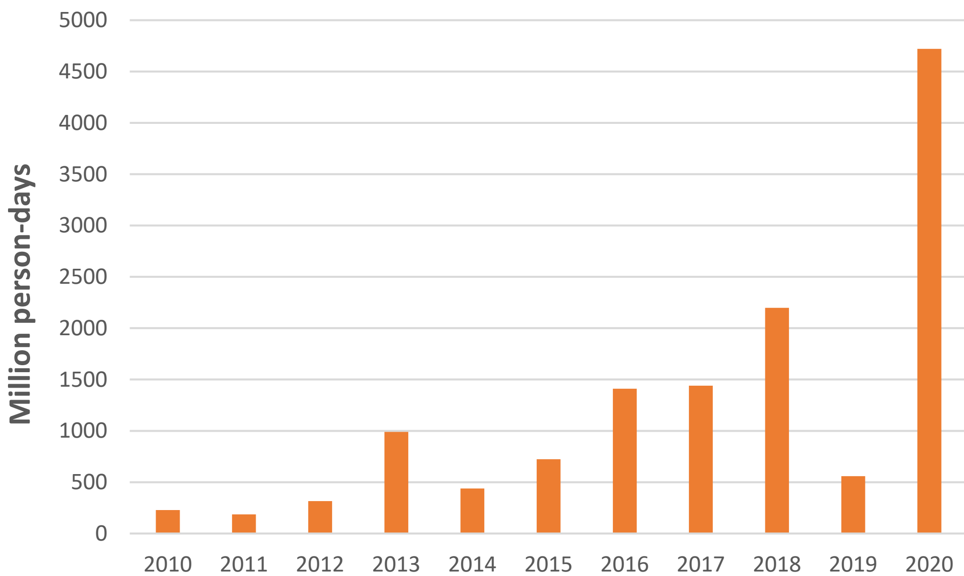
WILDFIRE SMOKE

Potential wildfire smoke exposures have been increasing in California since 2010, due to the increasing frequency, duration and severity of wildfires. This is reflected in the annual number of "person days" in areas where wildfire smoke is present.

Figure 1. Potential population exposures* to wildfire smoke, 2010-2020



Source: NOAA, 2021; US Census Bureau, 2010 (analysis based on Vargo, 2020)

** Graph presents the estimated number of people living in areas where smoke plumes were present multiplied by the number of days when the plumes were present in those areas.*

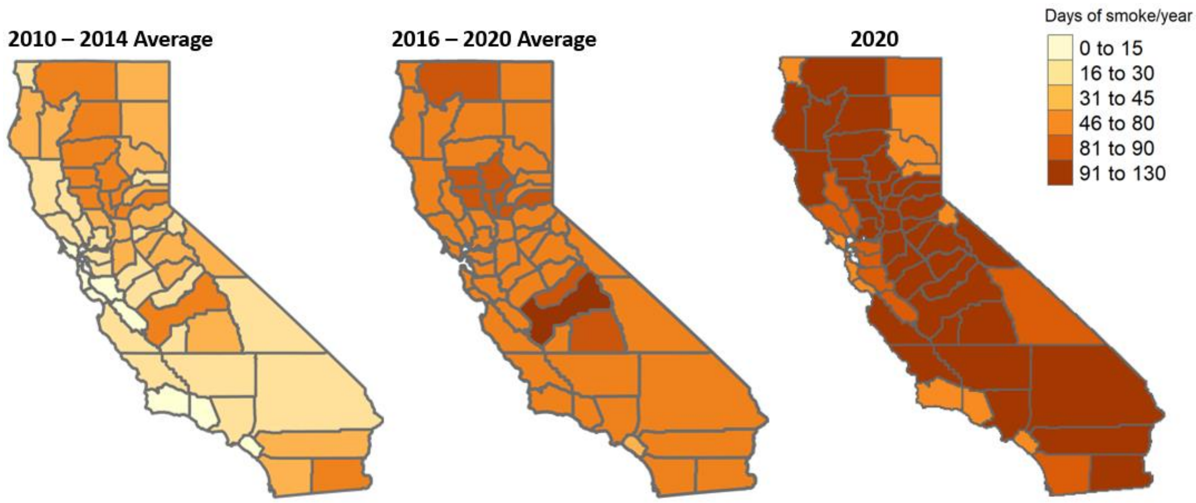
What does the indicator show?

