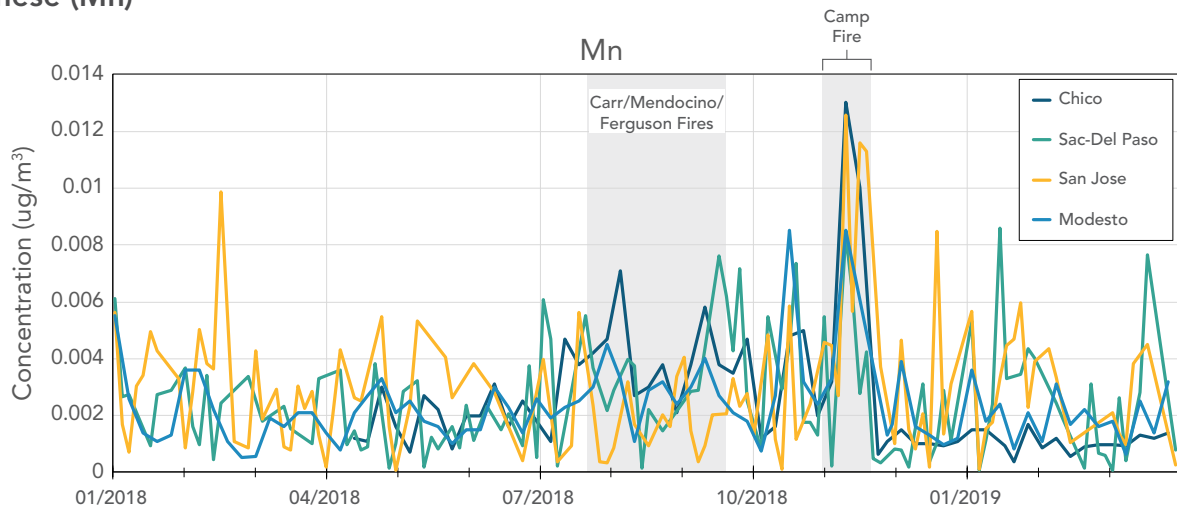
Lead (Pb)



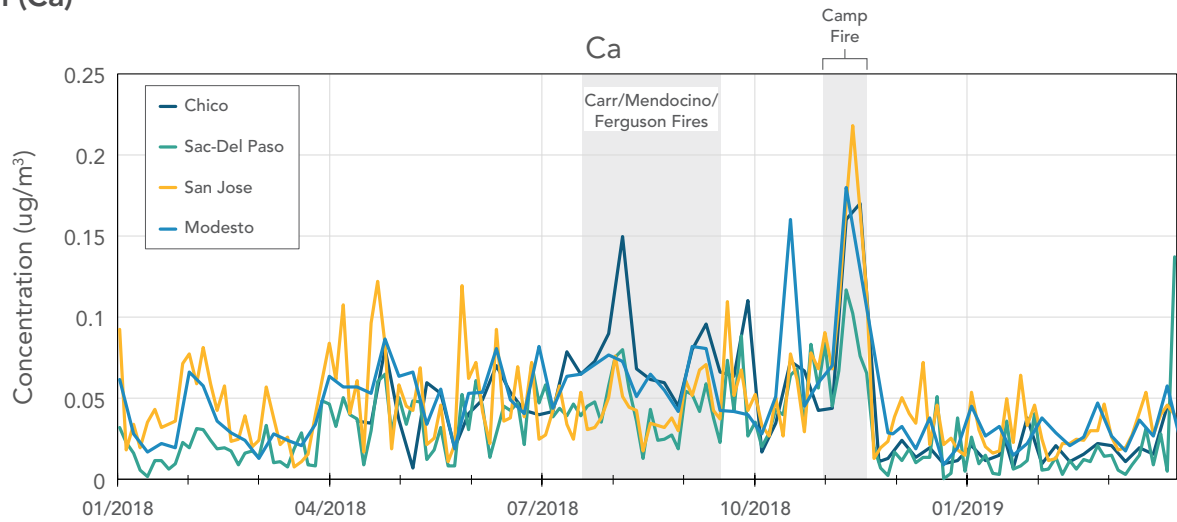
Zinc (Zn)



Manganese (Mn)



Calcium (Ca)

