Title

Wildfire Smoke Effects on Health: Implementing an Air Quality Alert System for UC San Diego

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Project Motivation

Wildfires in California have become a major issue, not only in terms of physical damage, but also in harmful health effects caused by wildfire smoke. During the last wildfire season, the Camp Fire in Butte County burned for weeks and prevailing winds blew that smoke all the way down to the Bay Area where air quality decreased to levels considered by the EPA to be 'very unhealthy' and even 'hazardous' in some areas (see Figure 1) (EPA AirNow). Schools were closed, games were cancelled, and at one time Northern California had the worst air quality in the world, above even China and India (Turkewitz and Richtel 2018). My own birthplace, Paradise, was almost completely burned down and my family in the Bay Area were among those who suffered from the horrible air quality caused by the smoke.

Researchers have discovered many negative health effects of wildfire smoke inhalation, including respiratory morbidity leading to exacerbations of asthma and chronic obstructive pulmonary disease (COPD), as well as cardiovascular morbidities and more (Liu et al. 2015). The pollutants in wildfires and their impacts vary depending on the composition and particle size but can include particulate matter (PM2.5 and PM10), carbon monoxide, nitrogen dioxide, ozone, hydrocarbons, and volatile organic compounds (Reid et al. 2016). Sensitive populations such as children, people with pre-existing conditions, and the elderly are especially susceptible to the effects of these pollutants. By taking measures to reduce exposure to wildfire smoke, it is possible to reduce these health effects.

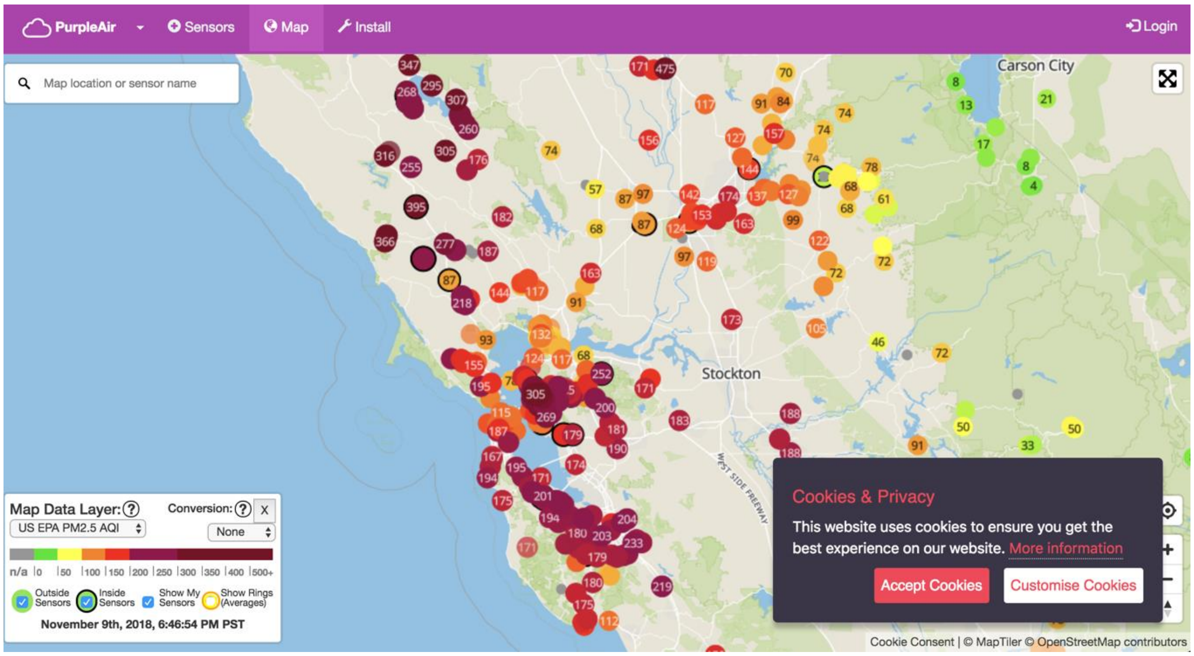
The projected increase of wildfires in California is due to both climatic and anthropogenic effects, including temperature increases, precipitation changes, a growing population, and land management practices. The many health effects caused by acute exposure to wildfire smoke demonstrate a need for an alert system during these events. This should include an email or text message alert with information about the fire and air quality as well as recommended actions to take. With an effective alert system and recommendations for different populations based on their vulnerabilities, we should see a decrease in these health effects during wildfire events compared to what we see currently.

Cities and Universities have struggled with finding the best way to implement an alert system such as this. There is not yet a standard system in place for California. Messaging sent out during wildfire smoke events has been mixed and sometimes contradictory. The UCSD campus is the perfect starting point for such a system due to its location near the coast (where smoke is likely to blow from rural fires to the east), its existing emergency management infrastructure, and its partnership within the UC system. Once the alert system is established here, it can serve as a model for the rest of the UC campuses, other schools and universities, city plans, and other jurisdictions with the eventual goal of reaching as many people in California as possible.

This project aims to answer the following questions: What are the health effects of wildfire smoke and which populations are most sensitive to these effects? What alert systems are currently in place and how effective are they? What should be the recommendations given to students, faculty, and staff at UCSD during a wildfire smoke event?

The result of the investigation into these questions is an air quality alert system for UCSD that includes both email alerts and a website. An email alert will be sent out to the entire

UCSD campus when air quality deteriorates to a specific threshold. The website link will be included in the email and contains information about air quality, vulnerable populations, and specific actions to take to reduce smoke exposure. The alert system will be managed by the Emergency Management & Business Continuity (EM&BC) of Environmental, Health, and Safety (EH&S) at UCSD.



Source: Screenshot of PurpleAir air quality map taken on November 9, 2018
Figure 1: Air quality levels around the Bay Area in California during the Camp Fire. In some areas, the AQI exceeded 300 (hazardous).

Executive Summary

Wildfires in California are increasing in number, intensity, and duration due to climate change (IPCC 5th assessment report). Temperature is projected to increase while precipitation will become more variable, increasing drought risk in California (4th assessment report: statewide summary). This increase in the dry season translates into an increased risk for wildfires, including well into the typical winter season, as we have seen in the last decade. Land management practices, fire suppression activities, and human ignitions have negatively impacted the natural landscape and led to more wildfires. By building further into the wildland urban interface and suppressing even small fires that are beneficial to the ecosystem, humans have contributed to the increase in large, destructive fires we have seen recently (2018 Strategic Fire Plan for California). Strong winds like the Santa Ana winds in southern California contribute to the spread of wildfires and harmful smoke. Since these winds blow from east to west, smoke from inland wildfires gets blown to the coast where larger populations reside. Wildfires, smoke, and wind are difficult to model because of the many different factors that affect them. Wildfires are modeled both under climate change and for real-time forecasting. In California under high emission scenarios, wildfires are projected to increase in frequency and size, especially in the Sierra Nevada region (Westerling 2018). Although wildfire models made for real-time forecasting have improved recently, there are still many areas for improvement. Smoke forecasting is another tool that has helped policy makers track smoke plumes for public health.

Health impacts from wildfire smoke inhalation vary, but there is strong evidence for respiratory morbidity, cardiovascular morbidity, mortality, and birth outcomes. Other health effects studied include mental health outcomes, systemic inflammation, diabetes, and cerebrovascular effects. There have been many studies that found exacerbations of asthma, COPD, and some cardiovascular effects from smoke exposure (Reid et al., 2016). Researchers have also found increases in mortality during smoke-affected days, but the specific causes leading to this is less clear (Reid et al., 2016). The main birth outcome associated with wildfire smoke exposure is low birth weight (Reid et al., 2016). Certain health conditions and social factors contribute to some populations being more vulnerable than others. These groups include children, older adults, pregnant women, individuals of lower socioeconomic status, and individuals with pre-existing respiratory or cardiovascular diseases (Liu et al., 2015; Reid et al., 2016). California is an area in the United States that will see some of the highest increases of wildfire smoke exposure with climate change (Liu et al., 2016). It is important to focus on vulnerable populations because they will see the worst effects of climate change and smoke exposure.