Potential population exposures to wildfire smoke have been increasing in California since 2010, based on "person-days," a metric that is calculated as the number of persons living in the areas where wildfire smoke plumes were present multiplied by the number of days when smoke was present (Vargo, 2020); see Figure 1. Areas of wildfire smoke plumes are based on satellite imagery from the National Oceanic and Atmospheric Administration's Hazard Mapping System's Fire and Smoke Product (HMS Smoke) (NOAA, 2021).

The maps in Figure 2 show the number of days, by county, when wildfire smoke was present at different time periods. From 2010 to 2014, 11 California counties experienced at least 46 smoke days each year on average; three of these counties had 60 to 66 smoke days per year. The rest of the counties had 45 or less smoke days per year. From 2016 to 2020, 56 of the state's 58 counties experienced at least 46 smoke days each year on average: two counties had 34 and 45 smoke days per year, 46 counties had 46 to 80 smoke days per year, and ten had more than 80 smoke days per year. About 3.5 times more acres burned on average in the latter compared to the earlier five-year period, which includes a record-high 4.2 million acres burned across the state in

2020 (see *Wildfires* indicator). That year, smoke plumes were present in every county for at least 46 days; 36 counties had at least 91 smoke plume days.

Figure 2. Number of wildfire smoke days by California county



Source: NOAA, 2021 (analysis based on Vargo, 2020)

Maps present the number of days per county when smoke plumes were present. Left, average number of smoke days per year, 2010-2014. Middle, average number of smoke days per year, 2016-2020. Right, number of smoke days in 2020.

Why is this indicator important?

With the rise in the frequency and duration of wildfires in California, human and environmental exposures to harmful pollutants are also increasing. Wildfire smoke is a complex mixture that is determined by many factors unique to the burn site, such as the type of vegetation burned and weather conditions. A large portion of the resulting air pollutants consists of particulate matter, with a higher proportion of fine particulate matter (2.5 microns or less in diameter, or PM2.5) than typical ambient air pollution (Holm et al., 2021). PM2.5 can be inhaled into the deepest recesses of the lungs, enter the bloodstream, and affect the heart and other vital organs. Recent studies, including one in Southern California, suggest that wildfire particulate matter has greater carbon

Photo Credit: Christopher Michel

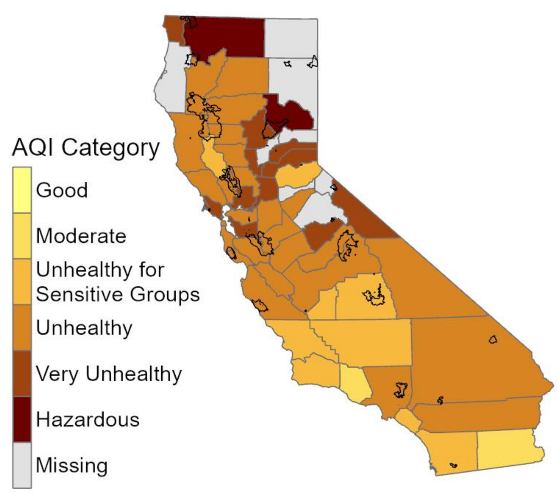
The San Francisco-Oakland Bay Bridge at noon on September 9, 2020 content and thus more potential to cause inflammation in the lungs than ambient PM2.5 (Aguilera, 2021a).

Other hazardous compounds in wildfire smoke include carbon monoxide, ozone precursor compounds, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (Black et al., 2017). Some compounds are known human carcinogens (e.g., benzene, formaldehyde and certain PAHs). Wildfires that burn structures are reported to produce smoke that contains toxic heavy metals such as lead and zinc (CARB, 2021a).

Scientists observed that, between 2001 and 2020, wildfire emissions across the western United States led to widespread co-occurrence of high PM2.5 and ground-level ozone air concentrations (Kalashnikov et al., 2022). As summer and fall wildfires become larger and more severe, the co-occurrence of these air pollutants may pose a greater threat to public health.