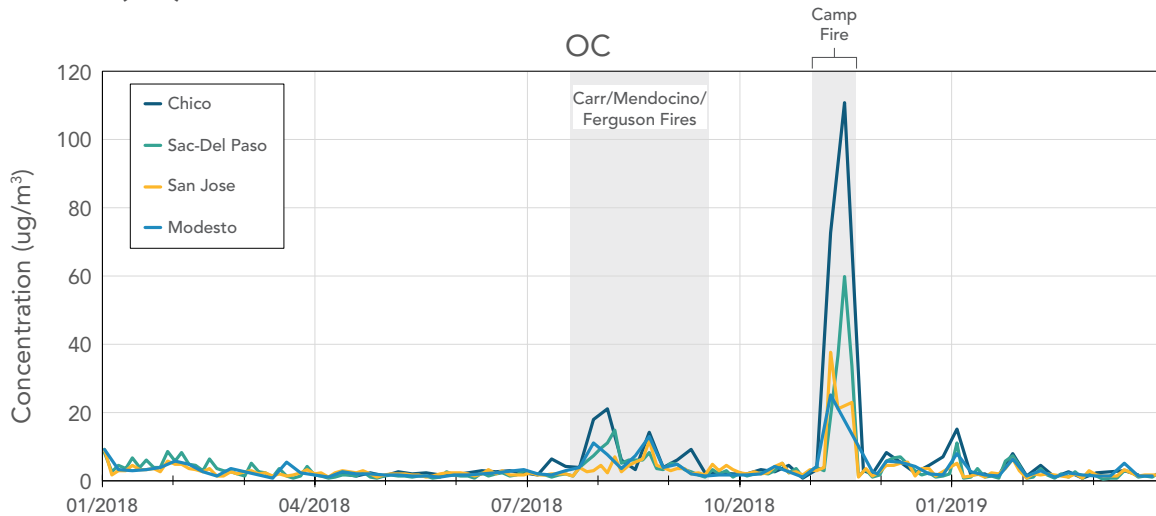


Chemical Species

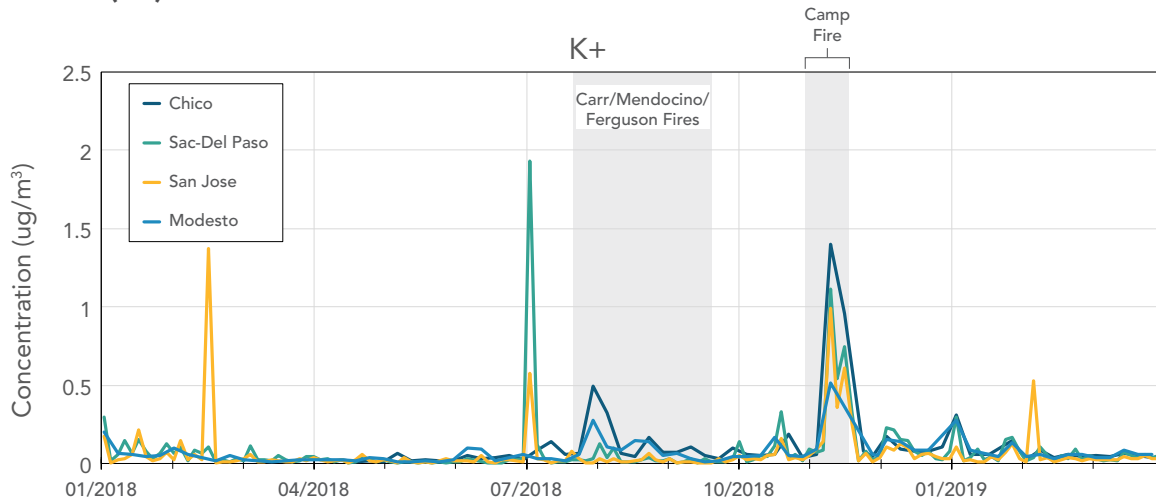
Organic carbon (OC) and potassium ions (K^+) are known chemical tracers for biomass burning and can help track the influence and intensity of wildfire smoke. All four selected sites showed elevated concentrations of these species during both the summer wildfires and the Camp Fire, with concentrations during the Camp Fire much higher than during the summer wildfires (Figure 6). The Chico site recorded concentrations of organic carbon and potassium ions of about 36 times and 24 times higher than normal, respectively. The increased concentrations of organic carbon and potassium ions continued until the end of November 2018, when the Camp Fire was fully contained.

FIGURE 6: $PM_{2.5}$ ORGANIC CARBON AND POTASSIUM IONS CONCENTRATIONS BETWEEN JANUARY 2018 AND MARCH 2019

Organic carbon (OC)



Potassium ions (K^+)



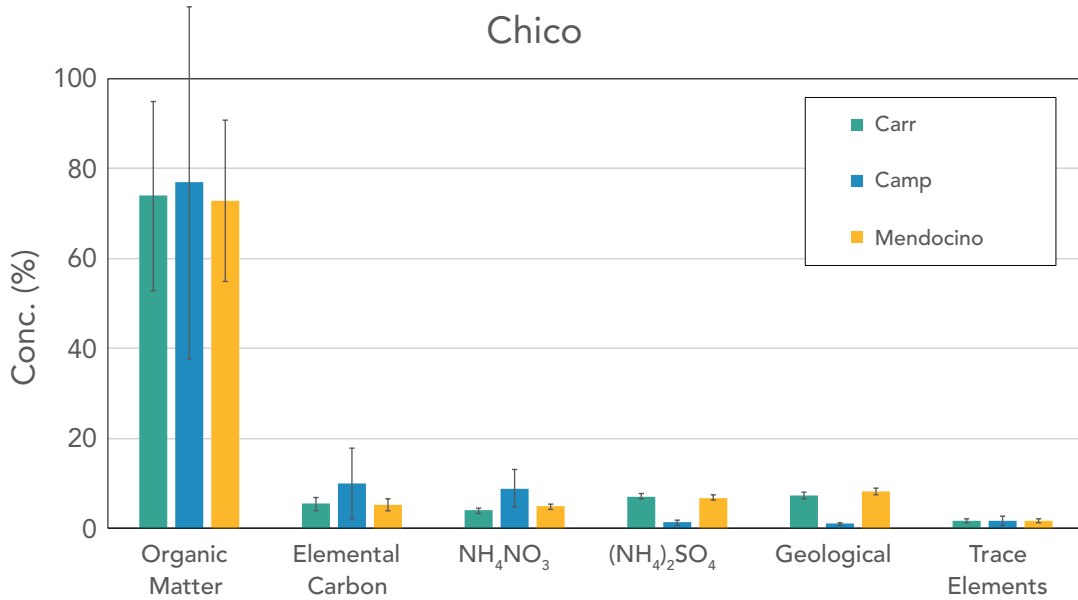
Other chemical species collected from samples taken during the Camp Fire and the summer wildfires were also compared for the selected monitoring sites. In general, organic matter contributes far less than ammonium sulfate and ammonium nitrate to ambient $PM_{2.5}$ concentrations in California.⁴ The analysis of the Camp Fire data, however, as well as that from the summer wildfires, showed the

⁴ CARB, 2015 ARB Review of San Joaquin Valley $PM_{2.5}$ State Implementation Plan, Appendix A. Weight of Evidence Analysis, page A-16, arb.ca.gov/resources/documents/2015-and-2008-san-joaquin-valley-pm25-attainment-plans, last accessed 7/20/20.

majority of $PM_{2.5}$ was composed of organic matter, with lesser contributions from elemental carbon, ammonium nitrate, ammonium sulfate, geologic materials, and trace elements. The differences between the wildfires, however, were not as clearly seen as in the figures above (Figures 4 through 6). These difference could be due to traditional seasonal patterns in chemical formations, winter versus summer, for example, or even monitor sampling schedule differences (Figure 7). The data is presented here, but the differences are not considered significant enough to draw any conclusions regarding the differences between the Camp Fire and the summer wildfires.