Due to the many adverse health effects that wildfire smoke causes, there is a need for an alert system and plan for those affected. There are some systems in place, but very few have been formally evaluated. The AirNow website developed by the EPA and other agencies contains information on air quality, fires, air pollutants, health, and more. It also has its own alert system called EnviroFlash that anyone can sign up for to receive notifications of poor air quality. There is a lot of useful information related to wildfire smoke and health and recommended actions, but navigating the website is not easy and it takes a long time to find what you're looking for. The Bay Area Air Quality Management District contains information about air quality and how to reduce exposure to PM2.5, as well as a "spare the air" program that alerts residents when air quality has reached unhealthy levels. They are also in the process of creating a wildfire response plan so that residents will receive more specific information about wildfire smoke and actions to take during wildfire smoke events. Oregon has a guidance document and blog website for severe smoke episodes. While the document represents a good example for how to organize different agencies, the website is unorganized and lacks usability. Canada also experiences many wildfires, so they have their own plans and air quality index for smoke events. There was a study done on the effects of air quality alerts in Canada on human health, but it focused on smog days rather than wildfire smoke events. The San Diego Air Pollution Control District has information on daily air quality levels but has no action plan or alert system in place for high pollution days. There is also no information on its website about wildfire smoke and the pollutants associated with that. There is a lot of room for improvement for San Diego when planning for wildfire smoke events, especially within the San Diego Air Pollution Control District.

As part of the implementation of the UCSD air quality alert system, four alert email templates and a website on wildfires and air quality hosted on the Environment, Health, and Safety website were created. The four emails include an initial alert detailing the fire and air quality on the campus, a follow-up email for if air quality worsens but the campus remains open, a separate follow-up email for if air quality worsens and classes are cancelled, and a final email for when air quality improves and campus operations return to normal. The initial alert is triggered when the air quality index passes 100 and confirmed with a call to San Diego Air Pollution Control District. The wildfires and air quality website includes a map of current air quality in San Diego, some health information about wildfire smoke effects, and recommended actions for both sensitive groups and the entire campus. The website is only one page so that students can get the critical information they need without searching through multiple pages. The website also contains links to outside resources if they want more information. The link to the website is located in the email alerts so that students, faculty, and staff can easily access it.

The air quality alert system was made for UCSD but can easily be expanded to other UC and non-UC universities. Due to the increase of wildfires and smoke events, the effort to create and improve air quality alert systems should be expanded across California. Evaluation of available alert systems should also be continued to determine the most effective methods.

Background

Wildfires: Contributing Factors and Climate Change Impacts

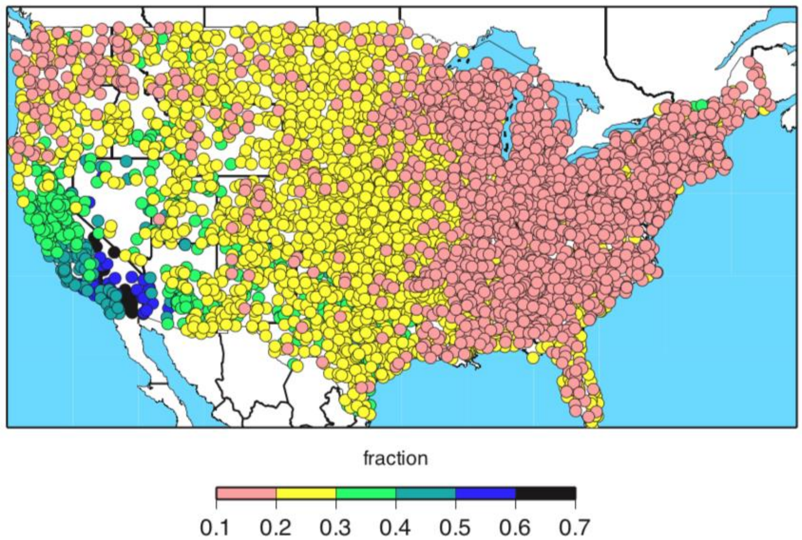
Wildfires are dangerous and hard to predict with high spatial and temporal resolution. Due to land management practices, fire suppression techniques, expanding development, and a changing climate, California has seen an increase in the number, area burned, and duration of wildfires (2018 Strategic Fire Plan for California). The incidence of wildfires depends on many different factors, including land use, fuel availability and type, wind patterns, temperature, and precipitation. Wildfires are also incredibly diverse with some lasting only a few hours and others lasting weeks and spreading across many acres. Climate change has caused rising temperatures and more variable precipitation, which has led to longer droughts and increased fuel for fires (4^{th} assessment report: statewide summary). The many factors that wildfires depend on makes them both difficult to predict and difficult to model. However, recent research has used a variety of climate modeling techniques to track wildfires real-time and to predict how wildfires will change in the future with climate change. The general consensus is that wildfires (around the world and in California) will increase in number, intensity, and duration as climate change continues, especially for high emission scenarios (IPCC 5^{th} assessment report).

Temperature and Precipitation

Temperature and precipitation are the two main climatic factors that influence the prevalence and intensity of wildfires in California. Historical trends as well as the future direction of change indicate warming in California. Observed changes in temperature from the early 1900s to now have shown parts of California warm over 2°F, including the San Diego region (4^{th} assessment report: statewide summary). Both RCP 4.5 and RCP 8.5, climate change scenarios for modest emissions and high emissions, respectively, project increases in annual average daily maximum temperatures in California through the end of the century (4^{th} assessment report: statewide summary).

California also has highly variable precipitation, with most of the precipitation falling during extreme weather events or atmospheric rivers (Dettinger et al., 2011). While the number of precipitation events is projected to decrease overall, the intensity of these atmospheric river events will increase (Dettinger, 2016). Therefore, California will get more precipitation from a few large events over a shorter time period throughout the year, rather than smaller rainfall events dispersed throughout the year.

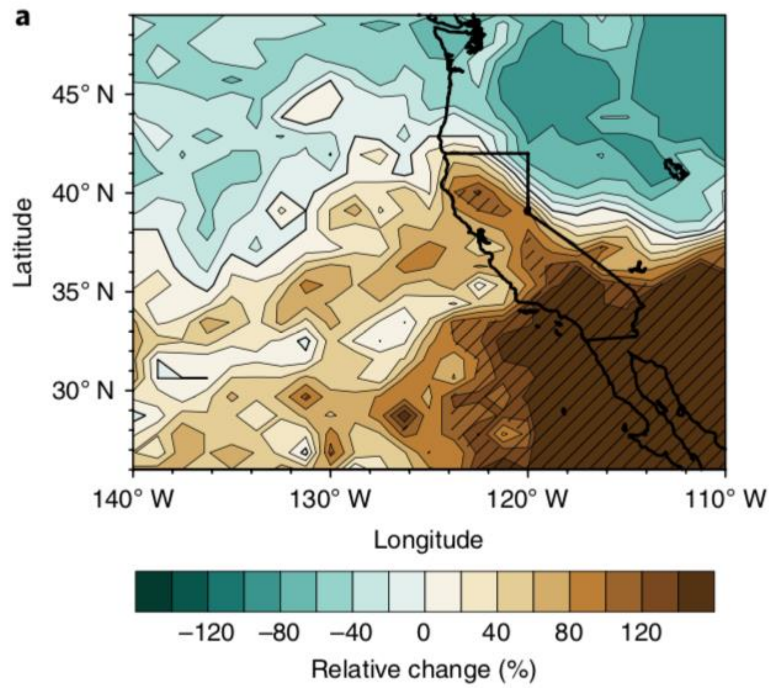
FIGURE 4 | VARIATION IN ANNUAL PRECIPITATION



Coefficient of Variation of annual precipitation observations, 1951-2008, showing that California has the highest variability of year-to-year precipitation. Coefficient of Variation, the standard deviation divided by the long-term average, is a measure of the range of low and high values of annual precipitation in the historical record. Locations with high coefficients experience large fluctuations in annual precipitation from year to year. Source: Dettinger et al., 2011.

Source: California’s Fourth Climate Change Assessment: Statewide Summary
Figure 2: Compared to the rest of the country, California (and especially Southern California) has the highest variability of year-to-year precipitation.