Scientists are investigating the relationship between PM2.5 concentrations characterized using the HMS Smoke plume categories and those measured by ground-level monitors. Although the concentrations do not completely align and there is uncertainty in the relationship, studies have found that higher ground-level PM2.5 concentrations were more frequently observed during heavy smoke plume days (Fadadu et al., 2020). In 2015, a study in Central California found a weak, but statistically significant relationship between smoke plume locations and increased surface PM2.5 concentrations (Preisler et al., 2015). Another study found that unhealthy levels of PM2.5 were more likely to occur on days with smoke plumes than on clear days (Larsen et al., 2018). In short, satellite-detected smoke plumes often co-occur with an increase in PM2.5 concentrations but there is no real relationship between the different HMS smoke plume categories and a specific ground-level PM2.5 concentration.

Figure 3. Air quality (based on maximum daily PM2.5 concentrations) within California Counties, September 11-12, 2020



Source: US EPA, 2021b

** Map presents the Air Quality Index category based on EPA-defined PM2.5 concentration ranges[1] (µg/m^3, 24-hour average) found within each county between September 11 and 12, 2020. Black outlines indicate active fires perimeters during this period.*

Wildfire emissions can severely impact air quality both locally and beyond areas directly impacted by fires, as smoke and ash particles can travel many miles from the original fire location. The 2020 fire season was marked by several large wildfires burning at the same time, leading to unprecedented air quality impacts across the state. Maximum PM2.5 levels persisted in the "hazardous" range of the Air Quality Index (AQI)[1] for weeks in several areas of the state (CAL FIRE, 2021). September 11 to 12, 2020 had particularly bad air quality with most of the state experiencing an AQI of "unhealthy" or worse (Figure 3).

The November 2018 Camp Fire in Paradise provides a good example of the impact of wildfires on air quality in distant regions. Concentrations of PM2.5 reached 415 $\mu g/m^3$ in Chico (15 miles west), 228 $\mu g/m^3$ in Sacramento (over 80 miles south), and 134 $\mu g/m^3$ in San Jose (about 200 miles southwest) (CARB, 2021a). For comparison, the California Ambient Air Quality Standard (which is the same value as the National Ambient Air Quality Standard) is an annual average of 12.0 $\mu g/m^3$; an additional federal standard is a 24-hour average of 35 $\mu g/m^3$ (CARB, 2021b). These standards represent the maximum concentration of a pollutant in outdoor air that will not be harmful to human health. In addition to PM2.5, smoke up to 150 miles away from the Camp Fire was found to include lead, zinc, calcium, iron, and manganese (CARB, 2021b).

Wildfire smoke darkens the skies, reduces visibility, and poses a clear threat to public health. A large body of research has connected PM2.5 exposure, including wildfire-specific exposure, to respiratory and cardiovascular health outcomes (Chen et al., 2021; Reid et al., 2019). These include decreased lung function, asthma, chronic obstructive pulmonary disease, pneumonia, cardiac arrest, and congestive heart failure. Exposure to wildland smoke may have mental health impacts, particularly in episodes of chronic and persistent smoke events (Eisenman et al., 2021).

Studies have reported on wildfire smoke impacts on public health in California; examples include:

- In 2015, a year with an extensive wildfire season, smoke exposure was found to be associated with cardiovascular and cerebrovascular emergency department (ED) visits for adults in eight California air basins, particularly for those over aged 65 years (Wettstein et al., 2018).

- During the October 2017 Northern California wildfires, in nine San Francisco Bay Area counties, fire-related PM2.5 was most consistently linked to ED visits for respiratory disease, asthma, chronic lower respiratory disease and acute myocardial infarction (Malig et al., 2021).

- Between 2013 and 2018, a 14.6 percent increase in respiratory disease-related ED visits in Shasta County was observed in weeks where wildfire PM2.5 was

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[1] AQI categories are good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous; these correspond to 24-hour average PM2.5 concentrations (in micrograms per cubic meter of air or $\mu g/m^3$) of 0.0 to 12.0; 12.1 to 35.4; 35.5 to 55.4; 55.5 to 150.4; 150.5 to 250.5; or 250.5 and higher, respectively.

≥5.5 μg/m^3; a 27.0 percent increase occurred during the 2018 Carr Fire (Casey et al., 2021). Health costs related to fire-related air pollution from all California wildfires in 2018 were estimated at $32.2 billion (Wang et al., 2021).