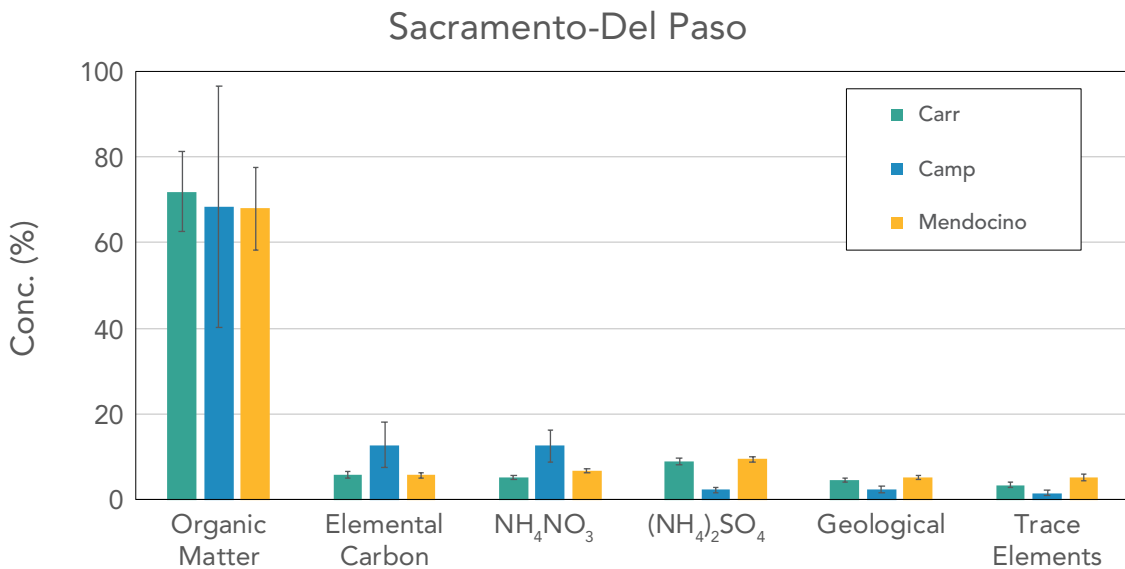
FIGURE 7: COMPARISONS OF $PM_{2.5}$ COMPOSITIONS DURING WILDFIRES IN 2018
 (PERCENT OF TOTAL $PM_{2.5}$ COMPOSITIONS \pm STANDARD ERROR)

Chico (sampling days: Carr: 7 ; Camp: 3; Mendocino: 9)

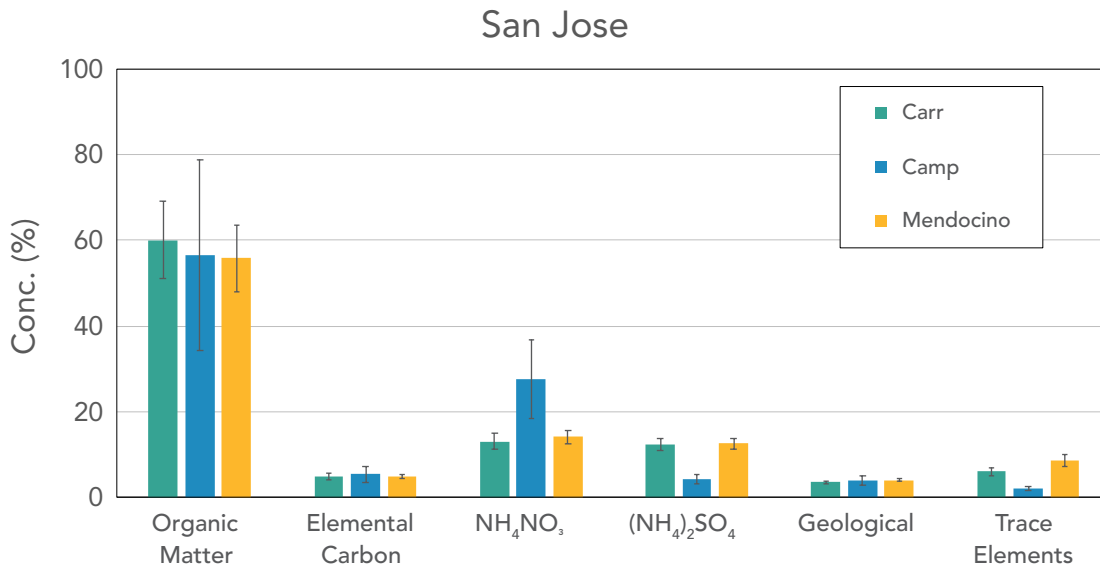


At Chico, the $PM_{2.5}$ components on November 10 (17.7 hour sampling time) & 16 (13.0 hour sampling time) were included.

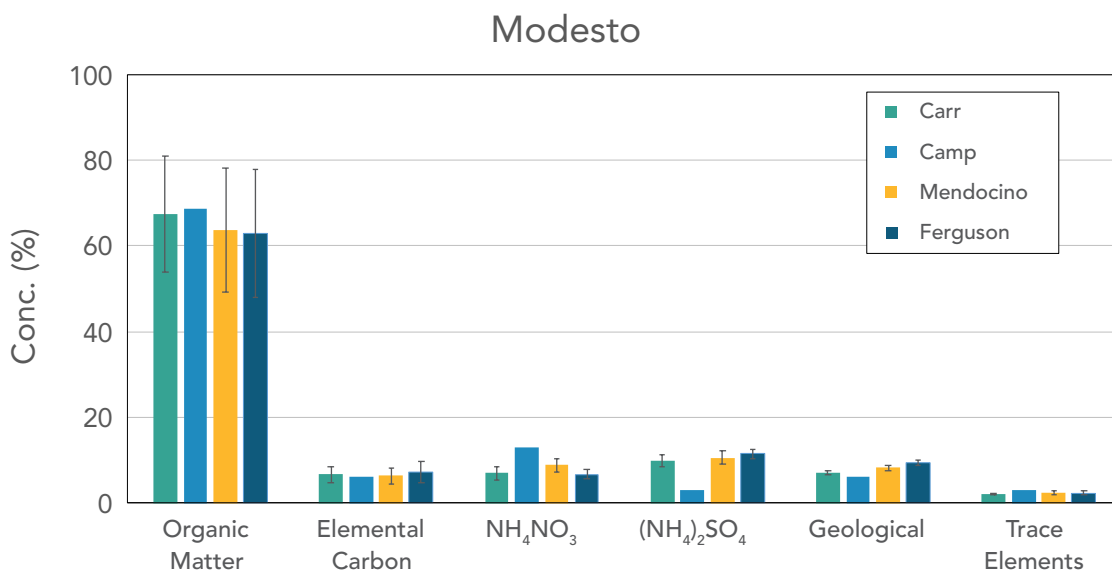
Sacramento-Del Paso (sampling days: Carr: 13; Camp: 6; Mendocino: 18)



San Jose (sampling days: Carr: 13; Camp: 6; Mendocino: 18)



Modesto (sampling days: Carr: 7; Camp: 1; Mendocino: 9; Ferguson: 3)



Health Impacts

As previously noted, wildfires produce complex mixtures of potentially harmful air pollutants, including particulate matter (PM) which is comprised of increased levels of metals, toxic air contaminants, and other chemical compounds. Smoke from any type of fire (e.g. forest, brush, crop, structure, tires, waste, or wood burning) is a complex mixture of tiny solid, liquid, and gas particles and chemicals produced by incomplete burning of carbon-containing materials. More specifically, smoke from structural fires, such as residential, commercial, and industrial fires, contains more than a hundred dangerous toxins and poisonous gases, including carbon monoxide and hydrogen cyanide. Carcinogenic compounds from the burning of household materials within structures, such as benzo(a) pyrene, toxic dioxin compounds, and benzene, have been reported.⁵ PM_{2.5} can be inhaled into the deepest recesses of the lungs and the association between PM_{2.5} and heart and lung effects is well documented in scientific literature.