This combination of warming temperatures and concentrated precipitation translates into an increased risk for drought. Even with an increase in precipitation during extreme weather events, the projected warming will increase moisture loss from soils, leading to drier seasonal conditions (Thorne et al., 2015). Seasonal summer dryness may also become prolonged, with Southern California experiencing large increases in extreme dry-event frequency (defined as exceeding the 100-year return interval) as well as an increase in the frequency of consecutively dry seasons (Swain et al., 2018).



Source: Swain et al., 2018
Figure 3: This figure shows the change in frequency of extremely dry seasons in California. Most of California will have over 80% more extremely dry seasons at the end of this century under RCP8.5 relative to the preindustrial era. Southern California will have the greatest percent change of dry seasons (Swain et al., 2018).

Fuel Availability and Anthropogenic Impacts

Humans have altered not only the climate with greenhouse gas emissions, but also natural ecosystem services like wildfires. Through land management practices, fire suppression techniques, and ignition patterns, we have disrupted natural processes and in doing so, made wildfires larger and more destructive (2018 Strategic Fire Plan for California).

Fuel availability for wildfires is determined in part by temperature and precipitation as well as other factors such as overgrowth from fire suppression activities and tree mortality by insects. The projected fewer but more extreme precipitation events could cause an increase of seasonal plant growth after the winter season, adding to the fuel availability for fires (Westerling et al., 2004). Warmer temperatures, drier conditions, and longer drought seasons will also contribute to worsening fire conditions.

The recent widespread tree mortalities in the Sierra Nevada region have been attributed to a combination of drought, human fire suppression activities, and a bark beetle outbreak (Stephens et al., 2018). Small, natural fires occurred in these California ecosystems for millennia, which cleared a lot of the undergrowth and dead fuel in the forests. When land managers began aggressive fire suppression techniques, putting out even small fires which the ecosystem needed, they unwittingly created an increase in fuel and destabilized forests by increasing competition and making them prone to pests like bark beetles (Stephens et al., 2018).

We are just recently starting to realize the damage we have caused with these fire suppression techniques, and more and more resources are being put toward clearance of flammable undergrowth and dead trees. But with fires becoming larger and more destructive, there is a delicate balance between putting money and resources toward fire prevention versus fire suppression. The increasing population in California has led to more houses and infrastructure in the wildland-urban interface in fire hazard severity zones (2018 Strategic Fire Plan for California). This has made more people vulnerable to wildfires and wildfire smoke. Since population is only projected to increase, people will continue to settle in these hazard zones.

Winds

Another element that contributes both to wildfire incidence and patterns of smoke travel is winds. The most well-known winds in California that contribute to wildfires are the Santa Ana winds, but the Sundowner and Diablo winds in Central and Northern California are similar. Santa Ana winds are strong, dry, easterly winds that originate with high pressure anomalies over the Great Basin or from large temperature gradients between the cold desert and warm ocean air (Hughes and Hall, 2010). The combination of these strong winds and low humidity often results in large wildfires that spread quickly. Santa Ana winds begin in the fall season and continue through the spring, peaking in December and January (Westerling et al., 2004; Guzman-Morales et al., 2016). Due to the variable precipitation in California, large wildfires have occurred throughout these seasons (Westerling et al., 2004).

Wind patterns are incredibly difficult to model, so there is not consensus on how the Santa Ana winds might be affected by climate change (4^{th} assessment report: statewide summary). One study found that due to the projected larger transient warming of the desert relative to surface air over the ocean, the wintertime temperature difference between the two would lessen, causing a reduction in Santa Ana wind occurrence (Hughes et al., 2011). However, it was also found that relative humidity will be reduced, and temperature will increase during Santa Ana events, indicating more favorable conditions for fire development (Hughes et al., 2011). These results were mirrored in another study that concluded reduced relative humidity would increase the probability of ignition success and therefore lead to more wildfires (Jin et al., 2014). A relationship between Santa Ana wind intensity and ENSO (El Niño Southern Oscillation) was found where seasonal Santa Ana wind intensity is enhanced during El Niño and subdued during La Niña (Guzman-Morales et al., 2016). This demonstrates potential for an ENSO-related prediction of Santa Ana wind activity and fire risk, but this has not yet been explored further (Guzman-Morales et al., 2016). Because wind is just one of many factors that contribute to wildfires, it is important to look at multiple variables when predicting wildfire occurrence.

Modeling Wildfires

Wildfires depend on many factors, both anthropogenic and climatic, including land use and development, fire management, ignition sources, air temperature, relative humidity, precipitation, wind, vegetation and fuel availability. This makes modeling incredibly difficult, for both weather and climate models, and not all of these factors can be included. The lack of data in certain areas like atmosphere and fuels also limits the ability of models to accurately predict wildfires (Bakhshaii and Johnson, 2019). Since almost all of these factors will be influenced by climate change, this adds another layer of complexity to the problem.

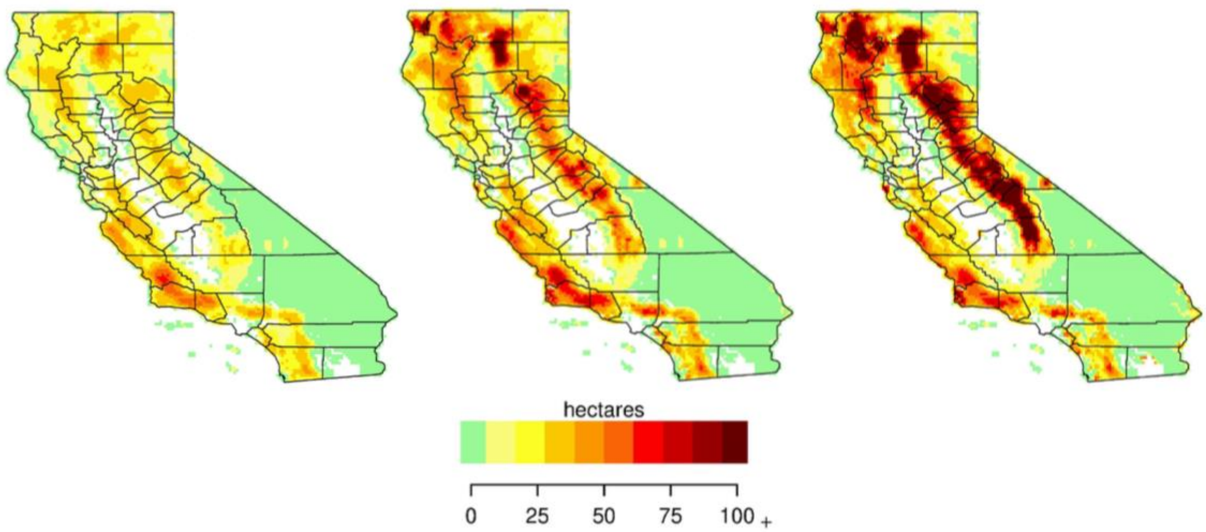
There have been recent efforts to improve wildfire modeling with varying degrees of success. Different types of models have been developed for different purposes, and some are more computationally demanding than others. The main goals of wildfire modeling are to create tools for fire research as well as real-time fire management (Bakhshaii and Johnson, 2019). If the model becomes too complex, it will take too long to run and will not be useful for real-time forecasting. Thus, there is a balance between incorporating enough elements and being able to run the model quickly.

With improvements in modeling, remote sensing, numerical methods, and increases in computing power, wildfire models have become more powerful and better able to couple with other models (Bakhshaii and Johnson, 2019). The coupling of wildfire models to computational fluid dynamics or mesoscale weather models allow for more complexity in different spatial and temporal scales (Bakhshaii and Johnson, 2019). A project developed at UCSD called WIFIRE has built a cyberinfrastructure for wildfire managers to use real-time and data-driven simulation, prediction, and visualization techniques of wildfire behavior (Crawl et al., 2017). With the web browser Firemap, different agencies can easily model fire behavior real-time and be able to see it on a map (Crawl et al., 2017). Others have tried to reduce the model simulation time by eliminating parts of the network that have only a small effect on the fire travel time distribution, while still producing an accurate outcome (Hajian et al., 2016).