Certain population subgroups are more susceptible to health impacts when exposed to wildfire smoke (US EPA, 2021b; Liu et al., 2017; Xi et al., 2020). These include people with cardiovascular disease, asthma or other respiratory diseases, and kidney disease. Older adults, children (18 years and younger) and pregnant people are also more vulnerable to the effects of wildfire smoke. During the 2020 wildfires, elevated PM2.5 levels were associated with increased risks of COVID-19 cases and deaths in many western US counties (Zhou, et al., 2021).

Children may be at an increased risk of negative respiratory effects from wildfire smoke due to their smaller airway size and developing lungs (Marabilli et al., 2009). A multi-country review of pediatric ED visits found an overall significant increase in respiratory symptoms and asthma hospitalizations within the first three days of exposure to wildfire smoke, particularly in children less than five years old (Henry et al, 2021). A California study found that exposure to wildfire-specific PM2.5 was associated with higher respiratory-related increases in pediatric hospitalizations compared to similar exposure to non-wildfire PM2.5 (Aguilera et al., 2021b). PM2.5 exposures are also associated with negative impacts on children's immune function, blood pressure and cardiovascular systems (Holm et al., 2021; Prunicki et al., 2021).

Studies suggest that maternal exposure to wildfire smoke during pregnancy is linked to reduced birth weight and preterm birth (Amjad et al., 2021). A California study estimated 6,974 excess preterm births as attributable to wildfire smoke exposure; this accounts for 3.7 percent of observed preterm births between 2006 and 2012 (Heft-Neal et al., 2021). Wildfire smoke exposure during pregnancy has also been associated with a variety of pregnancy complications, such as maternal gestational diabetes and hypertension (Park et al., 2021; Abdo et al., 2019).

Wildfire smoke effects can disproportionately fall on those in particular socioeconomic and occupational groups. People with lower income often have higher rates of respiratory conditions, fewer resources to employ measures that reduce smoke indoors (e.g., air conditioning or air purifiers) and less access to health care. Wildland firefighters (USDA, 2013; Black et al., 2017; Jung et al., 2021) are especially at risk due to unavoidable exposure to wildfire smoke. Some agricultural workers, already disproportionately affected by racial discrimination, exploitation, economic hardships, limited access to health care, language barriers, and fear of deportation, experience high levels of smoke exposure. During the December 2017 Thomas Fire, which burned over 280,000 acres in Santa Barbara and Ventura Counties, thousands of farmworkers continued working in the fields – most without respiratory protection – to prevent crop loss from smoke and ash (Mendez et al., 2020). This led to health impacts including coughing, headaches, difficulty breathing, nausea, and nosebleeds, as well as long-term effects such as respiratory illness. In addition, farmworkers are often exposed to other workplace hazards, such as pesticides and extreme heat.

As the extent of exposure to wildfire smoke increases and moves from periodic acute exposures to more chronic and long-term, it is important to track trends and patterns in potential population exposures to wildfire smoke. This information can be used to distribute health-relevant resources and communications to the most impacted areas and to assist in planning and preparation efforts. For example, the *US EPA Wildfire Smoke: A Guide for Public Health Officials* (Stone et al., 2019) recommends that health officials advise people to remain indoors during smoky conditions, use indoor air filtration systems, and wear respiratory protection when outside.

Wildfire smoke can increase business costs, affect job productivity, reduce earnings and impact tourism and outdoor recreation. Wildfires in recent years have deterred people from visiting the wine country and the Sierra Nevada region (Bauman et al., 2020; Wilson et al., 2020). Wildfire smoke and reduced visibility can elicit a sense of fear, require people to stay indoors, limit traffic to enable firefighting efforts, and ultimately cause tourists to cancel travel plans. A survey of people who visit the Sierra Nevada region reported that wildfire has significantly influenced past travel to the area and will most likely continue to do so in the future. Of those surveyed, 14 percent changed accommodations to avoid wildfire smoke. Outdoor workers in businesses serving tourists face reduced work hours due to visitor cancellations and uncertain work conditions on smoky days. Federal Occupational Safety and Health Administration (OSHA) standards have been proposed to adequately protect workers from wildfire smoke-related health risks (Layton, 2020).