Wildfire Smoke

Adverse health effects from exposure to wildfire smoke include increases in severity of respiratory problems, such as asthma, increases in emergency department visits for heart attacks and strokes, and increased risk of premature death.⁶ The U.S. EPA has estimated that short-term (days to weeks) exposure to wildfire-related PM_{2.5} results in between 1,500 and 2,500 deaths annually.⁷ During the 2007 San Diego wildfires, emergency department visits increased by 34 percent for respiratory conditions in general and by 112 percent for asthma in particular, compared to pre-wildfire periods.⁸ During the 2003 heavy wildfire smoke conditions in Southern California, there was a 34 percent increase in asthma hospital admissions.⁹

There is limited information on the potential health impacts due to long-term repeated exposure to wildfire smoke over multiple seasons.¹⁰ Since wildfire smoke contains PM_{2.5} and PM₁₀, the long-term health impacts from wildfire smoke are expected to be in line with the effects from those pollutants.¹¹

Smoke from Structural Fires

Since wildfires, and the Camp Fire in particular, can also burn structures, such as homes, associated buildings, and vehicles occupational studies can shed light on the long-term health impacts. For example, in a long-term study of U.S. firefighters, investigators reported an excess of lung, digestive, and urinary cancers, and a rare cancer of the lung - mesothelioma (associated with asbestos exposure). Recently, the investigators reported excess leukemia and excess chronic obstructive pulmonary disease (COPD)-related deaths associated with the amount of time spent at fires.¹² Some of these long-term health impacts, such as heart disease, reduced lung function, and lung cancer, are

5 Blais et al., *Fire Technology* 56:489-514, 2020; Van der Veen and Boer, *Chemosphere* 88:1119-1153, 2012.

6 Black et al., *Environ Toxicol Pharmacol* 55: 186–195, 2017.

7 Fann et al., (2018). The health impacts and economic value of wildland fire episodes in the US: 2008–2012. *Science of the total environment*, 610, 802-809.

8 Hutchinson et al., *PLoS Med.* 15(7): e1002601, 2018.

9 Delfino et al., *Occup. Environ. Med.* 66:189–97, 2009.

10 U.S. EPA (2019). *Wildfire Smoke: A Guide for Public Health Officials*. Officials, first published in 2002, Revised 2019. EPA-452/R-19-901 August 2029. Available at: airnow.gov/publications/wildfire-smoke-guide/wildfire-smoke-a-guide-for-public-health-officials

11 Booze et al., *Journal of Occupational and Environmental Hygiene* 1: 296–305, 2004; Coker et. al., *J Occup Environ Med.* 61(3): e91–e94, 2019; Smith et. al., *J Am Heart Assoc.* 18; 7(18): e009446, 2018. Finlay et.al., *PLoS Curr.* 4:e4f959951cce2c, 2012.

12 Daniels et al., *Occup Environ Med* 71:388-397, 2014; Pinkerton et. al., *Occup Environ Med* 77:84-93, 2020.

impacts also seen in populations exposed to PM_{2.5} and PM₁₀.^{13,14}

Among the many compounds present in structures are flame retardants, commonly used in consumer products, such as furniture, textiles, building materials, and electronics. One chemical group, called phosphorus flame retardants, has shown negative hormonal effects in laboratory tests. Further, these compounds are associated with increased hyperactivity in children.¹⁵ Given these many potential sources of these compounds, and considering the byproducts of the combustion of wood, plastics, and other chemicals released from burning structures, it is clear that the tiny particles, gases and chemicals in smoke generated from structure fires are hazardous to human health.

Health Concerns Regarding Wildfire Ash

Wildfire ash is made up of both large and small particles (dust, dirt, and soot) left behind after a fire. Ash deposited on surfaces indoors and outdoors can be inhaled if it becomes airborne during clean up, and exposure to ash and other products of the fire can irritate the eyes, nose, or skin and cause coughing and other health effects.^{16,17} Ash inhaled deeply into lungs may trigger an asthma attack or make it difficult to breathe for those with other respiratory diseases. In general, ash from burned structures is considered more hazardous than forest ash. Because of these ongoing concerns regarding the health effects associated with ash exposures, additional research is needed to assess health risks associated with cleanup efforts, as well as resuspension of ash deposited indoors.^{18,19}

Specific Pollutants

Fine Particulate Matter (PM_{2.5})

Long-term exposure to fine particulate matter has been linked to a wide range of human health effects, such as respiratory and heart-related illnesses and hospitalizations, adverse brain effects, depression, memory loss, learning disorders, reduced lung function development in children, and premature death. With respect to wildfire PM_{2.5} and smoke, several studies have shown strong associations between exposure and increasing severity of asthma, other respiratory disease, such as COPD, and an increase in inflammation or infections, including bronchitis and pneumonia, emergency department visits, and hospital admissions.^{20,21} Available studies link short-term exposures to PM_{2.5} with increased risk of heart disease and death. The short-term spikes in particulate matter from the Camp Fire and other wildfires in California are similar to some of the pollution levels seen in other countries such as China and India that experience high levels of

13 U.S. EPA. (2019). Integrated Science Assessment for Particulate Matter. Research Triangle Park, NC. Center for Public Health and Environmental Assessment, Office of Research and Development. U.S. EPA. EPA/600/R-19/188 December 2019.

14 Adetona et al., *Inhal Toxicol* 28:3, 95-1, 2016.

15 Xu et al., *Toxicology Res.* 6:63-72, 2017; Dishaw et. al., *Current Opinion in Pharm.* 19:125-133, 2014; Castorina et al., *Chemosphere* 189:574-580, 2017.

16 Kjellstrom et al., *Air and Water Pollution: Burden and Strategies for Control*. In: *Disease Control Priorities in Developing Countries: Chapter 43*, 2nd edition. Jamison DT, Breman JG, Measham AR, et al., editors. Washington (DC): The International Bank for Reconstruction and Development / The World Bank; New York: Oxford University Press; 2006.;

17 Gonino et al., *Sci Total Environ.* 665:226-234, 2019; Burton et. al. *Plos One* 11:e0153372, 2016; Alexakis et al., *Environ. Research* 183:109153, 2020; Re et. al., *Ecology and Environ. Safety* 194:110361, 2020.

18 Burton et. al. *Plos One* 11:e0153372, 2016.

19 Stein et al., *Environ Toxicol Chem* 31(11):2625-38, 2012.

20 Youssouf et al., *Int J. Environ Res Public Health* 11:11772-11804, 2014; Liu et al., *Environ. Res.* 136:12-132, 2015; Reid et al., *Environ. Health Perspectives.* 124:1334-1343, 2016.