There are still improvements to be made in these models, for example, none of the current models can predict which wildfires will turn into large fires (Bakhshaii and Johnson, 2019). And although we can identify "high hazard zone" areas where a wildfire is more likely to occur, models are not able to predict the magnitude of heat output or fire front size (Bakhshaii and Johnson, 2019). The advancements in technology of the computers will allow for even more complex models.

Some researchers have focused more on forecasting wildfires or modeling wildfires under different climate change scenarios rather than trying to track fires real-time. Fire risk forecasting uses wind speed, air temperature, rainfall, and other meteorological factors to model results like burn area and fire radiative power (Hernandez et al., 2015). This produces results useful for a wildfire alert system that can identify extreme fire risk for the season (Hernandez et al., 2015). In the wildfire simulations done by Anthony Westerling for California's Fourth Climate Change Assessment, under high global greenhouse gas emissions pathways (RCP 8.5), he found the mean annual area burned increased by 77% statewide and the maximum area burned increased by 178% by the end of the century (Westerling, 2018).

FIGURE 8 | PROJECTED AVERAGE ANNUAL AREA BURNED BY WILDFIRE



Average annual area in hectares burned using four GCMs and 30-year periods for RCP 8.5, mid-range population growth. (a) 1961-1990; (b) 2035–2064; (c) 2070–2099. Source: Westerling, 2018

Source: Westerling, 2018
Figure 4

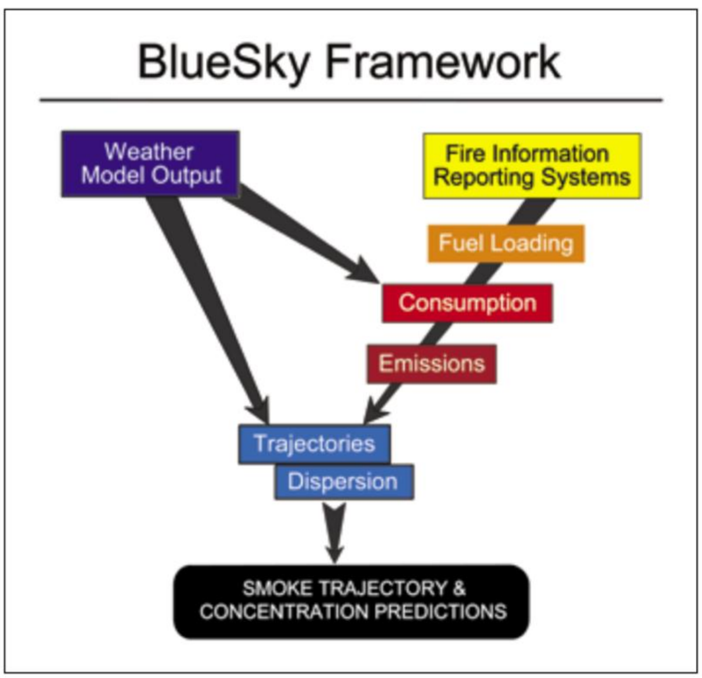
Extreme wildfire events that burn greater than 10,000 hectares were also found to increase in frequency (Westerling, 2018). The data used to produce these results included statistical models of large wildfire presence (number and size), population and development footprint scenarios, and fuels treatment scenarios (Westerling, 2018). This model did not include potential changes in wind regimes, which we have seen can have a large effect on wildfires (4th assessment report: statewide summary). Although wildfires are projected to increase with climate change, potential fuel treatments have been found to mitigate these increases (Westerling, 2018). However, population growth and continued urban sprawl will increase both property risk and health risk from wildfires (Bryant and Westerling, 2014). The costs in both physical damage as well as health care will therefore also increase.

Wildfires are influenced by many different factors, both natural and anthropogenic. Researchers are developing models both for use in real-time fire management and for research and forecasting into the future and under climate change. There have been improvements to these models in the past few years, but there is still much that can be improved upon to make the models faster and more accurate. For now, most models project an increase in area burned, intensity, and duration of wildfires under climate change. All of this translates into a need for wildfire planning, including alerting the public during wildfire events that create poor air quality from the smoke.

Wildfire Smoke

In addition to creating conditions favorable for wildfire formation, Santa Ana (and Sundowner and Diablo) winds cause smoke from wildfires to travel miles away from the source, to the highly populated coastal regions of California (see Figure 5). This smoke contains harmful pollutants, including carbon monoxide, nitrogen dioxide, ozone, hydrocarbons, volatile organic compounds, and particulate matter (PM) (Reid et al., 2016). PM2.5 and PM10 are the pollutants of greatest concern because of their effects on the eyes and respiratory system (EPA: Fires and Your Health). The smoke can linger in the air for weeks after a fire, increasing ambient air pollution levels dramatically. Due to this specific threat from smoke, scientists have created forecast systems for how smoke will travel in addition to fire forecasts.

Several agencies across North America and abroad have developed smoke forecast systems to balance land management needs against smoke impacts (O'Neill et al., 2008). These systems use fire activity data, fuels information, consumption and emissions models, and weather forecasts and dispersion models to predict smoke concentrations (O'Neill et al., 2008). They are not only used for wildfires, but also prescribed fires and agricultural fires (O'Neill et al., 2008). The BlueSky system, developed by the U.S. Forest Service, produces forecasts of hourly ground-level concentrations of PM2.5 from wildfires up to 48 hours into the future (Sakiyama 2013; O'Neill et al., 2008).



Source: PNW Science Update
Figure 5: The data input and models involved in the BlueSky framework

The National Oceanic and Atmospheric Administration's (NOAA) Smoke Forecasting System uses satellite imagery through the Hazard Mapping System to find the locations of fires (Rolph et al., 2009). It also uses part of the BlueSky framework and a few more models for smoke and fire detection (Rolph et al., 2009). This system is able to perform real-time detection and specification of smoke with the satellites, which makes it a useful tool for regulators and wildfire management (Rolph et al., 2009).

Eos, Vol. 85, No. 31, 3 August 2004

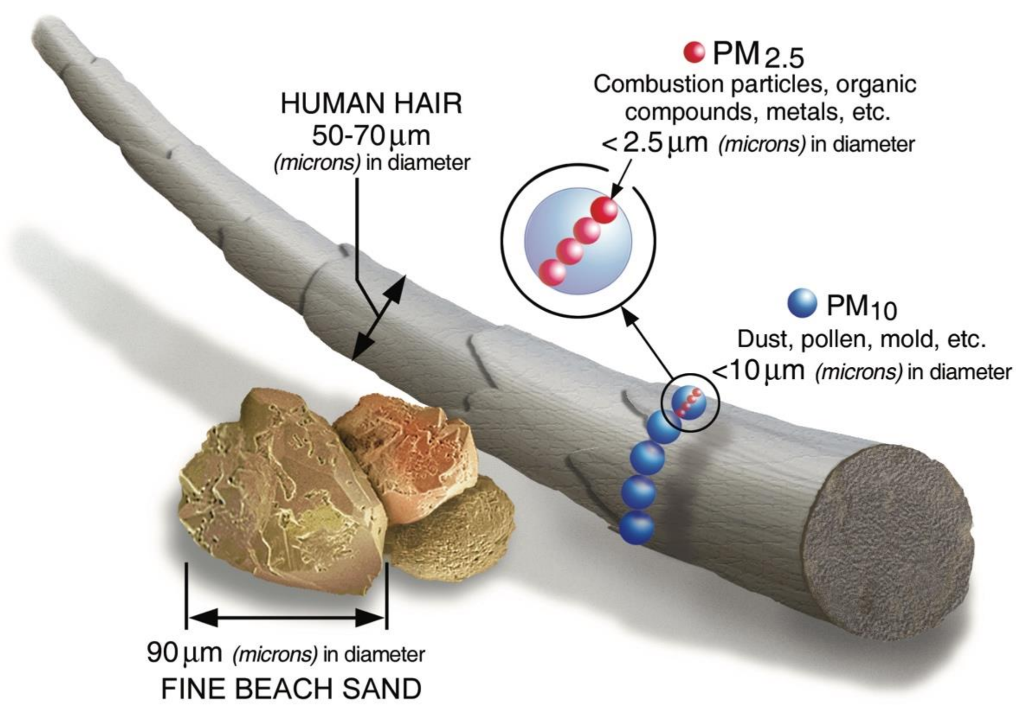
Fig. 1. Smoke from southern California wildfires is shown on 26 October 2003. Active fire perimeters are outlined in red in Ventura, San Bernardino, Los Angeles, and San Diego counties, and in Baja California, Mexico. Selected city names are in black; fire names in white. Source image courtesy of NASA/MODIS Rapid Response Team.