In addition to impacts on human health and well-being, smoke and toxic gases released by wildfires can impact the health of wildlife and ecosystems. Adverse health impacts of wildfire smoke have been reported to contribute to changes in behavior, movement and vocalization in terrestrial and aquatic species (Sanderfoot et al., 2021). Smoke is known to damage the lungs of birds and increase their susceptibility to respiratory infection. Wildfires have increasingly coincided with fall bird migration, where low visibility caused by smoke can disrupt the navigation for migratory species and create difficulties in finding food sources (Sanderfoot and Holloway, 2017; Overton et al., 2021). Wildfire smoke can also negatively impact watersheds, where deposition of smoke and ash in streams can result in dramatic increases in nutrient concentrations and fluctuations of pH, potentially harming aquatic organisms (David et al., 2018).

What factors influence this indicator?

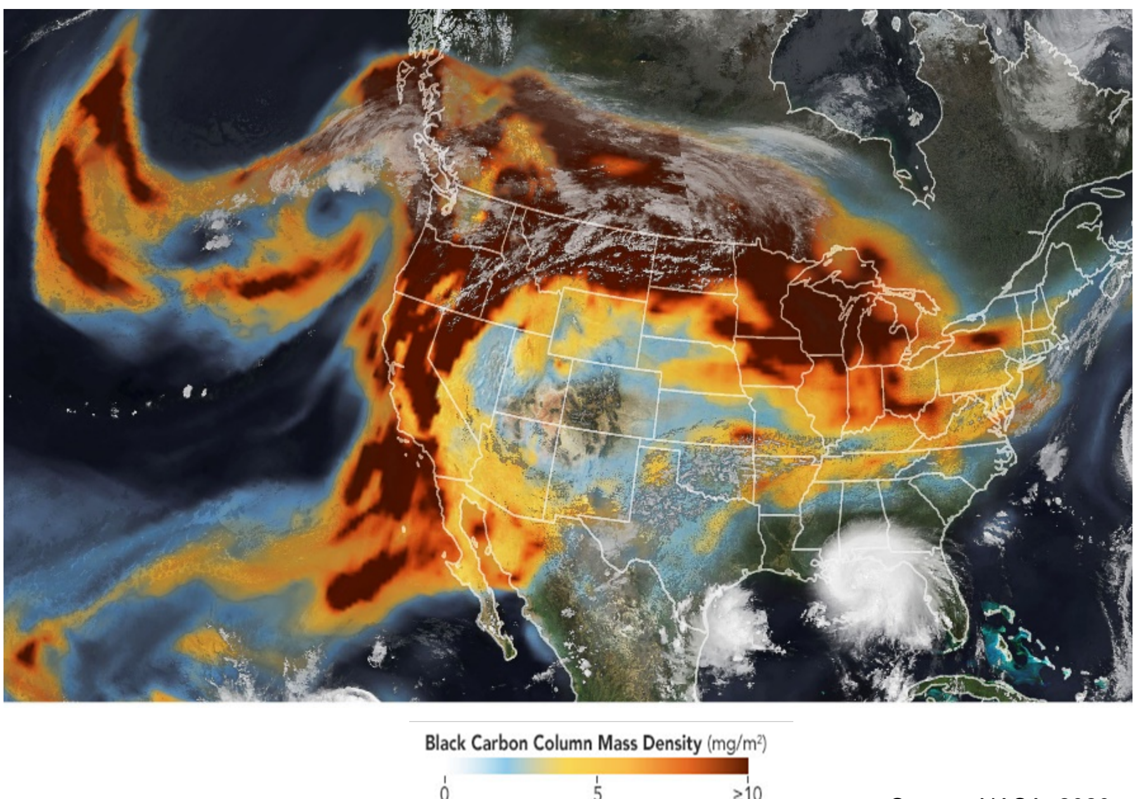
Wildfires are increasing in frequency, duration and severity due to conditions exacerbated by climate change, such as warmer temperatures, reduced precipitation and snowpack, and tree deaths (see *Wildfires* indicator; Goss et al., 2020). The fires are becoming more destructive as well, with 15 of the 20 most destructive wildfires in

California having occurred in the last ten years (Buis, 2021). Correspondingly, exposure to wildfire smoke across California has also increased substantially over time.

Particles from wildfire smoke stay suspended in the atmosphere and can be carried large distances from the source of the fire. The extent and duration of wildfire smoke are impacted by the size, severity, and duration of the source fires as well as wind and weather patterns (Sicard et al., 2019). The potential impact of human exposures is also dependent on the population density where the smoke travels.