21 U.S. EPA. (2019). Integrated Science Assessment for Particulate Matter. Research Triangle Park, NC. Center for Public Health and Environmental Assessment, Office of Research and Development. U.S. EPA. EPA/600/R-19/188 December 2019.

industrial and mobile source pollution. Both countries show subsequent increases in respiratory diseases and infections, and chronic heart and lung disease, resulting in increased medical visits, hospital admissions, and risk of death.^{22,23,24}

High levels of particulate matter in wildfire smoke posed serious health risks to residents of Butte County, as well as other areas affected by the Camp Fire. On some days, for example, the PM_{2.5} levels in Chico far exceeded the national 24-hour standard of 35 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$). Inhaling smoke from wildfires for a short time can acutely increase the severity of asthma and COPD.²⁵ Over the entirety of the Camp Fire period, the average concentration of PM_{2.5} at the sites shown in Figure 2 was 64 $\mu\text{g}/\text{m}^3$, a level almost twice the 24-hour standard, ranging from 20 to 144 $\mu\text{g}/\text{m}^3$. Chico was especially hard hit with the highest period average of 144 $\mu\text{g}/\text{m}^3$ and a maximum high daily-average of 412 $\mu\text{g}/\text{m}^3$, almost 12 times the 24-hour standard.²⁶

While more research is needed to specifically study health impacts from wildfire smoke, these high levels of particle pollution certainly had short-term effects on individuals with respiratory and heart illnesses and likely also contributed to long-term health effects.

Metals, Organic Carbon, Ammonium Nitrate, and Ammonium Sulfate

Particulate matter from wildfire is a complex mixture that typically contains elements that are highly toxic. In the following sections, information on potential health effects is provided for the metals, organic carbon, ammonium nitrate, and ammonium sulfate monitored in the Camp Fire as well as during the Carr, Mendocino, and Ferguson fires.

Lead (Pb)

CARB has led efforts to reduce lead exposures, including cleaner fuels regulations, and identified lead as a “toxic air contaminant” in 1997.²⁷ The EPA set the National Ambient Air Quality Standards (NAAQS) for lead at 0.15 $\mu\text{g}/\text{m}^3$, using a 3-month average concentration. The NAAQS for lead is set by calculating the monthly average of the lead concentrations at each monitor and averaging that value with the prior two months’ average concentrations. The NAAQS standard is based on health effects that include adverse brain development in children and high blood pressure, and reproductive effects, and cancer in adults. Infants and young children are especially sensitive to low levels of lead that are known to cause behavioral changes and learning deficits.

During the Camp Fire, for a period of 17 hours on November 10th, the ambient lead concentration was elevated to an average of 0.13 $\mu\text{g}/\text{m}^3$. Levels of PM_{2.5} recorded by the parallel filter sampler climbed dramatically after the shutdown of the over-loaded speciation sampler in 17 hours. Estimating the lead levels from the 17 hours of sampling to a 24-hour sampling time, the potential daily lead level would be approximately 0.17 $\mu\text{g}/\text{m}^3$ for the PM_{2.5} sample. While this higher level of lead was only seen for one day and therefore cannot be compared to the national 3-month average standard, the peak level of lead for the Camp Fire is concerning since lead is considered a toxic

22 Xu et al., PLoS One 11(4): e0153099, 2016.

23 WHO (2006). WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Summary of risk assessment. WHO WHO/SDE/PHE/OEH/06.02 200. 20. Avenue Appia, 1211 Geneva 27, Switzerland. Global update 2005. Available at: apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

24 Rajak et al., Int J Environ Health Res. 1-25, 2019.

25 Black et al., Environ Toxicol Pharmacol 55: 186–195, 2017; Liu et al., Environ. Res. 136:12-132, 2015.

26 U.S. EPA. (2020). Policy Assessment for the Review of the Particulate Matter National Ambient Air Quality Standards. Research Triangle Park, NC. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. U.S. EPA. EPA-452/R-20-002 January 2020. Available at: epa.gov/sites/production/files/2020-01/documents/final_policy_assessment_for_the_review_of_the_pm_naaqs_01-2020.pdf

27 California Air Resources Board (CARB) Lead & Health, arb.ca.gov/resources/lead-and-health; World Health Organization (WHO) Lead Poisoning and Health, August 2019.; U.S. EPA. (2014). Policy Assessment for the Review of the Lead National Ambient Air Quality Standards. Research Triangle Park, NC. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. U.S. EPA. EPA-452/R-14-001 May 2014. Available at: epa.gov/ttn/naaqs/standards/pb/data/140501_pa_pb_fin.pdf

air contaminant that accumulates in human bodies, especially children, and any increased levels of exposure could be harmful.²⁸

Manganese (Mn)

The short-term exposure to manganese from the wildfires is unlikely to pose health risks to the residents of Chico or those in other areas impacted by the wildfire smoke. During the Camp Fire, the ambient manganese concentration in Chico, the highest site, was 0.013 $\mu\text{g}/\text{m}^3$, lower than U.S. EPA reference concentrations of 0.05 $\mu\text{g}/\text{m}^3$ or the California Office of Environmental Health Hazard Assessment (OEHHA) 8hour manganese reference exposure level value of 0.17 $\mu\text{g}/\text{m}^3$.^{29,30}

Zinc (Zn)

Due to the lack of information on the health impacts of zinc, the health effects of short-term exposure during the Camp Fire could not be determined. Ambient zinc concentrations increased to 0.36 and 0.46 $\mu\text{g}/\text{m}^3$ in Chico and Modesto, respectively. The U.S. EPA does not set zinc reference concentrations for inhalation exposure and sufficient data and literature on exposure to zinc compounds was unavailable.³¹

Organic Carbon (OC) and Associated Organic Compounds

The highest organic carbon concentrations during the Camp Fire were reported in the Chico area. The speciation sampler at Chico detected peak concentrations of 111 $\mu\text{g}/\text{m}^3$, almost five times the peak concentrations (21 $\mu\text{g}/\text{m}^3$) recorded at the same site during the Carr, Mendocino, or Ferguson fires. The average organic carbon concentration at Chico during the Camp fire (92 $\mu\text{g}/\text{m}^3$ for two days of sampling) was approximately ten times higher than what was recorded during the summer wildfires.