Source: Westerling et al., 2004
Figure 6

Smoke forecasting is useful for public agencies as an intervention tool to reduce health effects from smoke. Rappold et al. simulated public health forecast-based interventions during a wildfire smoke event in North Carolina to see if there was a health benefit (Rappold et al., 2014). Three different thresholds for PM2.5 were used and the health outcomes looked at were emergency department visits for exacerbations of asthma and congestive heart failure (Rappold et al., 2014). The greatest risk reductions were found with interventions at the lowest threshold (PM2.5 ≤ 20 $\mu g/m^3$) (Rappold et al., 2014). Although this study was based on a simulation, it demonstrates a great potential for the use of smoke forecasting based interventions for the reduction of adverse health effects.

Health Impacts of Wildfire Smoke

With the increases in wildfires that we have seen in the past few decades, there has been more interest in finding the different health impacts associated with inhalation of wildfire smoke. Particulate matter has been identified as the pollutant of most concern for the public and has therefore been studied the most (U.S. Forest Service, 2010). There have already been several review papers published on the topic of wildfire smoke health effects, with agreement and disagreement on different areas between studies. The main areas researched, and the ones discussed here include respiratory morbidity, cardiovascular morbidity, mortality, and birth outcomes. Along with these more serious health effects, some minor short-term health impacts include eye and respiratory tract irritation (CARB and CDPH 2016). Most studies determined an association between wildfire smoke and health outcomes by looking at hospital records, which contain information on emergency department visits, hospitalizations, medications, and physician visits (Reid et al., 2016). Some of the methods used to determine the effects of smoke inhalation include comparing data before and after a fire in the same location or comparing data in a location with a fire with a different location without a fire in the same time period (Liu et al., 2015). Because of both exposure differences and susceptibility differences, not everyone is affected by wildfire smoke the same way, and work has been done to identify the most vulnerable populations. Some research has also been done on how particulate air pollution and health impacts will be affected under climate change.



Source: EPA.gov

Figure 7: PM2.5 is particulate matter less than 2.5 microns in diameter and is found in high concentrations in wildfire smoke. When inhaled, these particles can get deep into your lungs and enter the bloodstream, causing harmful health effects.

Respiratory Morbidity

Respiratory health effects include asthma, chronic obstructive pulmonary disease (COPD), lung function, respiratory infections, pneumonia, and bronchitis. The negative effects of smoke exposure on asthma and COPD are generally agreed upon across studies. Smoke exposure contribution to exacerbation of asthma has been seen in the form of increased physician visits, emergency department visits, hospitalizations, and medication dispensation/consumption (Reid et al., 2016; Liu et al., 2015).

There are similar results for the association between wildfire smoke exposure and exacerbation of COPD (Reid et al., 2016). Using a new exposure model tool, Yao et al. found an increase in modeled PM2.5 was associated with an increase in physician visits for COPD comparable to measured PM2.5 (Yao et al., 2016). Bronchitis and pneumonia have also been found to increase during wildfire smoke events, both for physician visits and emergency department visits (Reid et al., 2016). During and after the 2003 southern California wildfires, bronchitis and pneumonia hospital admissions increased (Delfino et al., 2009). This association was also found in a study done in Australia (Martin et al., 2013).

While the evidence for associations between wildfire smoke and bronchitis and pneumonia is strong, associations between wildfire smoke and other respiratory infections is less consistent. Some studies have found increases in emergency department and physician visits for respiratory infections during wildfires, but others did not find any association (Reid et al., 2016). In an earlier review of health impacts from wildfire smoke, over 90% of the 45 studies looked at associated wildfire smoke with respiratory morbidity (Liu et al., 2015). While different respiratory effects may have stronger associations than others, there is strong evidence overall for the association between wildfire smoke and respiratory morbidity.

Cardiovascular Morbidity

Cardiovascular morbidity and some specific end points have been studied in relation to wildfire smoke. This includes cardiac dysrhythmias/arrhythmias, angina, ischemic heart disease, cardiac arrest, acute myocardial infarction, and congestive heart failure. The evidence for associations between wildfire smoke and cardiovascular morbidity is mixed with many studies finding no association for grouped cardiovascular outcomes, but more associations found for specific end points (Reid et al., 2016). Specifically, cardiac arrests and hospitalizations for ischemic heart disease are associated with PM2.5 from wildfire smoke (Dennekamp et al., 2015; Haikerwal et al., 2015). In addition, 23.9 excess out-of-hospital cardiac arrests were estimated to occur in Melbourne, Australia due to elevations in PM2.5 during twelve days of the 2006/2007 fire season (Dennekamp et al., 2015). Haikerwal et al., 2015 also found an increased risk of out-of-hospital cardiac arrests as well as ischemic heart disease for the same fire season in Australia. Due to the variety of methods and study conditions, the findings for cardiovascular morbidities from wildfire smoke exposure vary. However, any cardiovascular association found is cause for concern.

Mortality

Wildfire smoke exposure and all-cause mortality has been associated in many recent studies, but the specific causes of mortality are not as clear (Reid et al., 2016; Liu et al., 2015).

Two long term studies done in Australia found a significant increase in mortality associated with smoke-affected days and wildfire-related PM10 (Johnston et al., 2011; Morgan et al., 2010). Other studies have looked at the interaction between high temperatures and PM10 smoke exposure, mainly during the summer season. During a major heat wave in Russia, high temperatures and air pollution from wildfires contributed to more than 2,000 of the 11,000 nonaccidental deaths from this period (Shaposhnikov et al., 2014). There have also been a few studies that have attributed wildfire smoke specifically to cardiovascular mortality, but less for respiratory mortality.

Birth Outcomes

Many studies have already been done on associations between birth outcomes and exposure to ambient air pollution, but there have also been a few recent studies on links between wildfire smoke exposure and birth outcomes (Reid et al., 2016). Lower birth weights have been found in babies whose mothers were exposed to wildfire smoke and agricultural burning (Holstius et al. 2012; Candido da Silva et al., 2014). During the 2003 southern California wildfires, mothers in their second and third trimesters had lower birth weight babies than babies born before the fires and more than nine months after the fires (Holstius et al., 2012). There are both biological (exposure to smoke) and psychosocial (stress caused by wildfires) pathways to explain this outcome, but this study could not differentiate between the two (Holstius et al., 2012). Some of the possible biological mechanisms include hypoxia, alteration of maternal-placental exchanges, endocrine disruption, and oxidative stress pathways leading to a higher risk of infections (Holstius et al., 2012). It is possible that lower birth weight is a result of a combination of both biological and psychosocial factors, but further studies are needed to distinguish these contributions (Holstius et al., 2012). A study on Amazon forest fires and birth weight was less conclusive and could not attribute smoke from these forest fires as leading to low birth weights (Prass et al., 2012).