In the summer of 2020, smoke from wildfires burning in California, Oregon and Washington drifted across northern states and reached the eastern US (Figure 4). However, the smoke did not have equally strong effects on air quality at ground level everywhere. While people living in communities near the fires in California and Oregon experienced very unhealthy air quality from September 14-16, surface air quality in the eastern US remained mostly good because the smoke was traveling high (above breathable space) in the atmosphere (NASA, 2020).

Figure 4. Satellite image of wildfire smoke plume across the continental United States (September 14, 2020)



Source: NASA, 2020

Jet stream winds transport black carbon across the United States from fires originating on the West Coast. [NASA Earth Observatory images by Joshua Stevens.]

Technical considerations

Data characteristics

Wildfire smoke plumes for years 2010–2020 are from HMS Smoke (NOAA, 2021). HMS Smoke uses visible imagery from satellites to generate smoke plumes associated with fires. Trained analysts manually validate and trace smoke plume locations from two Geostationary Operational Environmental Satellites (GOES). Visible imagery is available at one kilometer (km) spatial resolution. Aerosol Optical Depth information collected from GOES satellites, called the GOES Aerosol and Smoke Product (GASP), are used to provide an objective and quantitative estimate of smoke density. HMS Smoke layers for a specific day are created from several satellite passes, and so multiple plumes may exist over any single location on a given day. To resolve plumes to one observation for each day and location, a single day's plumes are treated as flattened layers so that the coverage of smoke plumes are defined by any HMS collection in that day. The sum of the individual days was used to derive the total smoke days per year.

Information on population was obtained from the 2010 US Census Centers of Population (US Census Bureau, 2010). The latitude and longitude fields from the "Centers of Population" file were used to create a spatial file of points and intersected with HMS Smoke plumes. The block group scale is the finest scale for which the "Centers of Population" exist, and they were used to best represent the locations where populations within Census tracts reside. To combine HMS Smoke plume information with US populations, a function written in R and implemented with RStudio was employed. The full script for processing can be accessed and amended and is available within Vargo et al. (2020).

A "person-days" metric is used to present the results and provides a way of estimating potential exposure, particularly for large areas with widely varying population densities. The use of person-days has been used previously in research to describe smoke plume exposures (Schweizer et al, 2019). Presentation of results as person-days may emphasize the burden of wildland fire smoke in densely populated areas where more people are present, even though potential PM2.5 levels may be higher or more frequent in less populated, rural areas.

AirData represents how the air quality is fluctuating at ground level. The US EPA hosts data from a collection of ground air quality monitors that is quality assured and controlled by state, local, and tribal agencies (US EPA 2021b). The data include daily PM2.5 concentrations for 164 stations throughout California. To give a snapshot of the worst-case scenario, the AQI categories based on the maximum observed PM2.5 concentration within each county are presented in the map in Figure 3. Daily averaged PM2.5 concentrations for each monitoring station were grouped by county, and the date with maximum PM2.5 concentrations for each county was noted (September 11, 2020). Some of the counties were missing data for September 11 so PM2.5 data for September 11th though September 12th were compiled.

Strengths and limitations of the data

HMS Smoke has many strengths: it is freely available, released in a timely manner, allows for daily calculations, it is available continuously across California, and can be used to compare locations across the state. In addition, HMS Smoke is particularly unique in that it gives fire-specific estimated smoke plumes (US EPA, 2021b). HMS Smoke has also been validated and shown to correlate with elevated PM2.5 concentrations measured by ground-level monitors (Preisler et al., 2015; Larsen et al., 2018; Fadadu et al., 2020).

The satellite imagery consists of visible bands and therefore is affected by cloud cover, is unable to differentiate land surface elevation or determine the height of smoke plumes. The HMS Smoke is also generated from satellite passes occurring during daylight hours, with no nighttime data. As mentioned above, presentation of results as person-days may emphasize the burden of wildland fire smoke on densely populated areas and understate the more frequent exposures occurring in rural areas.