The organic carbon component of $\text{PM}_{2.5}$ from wildfires and biomass combustion accounts for approximately 50 to 67 percent of the PM mass, is a complex chemical mixture, and contains numerous toxic compounds. One example of a toxic class of compounds present in organic carbon in wildfires is polycyclic aromatic hydrocarbons (PAHs).³² Many PAHs, or their chemical derivatives, can cause DNA damage and cancer.³³ These compounds can also cause inflammation that can damage the lungs and other organs, such as the heart.³⁴ Additional toxic compounds present in organic carbon from wildfires, especially from burning of structures, include plasticizers, flame retardants, metals, and aldehydes.³⁵ To our knowledge, the levels of PAHs and these additional toxic compounds were not measured during the Camp Fire. The level of organic carbon measured in the Camp Fire can potentially result in increased health risks since organic carbon is a principal

28 U.S. EPA (2013) Integrated Science Assessment (ISA) for Lead. Research Triangle Park, NC. National Center for Environmental Assessment-RTP Division, Office of Research and Development, U.S. EPA/600/R-10/075F June 2013, Errata Sheet created 5/12/2014. Available at: cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=255721

29 U.S. EPA. (2012). Inhalation Health Effect Reference Values (IHERV) for Manganese (CASRN 7439-96-5 – Manganese) and Compounds (CASRN 1344-43-0; 1317-35-7; and 1129-60-5). Research Triangle Park, NC. Office of Research and Development, National Center for Environmental Assessment. U.S. EPA. EPA/600/R-12/047F5. December 2012. Available at: nepis.epa.gov/Exe/ZyPDF.cgi/P100KJKC.PDF?Dockey=P100KJKC.PDF

30 CalEPA OEHHA (2014). Manganese & Manganese Compounds (CAS Number 7439-96-5). Technical Support Document for Noncancer RELs, Appendix D1. CalEPA OEHHA. December 2008 Updated July 2014. Available at: oehha.ca.gov/media/downloads/cnr/appendixd1final.pdf

31 U.S. EPA. (2005). Toxicological review of Zn and compounds (CAS No. 7440-66-6) In Support of Summary Information on the Integrated Risk Information System (IRIS). Washington D.C. National Center for Environmental Assessment. U.S. EPA. E. PA/635/R-05/002 July 2005. Available at: cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/0426tr.pdf

32 Navarro et al., J. Occup. Environ. Hygiene 16(11): 735-744, 2019.

33 Kim et al. Environ. Health Perspectives. 017011-1-14, 2018; World Health Organization (WHO). IARC Monographs on the Evaluation of Carcinogenic Risk to Humans. Volume 95, 2010; Agency for Toxic Substances and Disease Registry (ATSDR) Toxicity of Polycyclic Aromatic Hydrocarbons (PAHs), 2009.

34 Kim et al. Environ. Health Perspectives. 017011-1-14, 2018 Liu et al., Environ. Res. 136:120-132, 2015.

35 Hand et al. Adv. Meteorology article ID 367674 doi 10.1155/2013/367674. 2013; Vincente et al. Environ. Sci. 53:122-131, 2017; Simoneit, et al., Environ. Sci. Technol. 39:6961-6970, 2005.

component of PM_{2.5} and contains numerous toxic compounds that can cause potential acute lung and heart damage and chronic health effects, such as cancer.

Ammonium Nitrate and Ammonium Sulfate

Adverse health effects evaluated in various studies for short-term nitrate and sulfate exposure include reduced lung performance and function.³⁶ Ammonium nitrate and ammonium sulfate are not generally major components of wildfire smoke. The levels of both during the peak days of the Camp Fire appear to be well below the levels that would cause adverse health effects from short-term exposure.

Health Effects Summary

The Camp Fire had very unique attributes compared to other, more vegetation-based wildfires, including a very high level of structural burning that resulted in spikes in toxic emissions that added to the burden of illness. Based on published studies, children and the elderly would have been the most susceptible to these effects.³⁷ Growing epidemiological evidence suggests that exposure to wildfire PM has been associated with a range of adverse human health effects, especially heart disease and premature death.

During the Camp Fire, the complex mixture of wildfire smoke and the materials burned, including structures and their contents (such as motor vehicles), make exact estimations of health effects challenging. In order to better understand the health effects of the Camp Fire and future wildfire incidents, additional research is needed.

Areas where CARB is engaged in, or recommending, additional research on this subject include both short- and long-term health effects of wildfire smoke, as well as the effects of certain toxic components of smoke, as outlined in the next section of this report.

36 Kleinman et al., Environ. Res. 21:313-26, 1980.; Utell et al., J. Appl Physiology 46:189-196, 1979.; arb.ca.gov/resources/sulfate-and-health.

37 Liu et al., Environ. Res. 136:12-132, 2015; Reid et al., Environ. Health Perspectives. 124:1334-1343, 2016; Wettstein, et al., J. Am. Heart Assoc. 7(8): e007492, 2018; McCoy et al., Applied Econ. Letters, 2020.

Going Forward

Health Effects Research

Further research is needed on the health impacts of wildfire smoke, both from traditional wildfires that burn primarily vegetation and from those that burn large numbers of structures, cars, and trucks. The following topics will require further investigation.

Complex mixtures of smoke

Future measurements and research should study more toxic components in the complex mixture of wildfire smoke and their combined effects to provide a clear understanding of their potential for acute and chronic health outcomes to the public. For example, the PAHs and persistent chemicals, such as flame retardant compounds used in building materials, furniture, and vehicles, when combusted could produce additional toxic compounds. Certain flame retardant chemicals, especially phosphorus flame retardants (PFRs), cause DNA damage. These compounds are very similar in chemical structure to organophosphate pesticides that are highly toxic and cause nerve damage. However, the toxicity of combusted PFRs is unknown.

High short-term exposures

Most health effects of wildfire smoke are based on short-term exposure (i.e. over a few days to weeks). There have been consistent findings that exposure to wildfire smoke increases the severity of lung diseases, such as asthma and COPD. Smoke exposure from wildfires has also been associated with an increase in emergency department visits for heart disease and stroke.³⁸ Future studies should provide deeper insights into oxidative stress damage during wildfires and report changes in respiratory symptoms and healthcare-seeking behavior after wildfires. The chemical and physical components of wildfire smoke that impact lung and heart health should be considered and measurements of ultrafine PM and their association with health effects would be prudent to study. CARB-funded investigators are currently studying the associations between short-term exposure to wildfire PM_{2.5} and loss of work days and increases in asthma attacks.

Repeated or long-term exposure to wildfires

It is equally important to study the health effects people may experience from cumulative exposures, multi-day exposures, or multiple consecutive fire seasons. Long-term exposure to wildfires that burn a mixture of natural and synthetic materials may contribute to an elevated overall lifetime risk for heart disease, lung disease, and cancer. Future studies concerning these health effects on the general population and their association with specific chemical and physical components of wildfire smoke should be considered, along with effects on the brain (nervous system), and leukemia and other cancers (as reported among firefighters). Also, long-term effects on children's health including asthma should be considered. CARB is funding a long-term health effects study in which primates were naturally exposed during infancy to wildfires and continue to be monitored throughout adulthood.