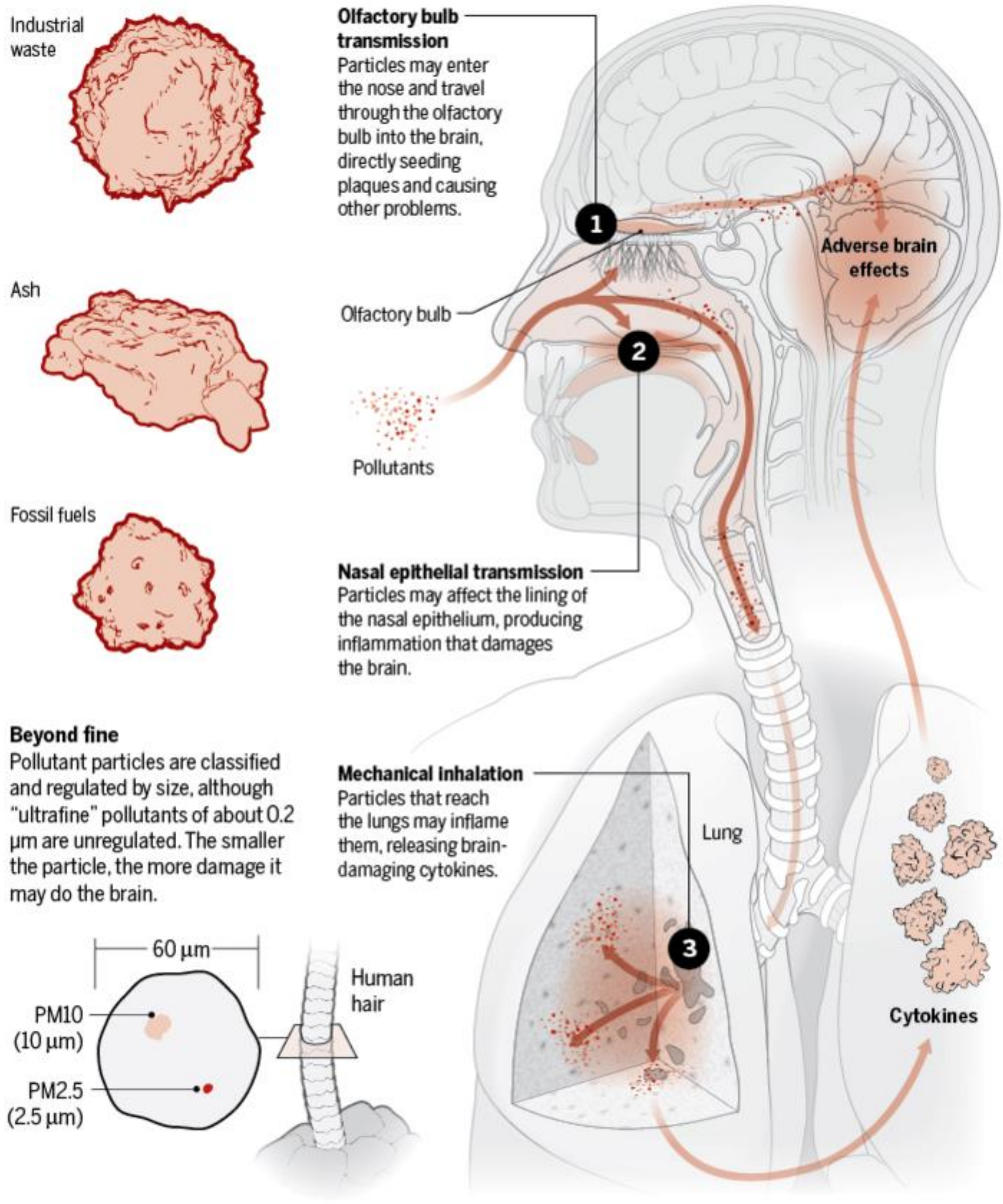
Other Health Effects

There have been fewer studies on a wide range of health outcomes, including but not limited to, mental health outcomes, systematic inflammation, diabetes, and cerebrovascular effects. Although there have been many studies looking at mental health effects related to wildfires, few have looked specifically at smoke exposure as the cause, and even fewer associated mental illness with wildfire smoke (Reid et al., 2016). In fact, neither of the two unbiased studies included in the Reid et al. review found an association between mental illness and wildfire smoke.

Both in vivo and in vitro studies of animals and humans have shown increased inflammatory responses associated with wildfire smoke and wildfire-derived PM (Reid et al., 2016; Liu et al., 2015). The increased inflammatory responses in humans include elevated band neutrophil counts, elevated cytokines, elevated C-reactive protein, and elevated IL-12 (Tan et al., 2000; Van Eeden et al., 2001; Huttunen et al., 2012). These inflammatory responses lead to both respiratory and cardiovascular effects (Reid et al., 2016).

One study looking at wildfire smoke and different health outcomes did not find an association for diabetes (Lee et al., 2009). However, a few studies have identified those with diabetes as having an increased risk to air pollution impacts (Devlin et al., 2014; Ruckerl et al., 2014; Schneider et al., 2008). Ruckerl et al. draws attention to studies that show people with type 2 diabetes are more sensitive to pollution-triggered cardiovascular events. Nevertheless, studies looking directly at wildfire smoke and diabetes are few and far between and do not have conclusive evidence about the effect of wildfire smoke exposure on people with diabetes.

Cerebrovascular effects and other brain diseases are also being studied in relation to air pollution and wildfire smoke. Cerebrovascular effects are closely related to cardiovascular effects and include ischemic stroke and cerebral hemorrhage. Along with an increase in cardiovascular emergency department visits during wildfire smoke days, cerebrovascular visits were also seen to increase (Wettstein et al. 2018). New research is being done on the effects of air pollution on dementia and similar cognitive aging diseases (Underwood 2017). This is part of a wider literature on long-term effects of air pollution, rather than the short-term effects of wildfire smoke we have been focused on thus far. A recent study found an association between air pollution and dementia by using fifteen years of Medicare records and data from EPA air quality monitors (Bishop et al., 2018). Specifically, a 9.1% increase of the mean in average decadal exposure of PM2.5 increases the probability of receiving a dementia diagnosis by 1.3 percentage points (6.7% of the mean) (Bishop et al., 2018). Although this study is talking about a long-term effect of chronic air pollution exposure and was not specifically related to wildfire smoke, it has important implications for air pollution effects in general and lays the groundwork for future research in this area.



Source: Underwood, Science 2017

Figure 8: Pollutants can damage the brain over time directly or from a distance by triggering the release of inflammatory molecules.

Vulnerable Populations

Due to different physiological, environmental, and social factors, certain groups of people are more vulnerable to the harmful effects of air pollution than others. These groups of people will henceforth be referred to as vulnerable populations or sensitive groups, interchangeably. Identifying vulnerable populations is important for health officials, public policy, and our own knowledge. There have been several vulnerable populations identified in the literature on air pollution from wildfire smoke with varying degrees of agreement. These vulnerable groups also vary depending on what health outcome you are looking at and what pollutant you are studying. In general, the identified vulnerable populations for health effects from wildfire smoke include children, older adults, pregnant women, individuals of lower socioeconomic status (SES), and individuals with pre-existing respiratory or cardiovascular diseases (Liu et al., 2015; Reid et al., 2016). In addition, certain areas of the United States will be more at risk to wildfires and wildfire smoke due to climate change forecasts.

Children have been identified as a sensitive group, mostly for respiratory morbidities, for a few different reasons. Children are still undergoing lung growth and development, have incomplete metabolic systems, immature host defenses, and high rates of infection by respiratory pathogens (WHO, 2005). In addition, they have specific activity patterns that make them more vulnerable like playing outside more than adults. These factors all lead to higher exposure to air pollution and more pollutants are able to reach children's lungs (WHO, 2005). Long-term exposure to air pollution as a child can affect the functional capacity of the lungs as they enter adulthood (WHO, 2005). Most of the evidence for these health effects comes from ambient air pollution studies, but there have been some recent studies that focus on wildfire smoke. One example of this is a study on the health impacts of burning the Brazilian Amazon region which found children experienced a disproportionately high increase in hospitalizations for respiratory disease (Ignotti et al., 2010). Looking at the 2003 southern California wildfires, one of the strongest wildfire-related PM2.5 associations with hospital admissions was for children (Delfino et al., 2009).

Older adults are susceptible to health effects from air pollution, and adverse health effects in general, mainly due to natural ageing processes. This includes a decline in immune defenses and respiratory function and a predisposition to respiratory infections (Bentayeb et al., 2012). Several literature review papers have identified the elderly as having a greater risk for cardiovascular and respiratory diseases due to particulate air pollution (Anderson et al., 2003; Bentayeb et al., 2012; Liu et al., 2015). In the study of the Brazilian Amazon region, older adults (≥ 65 years old) had the highest rate of hospitalization during the fires due to respiratory disease (Ignotti et al., 2010). A similar outcome was found for wildfire smoke in Australia (Morgan et al., 2010). Susceptibility for the elderly is also due to a higher prevalence of underlying cardiovascular and respiratory conditions that may be worsened by wildfire smoke exposure (Makri and Stilianakis, 2008).