AirData is freely available, allows for near daily calculations and is available from 1980 to the present. The sensors are located at near ground-level and are distributed throughout California (and the rest of the USA). Though the monitors are showing the air quality directly where people live, the monitors only represent air quality near where the monitors are located. The sensors are mostly located near more populated regions, leaving large spatial gaps in ground-level air quality. Furthermore, some stations do not have daily data available, which leads to gaps in daily time series analysis.

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References:

Aguilera R, Corringham T, Gershunov A and Benarnhia T (2021a). Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature Communicatons* **12:** 1493.

Aguilera R, Corringham T, Gershunov A, Leibel S and Benarnhia T (2021b). Fine particles in wildfire smoke and pediatric respiratory health in California. *Pediatrics* **147**(4):e2020027128.

Bauman MJ, Yuan J and Williams HA (2020). Developing a measure for assessing tourists' empathy towards natural disasters in the context of wine tourism and the 2017 California wildfires. *Current Issues in Tourism*, **23**(19).

Black C, Tesfaigzi Y, Bassein JA and Miller LA (2017). Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. *Environmental Toxicology and Pharmacology.* **55:** 186–195.

Buis A (2021). The Climate Connections of a Record Fire Year in the U.S. West. Retrieved December 10, 2021

CAL FIRE (2021). *2020 Fire Siege Report.* California Department of Forestry and Fire Protection.

CARB (2021a). *Camp Fire Air Quality Data Analysis.* California Air Resources Board.

CARB (2021b). California Air Resources Board. Inhalable Particulate Matter and Health (PM2.5 and PM10). Retrieved October 20, 2021.

David AT, Asarian JE and Lake FK (2018). Wildfire smoke cools summer river and stream water temperatures. *Water Resources Research* **54**: 7273–7290.

Fadadu RP, Balmes JR, and Holm SM. (2020). Differences in the Estimation of Wildfire-Associated Air Pollution by Satellite Mapping of Smoke Plumes and Ground-Level Monitoring. *International journal of* environmental research and public health, **17**(21): 8164.

Goss M, Swain DL, Abatzoglou JT, Sarhadi A., Kolden CA, et al. (2020). Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters* **15**(9).

Holm SM, Miller MD and Balmes JR (2021). Health effects of wildfire smoke in children and public health tools: a narrative review. *Journal of Exposure Science and Environmental Epidemiology* **31:** 1–20.

Holstius DM, Reid CE, Jesdale BM and Morello-Frosch R (2012). Birth weight following pregnancy during the 2003 Southern California wildfires. *Environmental Health Perspectives* **120**(9): 1340-5.1104515.

Kalashnikov DA, Schnell JL, Abatzoglou JT, DL Swain and Singh D (2022). Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Science Advances* **8:** eabi9386.

Knapp KR, Frouin R, Kondragunta S and Prados AJ. (2005). Toward aerosol optical depth retrievals over land from GOES visible radiances: determining surface reflectance. *International Journal of Remote Sensing*, **26**(18): 4097-4116.

Kochi I, Champ P, Loomis J and Donovan G (2016). Valuing morbidity effects of wildfire smoke exposure from the 2007 Southern California wildfires. *Journal of Forest Economics* **25**: 29-54.

Larsen AE, Reich BJ, Ruminski M and Rappold AG (2018). Impacts of fire smoke plumes on regional air quality, 2006–2013. *Journal of Exposure Science & Environmental Epidemiology* **28**:319-327.

Layton, K (2020). Proposed Federal OSHA Standards for Wildfire Smoke. *Seattle Journal of Technology, Environmental and Innovation Law* **10**(1), Article 5.

Liu JC, Pereira G, Uhl SA, Bravo MA and Bell ML (2015). A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research* **0**: 120-132.

Liu JC, Wilson A, Mickley LJ, Ebisu K, Sulprizio MP, et al. (2017). Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *American Journal of Epidemiology* **186**(6): 730–735.

Méndez M, Flores-Haro G and Zucker L (2020). The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum* **16**:50-62.

Mirabelli MC, Künzli N, Avol E, Gilliland, FD, Gauderman WJ, et al. (2009). Respiratory symptoms following wildfire smoke exposure: Airway size as a susceptibility factor. *Epidemiology **20***(3).

NASA (2021). National Aeronautic and Space Administration: A Meeting of Smoke and Storms. Retrieved December 22, 2021.

NOAA (2021). National Oceanic and Atmospheric Administration, Office of Satellite and Product Operations. Hazard Mapping System Fire and Smoke Product. Retrieved November 1, 2021.