Chemical-biological analysis of smoke

The toxic compounds of wildfire smoke can be analyzed chemically, and their toxicity measured using biological analysis. The chemical analyses in combination with biological analyses could help develop a screening tool for evaluating potential short-term and long-term health effects

38 Reid et al., Environ. Health Perspectives. 124:1334-1343, 2016; Wettstein, et al., J. Am. Heart Assoc. 7(8): e007492, 2018

and improve understanding of the biological pathways for toxic constituents of smoke to harm to the lungs, heart and other organs. This approach would provide important information to assess exposure, toxicity, and rapid analyses of the potential health hazard risks from wildfire smoke. Priority should be given to research on exposure and health risks to vulnerable and highly impacted communities.

Modeling

Modeling the transport and dispersion of smoke and toxic emissions from burning structures and motor vehicles is a useful tool for estimating the impact of the Camp Fire on regional air quality and exposure, and can help fill in the spatial gaps between measurements in the surface monitoring network. Estimating emissions from wildfires, and the chemical and physical characteristics of those emissions, is inherently uncertain since the fire itself precludes direct measurement of the emissions. To account for some of this uncertainty, CARB's modeling efforts will focus on utilizing multiple modeling platforms, emissions estimates, and plume rise calculations and will evaluate the ability of the modeling systems to capture the magnitude and spatial/temporal variations observed in the surface monitoring network. When available and applicable, CARB staff will also compare modeling output to satellite products and community based sensor networks.

Monitoring

Over the next couple of years, CARB plans to expand its air quality monitoring efforts during select wildfire events to better understand the air quality impacts. The data collected will help with exposure assessments and improve overall messaging to the public. CARB's air monitoring efforts will be determined by the wildfire impacts and staff's ability to collect air quality information at existing monitoring sites (see Appendix C). CARB is proposing one to two sampling events per year that cover one or potentially a combination of wildfire scenarios based on recent wildfire history. Scenarios include northern foothill community fires that threaten structures and have smoke impacts to local, Sacramento and San Joaquin Valley, and Bay Area communities; coastal and Valley fires that threaten structures and impact Central Valley and Bay Area communities; and, southern mountain and canyon community fires threatening structures that impact desert areas and the Los Angeles and San Diego basins.

Although each scenario can be different, the response will be targeted using existing air monitoring stations when available and in proximity to the wildfire impacts, and deploying portable samplers. Air monitoring stations in direct line of wildfire impacts may have their instrument sampling frequencies modified to accommodate particulate matter loading (e.g. from 24 hours to 8 hour sampling events) in order to capture quality data. In areas where air monitoring stations are not located and public impacts are projected, portable samplers will be deployed to capture particulate matter and some toxic air contaminants. Sampling durations will be set to appropriately capture quality data. Deployments will be conducted in parallel with any California Office of Emergency Services (CalOES) "Mission Task" that requests environmental beta-attenuation mass (EBAM) monitor deployments for emergency Air Quality Index (AQI) determinations. All wildfire monitoring and laboratory activities will be based on available resources and every attempt will be made to minimize turn-around times on data reporting.

Numerous nonregulatory, low-cost sensors were in operation throughout Northern California during the Camp Fire. These sensors were deployed by schools, businesses, and individuals and helped monitor immediate smoke impacts. U.S. EPA has begun a project to incorporate these sensors onto its AirNow website in a pilot program launched in August 2020 and incorporated into EPA's current mapping software.

Appendix A: Resources

Additional information regarding wildfires, monitoring, air quality, and health risks can be found in the following documents:

California Air Resources Board

Wildfires

arb.ca.gov/our-work/programs/wildfires

Incident Air Monitoring

arb.ca.gov/our-work/programs/incident-air-monitoring

Air Quality and Meteorological Information System

arb.ca.gov/aqmis2/aqmis2.php

Protecting Yourself from Wildfire Smoke

arb.ca.gov/protecting-yourself-wildfire-smoke

California Department of Public Health

Wildfire Smoke: Considerations for California’s Public Health Officials (CDPH 2019)

[cdph.ca.gov/Programs/EPO/CDPH%20Document%20Library/Wildfire%20Smoke%20Considerations%20for%20California's%20Public%20Health%20Officials%20\(August%202019\)_508.pdf](http://cdph.ca.gov/Programs/EPO/CDPH%20Document%20Library/Wildfire%20Smoke%20Considerations%20for%20California's%20Public%20Health%20Officials%20(August%202019)_508.pdf)

U.S. Environmental Protection Agency

AirNow – Fire Information

airnow.gov/fires/

Wildfire Smoke A guide for Public Health Officials (U.S. EPA 2019)

airnow.gov/publications/wildfire-smoke-guide/wildfire-smoke-a-guide-for-public-health-officials/