Because some of the common effects of wildfire smoke exposure include respiratory and cardiovascular morbidities, it follows that those with pre-existing respiratory and cardiovascular diseases are more vulnerable. Those with pre-existing respiratory morbidities like asthma could have elevated sensitivity to environmental hazards due to weaker immune systems, which causes them to be more susceptible to the effects of wildfire smoke (Liu et al., 2015). A study looking specifically at susceptible populations for particulate matter-induced health effects found that different cardiovascular diseases, such as coronary heart disease, hypertension, and stroke, did make one more susceptible to the effects of air pollution (Sacks et al., 2011).

Pregnant women and their unborn children are vulnerable to a variety environmental conditions, including air pollution and wildfire smoke. Any pollutants that affects the mother will also be transferred to her fetus and may have detrimental effects. A causal relationship between particulate air pollution and respiratory deaths in the post-neonatal period has been determined as well as an association between birth weight and air pollution, principally for particulate matter (WHO, 2005). There have also been studies suggesting a biological mechanism for an air pollution effect on premature birth and intrauterine growth retardation, but not for birth defects (WHO, 2005).

Socio-economic status is one consideration that comes up in many different areas of climate change and pollution studies. This can be measured by income, education, or occupation, and low SES has been associated with a higher prevalence of preexisting diseases, limited access to medical care, and limited access to fresh foods (Sacks et al., 2011). All of these factors may contribute to increased susceptibility of wildfire smoke health effects. Studies have found an increased risk of mortality for short-term exposure to PM2.5 both for low income and low educational attainment groups (Franklin et al., 2008; Ostro et al., 2008). In North Carolina, emergency department visits for asthma and congestive heart failure due to wildfire smoke exposure were determined based on a stratification of socio-economic factors (Rappold et al., 2012). The difference in risk between bottom and top ranked counties by socio-economic factors was 85% for asthma and 124% for congestive heart failure, indicating SES as an important factor to consider in air pollution and wildfire smoke studies and policies.

In addition to specific populations that are more vulnerable to wildfire smoke, there are certain areas of the United States that will experience a higher exposure to wildfire smoke in the future with climate change. Under a moderate emissions scenario for mid-century, more than 82 million individuals will experience a 57% and 31% increase in frequency and intensity, respectively, of Smoke Waves (≥2 consecutive days with high wildfire-specific PM2.5) (Liu et al., 2016). The highest exposure is likely to occur in Northern California, Western Oregon, and the Great Plains (Liu et al., 2016). Therefore, there is a great need for risk management policies both for wildfires and health planning in California.

Primary prevention for wildfires includes forest management practices like debris clearing and firefighting activities when a wildfire begins. This is incredibly important for wildfire management, but as we know, some fires cannot be extinguished or contained right away, and secondary prevention measures for the protection of health is necessary. Due to the many adverse health effects that wildfire smoke causes, there is a need for an alert system and plan for those affected. The alert should notify everyone of the poor air quality conditions created by wildfire smoke, inform them of the negative health effects associated with smoke inhalation, and give recommended actions for how to reduce this exposure, both for the general population as well as sensitive groups. The next section outlines and evaluates available alert systems.

Assessment of Available Air Quality Alert Systems

When conducting research on currently available air quality alert systems and plans associated with these, there were not many to be found and even less that have been formally evaluated. Most of what was found includes various websites with air quality information and a few cities and states with air quality alerts set up rather than peer-reviewed scientific papers. In order to create a comprehensive air quality alert system for UCSD that included both a notification system as well as a website, alert systems, forecasting methods, website layouts, recommended actions, and other air quality resources were researched. The following is a description and evaluation of the most comprehensive air quality alert systems found, resources from these systems that informed the creation of the UCSD alert system, and what is (and isn't) already in place here in San Diego.

EPA AirNow

AirNow was developed by the US Environmental Protection Agency, National Oceanic and Atmospheric Administration (NOAA), National Park Service, and tribal, state, and local agencies (EPA: About AirNow, 2016). It is used to provide the public with easy access to national air quality information and the data is collected mostly by state and local agencies. The website contains maps of current and forecasted air quality, a map of current fires, the AQI (air quality index) chart and explanation of different levels, information about specific pollutants and their health effects, air quality action days for different cities, a link to sign up for air quality alerts, and more. In addition to information about general air quality and pollutants, the website also contains more specific information about wildfires, smoke, and health. Overall, it is a comprehensive platform that contains many great resources about air quality and wildfires, and actions to take. However, it is difficult to navigate, and the maps are better suited for scales at the national or state levels.

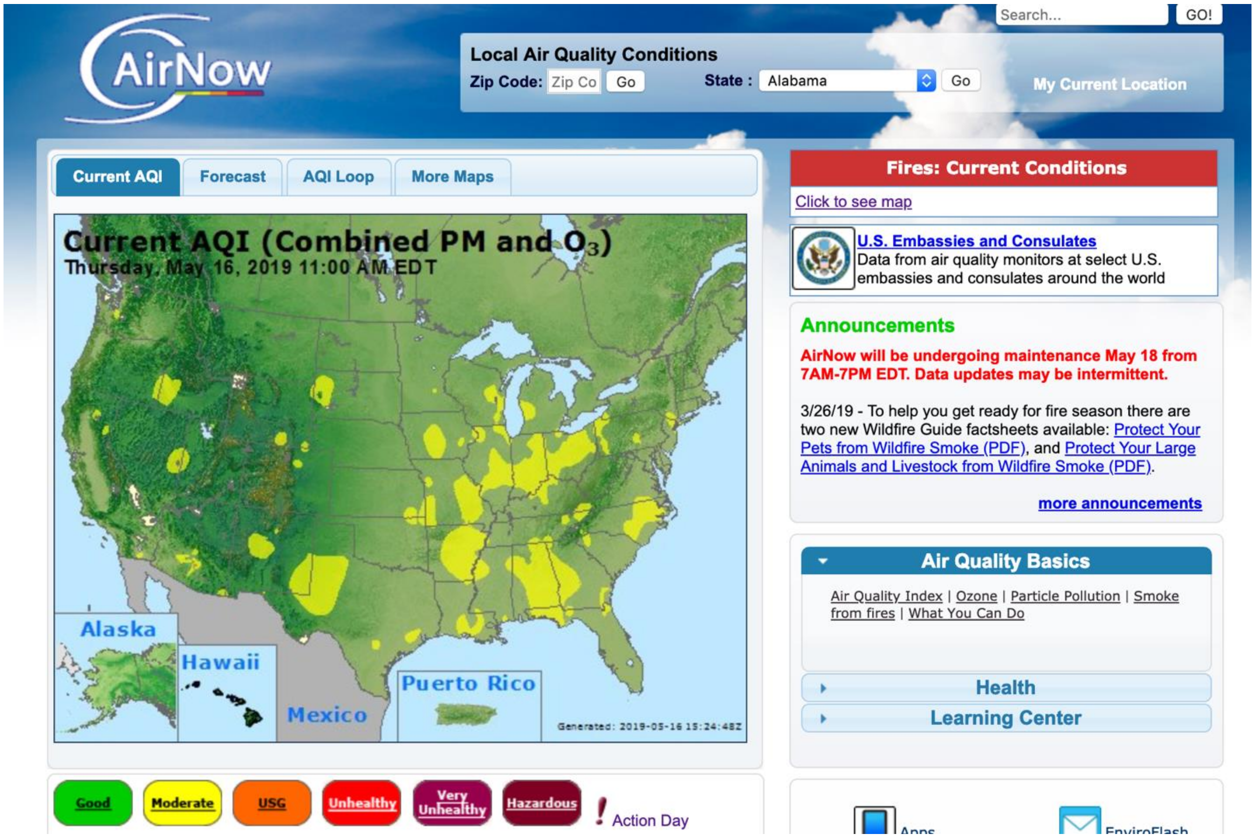
The air quality index (AQI) is a tool developed by the EPA to inform citizens of daily air quality in an easy to understand manner (EPA: Air Quality Index Basics). The index goes from 0 to 500, is divided into six categories, and designates the level of health concern for each category. Colors are also paired to the six ranges for ease of understanding. The EPA calculates the AQI for the five pollutants regulated by the Clean Air Act: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide (EPA: Air Quality Index Basics). There are national air quality standards for each pollutant to protect public health. The raw concentrations of the pollutants are converted to an AQI number, where a value of 100 corresponds to the national air quality standard. For example, a reading of 35.4 $\mu g/m^3$ for PM2.5 (the national standard) corresponds to an AQI of 100 (EPA: AQI Calculator). Levels above this are considered unhealthy for sensitive groups.