Orr A, Migliaccio CAL, Buford M, Ballou S and Migliaccio CT (2020) Sustained Effects on Lung Function in Community Members Following Exposure to Hazardous PM2.5 Levels from Wildfire Smoke. *Toxics* **8**(3): 53.

Preisler HK, Schweizer D, Cisneros R, Procter T, Ruminski M and Tarnay L (2015). A statistical model for determining impact of wildland fires on Particulate Matter (PM2. 5) in Central California aided by satellite imagery of smoke. *Environmental Pollution* **205**: 340–349.

Prunicki, M, Cauwenberghs N, Lee J, Zhou X, Movassagh H, et al. (2021). Air pollution exposure is linked with methylation of immunoregulatory genes, altered immune cell profiles, and increased blood pressure in children. *Scientific Reports* **11**: 4067.

Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, et al. (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives* **124**(9): 1334-1343.

Rooney B, Wang Y, Jiang HJ, Zhao B, Zeng Z-C, et al. (2020). Air quality impact of the Northern California Camp Fire of November 2018. *Atmospheric Chemistry and Physics* **20**(23):4597-14616.

Ruminski M, Kondragunta S, Draxler R and Rolph G. Use of environmental satellite imagery for smoke depiction and transport model initialization. *In: 16th Annual International Emission Inventory Conf.: Emission Inventories—Integration, Analysis, and Communications; 2007*.

Sanderfoot OV and Holloway T (2017) Air pollution impacts on avian species via inhalation exposure and associated outcomes. *Environmental Research Letters* **12**(8): 083002.

Sanderfoot OV, Bassing SB, Brusa JL, Emmet RL, Gillman SJ, et al. (2021). A review of the effects of wildfire smoke on the health and behavior of wildlife. *Environmental Research Letters* (accepted manuscript online 19 October 2021).

Schweizer D, Preisler HK and Cisneros R (2019). Assessing relative differences in smoke exposure from prescribed, managed, and full suppression wildland fire. *Air Quality Atmosphere and Health* **12**:87–95.

Sicard M, Granados-Muñoz MJ, Alados-Arboledas L, Barragán R, Bedoya-Velásquez AE, et al. (2019). Ground/space, passive/active remote sensing observations coupled with particle dispersion modelling to understand the inter-continental transport of wildfire smoke plumes. *Remote Sensing of Environment* **232**.

UC Davis (2021). UC Davis Western Center for Agricultural Health and Safety: How do wildfires affect the health and safety of people in agriculture?. Retrieved October 20, 2021.

US Census Bureau (2010). Census Population 2010. Retrieved September 20, 2021.

US EPA (2019). *Wildfire Smoke: A Guideline for Public Health Officials*. US Environmental Protection Agency.

US EPA (2021a). US Environmental Protection Agency: Which Populations Experience Greater Risks of Adverse Health Effects Resulting from Wildfire Smoke Exposure? Retrieved December 10, 2021.

US EPA (2021b). United States Environmental Protection Agency. Air Quality System Data Mart [internet database]. Retrieved December 10, 2021.

US EPA (2022). United States Environmental Protection Agency. AirNow - How are the map contours made? What interpolation method is used? Retrieved January 22, 2022.

USDA (2013). *Wildland firefighter smoke exposure*. United States Department of Agriculture, Forest Service.

Vargo JA (2020). Time series of potential us wildland fire smoke exposures. *Frontiers in Public Health* **8**: 126**.**

Vicente A, Alves C, Calvo AI, Fernandes AP, Nunes T, et al. (2013). Emission factors and detailed chemical composition of smoke particles from the 2010 wildfire season. *Atmospheric Environment* **71**: 295-303.

Wang D, Guan D, Zhu S, MacKinnon M, Geng G, et al. (2021). Economic footprint of California wildfires in 2018. *Nature Sustainability* **4:** 252–260.

Wilson J, Tierney P and Ribaudo C (2020). *Impact of Wildfire on Tourism in the Sierra Nevada Region Synthesis of Research Findings and Recommendations*. Prepared for the Sierra Nevada Conservancy.

Zhou X, Josey K, Kamereddine L, Caine MC, Liu T, et al. (2021). Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances* **7**(33).