Appendix B: Satellite Imagery and PM_{2.5} AQI Values³⁹

November 8, 2018

November 9, 2018

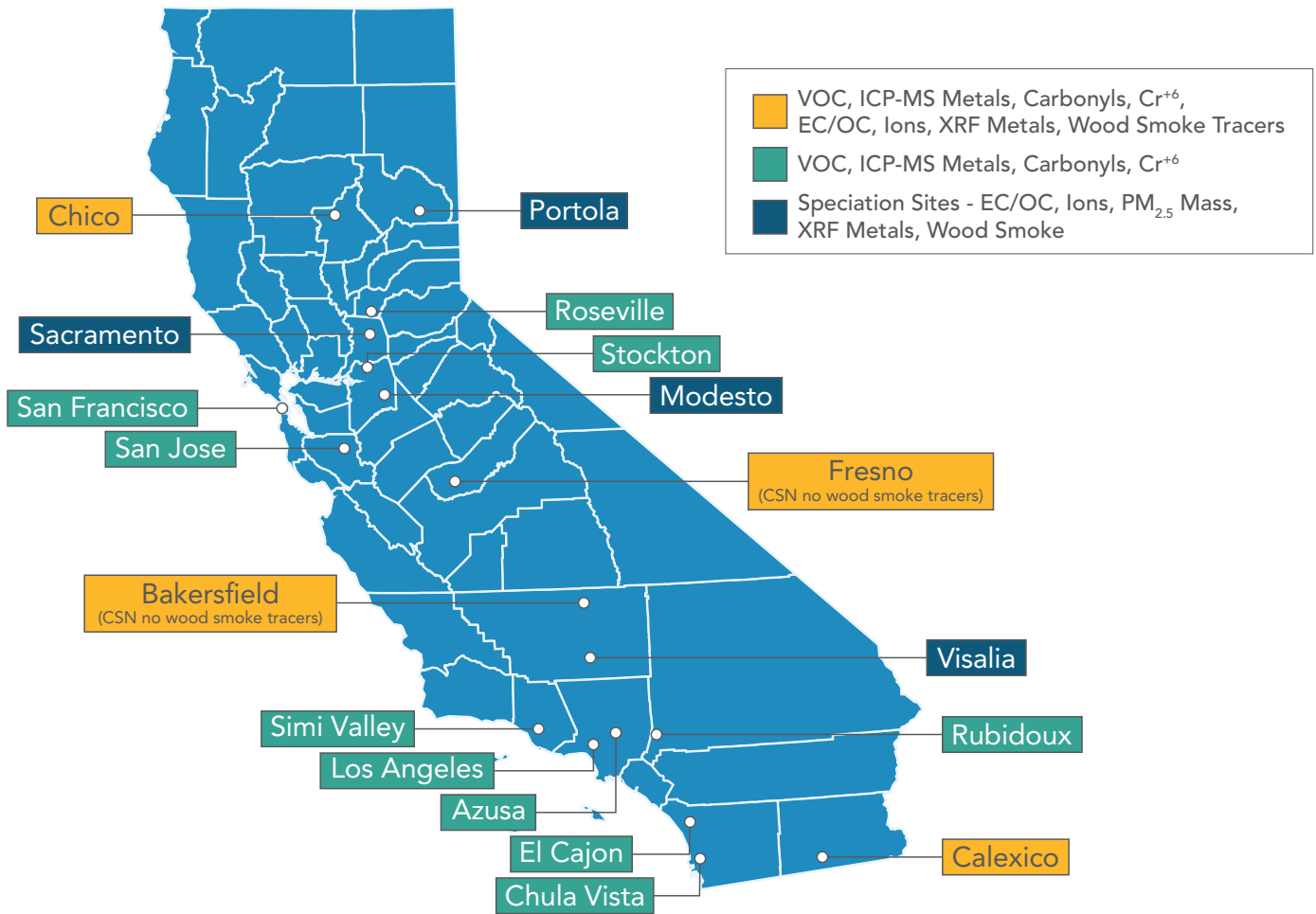
³⁹ MODIS Terra and Aqua Corrected Reflectance (True Color) Satellite Images, NASA Worldview, worldview.earthdata.nasa.gov, downloaded 10/7/20

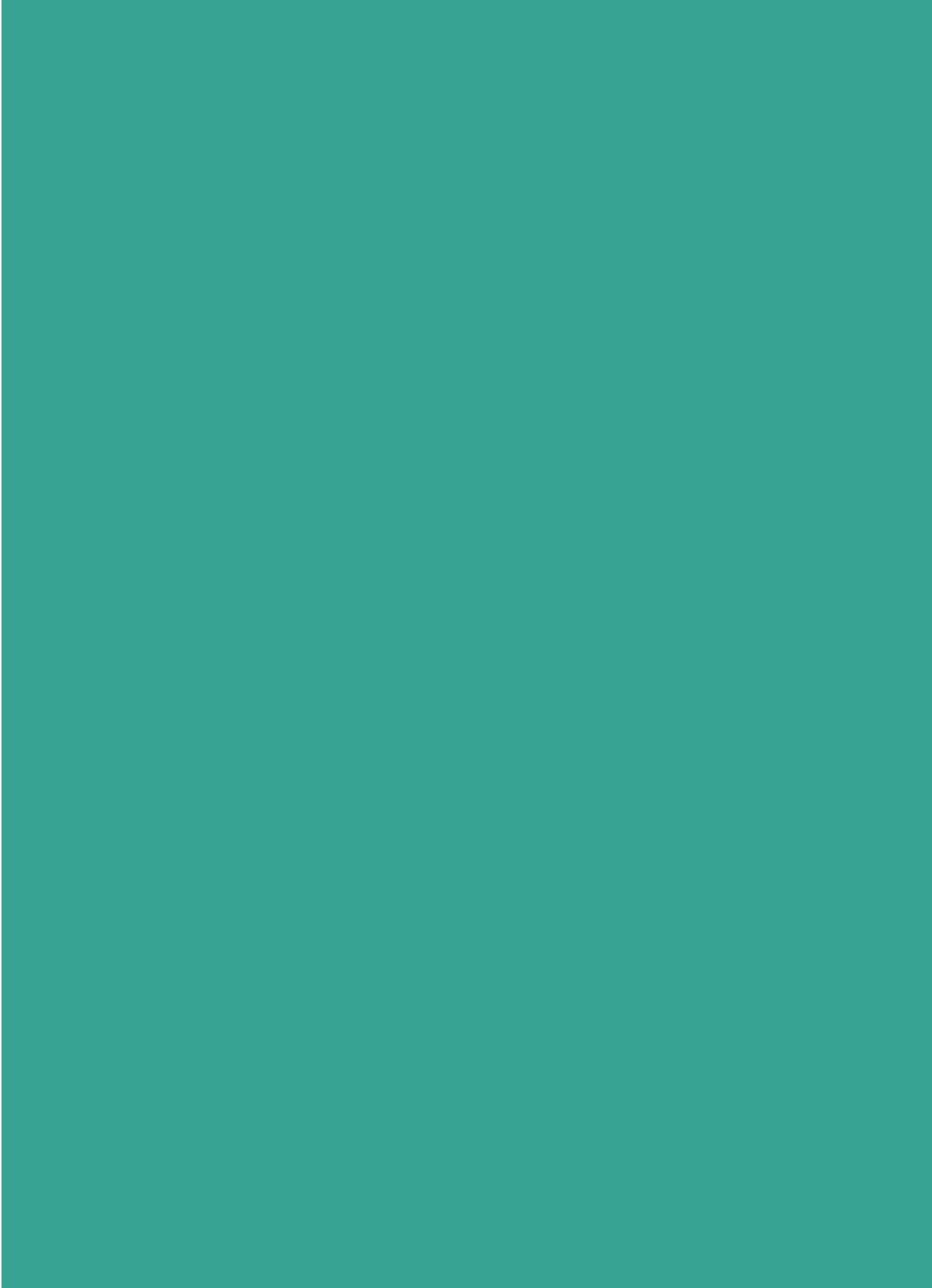
November 16, 2018

November 18, 2018

November 22, 2018

Appendix C: Toxics Air Monitoring Sites





California Air Resources Board
1001 I Street
P.O. Box 2815
Sacramento, CA 95812
(916) 323-2514
arb.ca.gov

Air Quality Planning & Science Division
Monitoring & Laboratory Division
Research Division
arb.ca.gov/our-work/programs/wildfires