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk.
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health alert: everyone may experience more serious health effects.
Hazardous	301 to 500	Health warnings of emergency conditions. The entire population is more likely to be affected.

Note: Values above 500 are considered Beyond the AQI. Follow recommendations for the "Hazardous category." Additional information on reducing exposure to extremely high levels of particle pollution is available here.

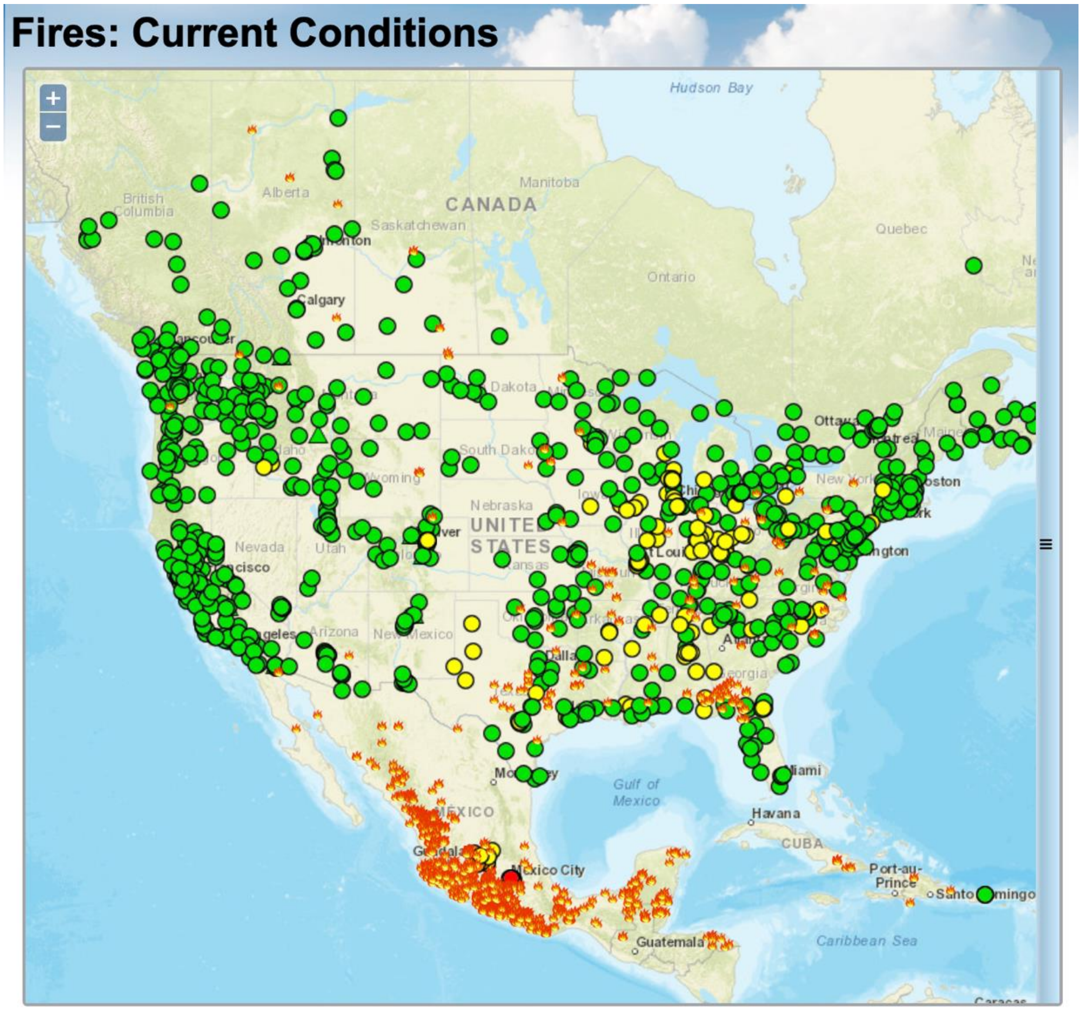
Source: https://airnow.gov/index.cfm?action=aqibasics.aqi
Figure 9: EPA AQI chart with numerical value, health concern level, and meaning for each level. The AQI tool is used in the United States and Canada when reporting on air quality.

The map on the home page of AirNow (see Figure 10) shows the current AQI across the country, with combined PM and Ozone data. The AQI level is determined by whichever of these pollutants is higher. You can also view a forecast of AQI for the current day, which shows how the AQI is projected to change. You can't zoom in on the map on the home page directly, but you can type your zip code into the box on the top of the page to view air quality in your area. When typing in a zip code for San Diego, the map displays the greater San Diego area from Anaheim in the north to Palm Springs and El Centro in the east. You cannot zoom in any closer than this. The map is displayed in different colors based on the AQI designation and the air quality index numbers for PM2.5 and ozone are displayed next to the map.



Source: https://airnow.gov/index.cfm?action=airnow.main
Figure 10: A screenshot of the home page of the AirNow website taken on 5/16/2019

At the bottom of the home page is a link for Fires: Current Conditions that takes you to a map of the United States, Canada, and Mexico (Figure 11). The default map shows the PM2.5 AQI from AirNow and temporary monitors as well as fire locations which are detected by NOAA satellites (EPA: Fires Current Conditions). With the side bar, you can also overlay incident information that shows prescribed fires and smoke plumes, also from NOAA's hazard mapping system. This map does allow you to zoom closer to a specific city, but the only air quality monitors shown in San Diego County are located in El Cajon and Alpine, east of San Diego. Also included on this page are links to pdf documents about protecting yourself, pets, and livestock from wildfire smoke and ash.



Source: https://airnow.gov/index.cfm?action=topics.smoke_wildfires
Figure 11: A screenshot of the map that is on the AirNow Fires: Current Conditions page. Taken on 5/16/2019.

AirNow has several different pages that deal with health, and a few that talk about wildfire smoke and health specifically. Because smoke has high levels of particulate matter, health messaging is focused around this pollutant. There is a great informational page on AirNow titled “How smoke from fires can affect your health,” but it is not accessible from the home page, so it requires a little digging to get to. This page includes a list of vulnerable populations, some health effects you may experience from wildfire smoke, and ways to protect yourself before and during a fire. Some of these actions include staying indoors, wearing an N-95 respirator mask, keeping particle levels inside low, buying an air cleaner for inside, and making a plan for medications and evacuation if you have preexisting respiratory or cardiovascular diseases (EPA: How smoke from fires can affect your health, 2017).

Another resource tucked away within AirNow is the EnviroFlash alert system. The subscription asks for your email address, zip code, and nearest EnviroFlash city to get alerts about. You can sign up for action day notifications, forecasts, and current conditions if available for your city (this is not available for San Diego). This alert system is a good option for people who want to receive direct notifications in cities that don't have another system in place. However, there is no information on this EnviroFlash webpage about when or why an action day will be called.

Another one of the links at the bottom of the AirNow homepage is "air quality action days/alerts." Different cities across the United States have action days that they declare when air quality becomes unhealthy. They are called at different levels based on what the air pollution control agency has chosen, but most are called either at code orange (AQI 101) when the air quality is unhealthy for sensitive groups, or at code red (AQI 151) when the air quality is unhealthy for everyone (EPA: Action Days). Depending on the city and program in place, an alert will be sent out to those who have signed up and certain actions like using a wood-burning fireplace are prohibited. There is no action day program or notification system in the County of San Diego, so it is unclear whether an alert for an action day would go out through EnviroFlash or not for San Diego and other cities without action days.

The EPA has a lot of useful information on their AirNow website. If you are willing to spend some time going through the pages and different links located around the site, there is valuable information about air quality, pollutants, wildfire smoke, and health effects. However, when looking for this type of information most people will not take the time to search through many pages on a website. They will only see what is on the home page. The map on the home page of AirNow is not interactive or user-friendly and the information about health effects from smoke and recommended actions is not easy to find. Since there are some good pages within the site, I made links available to these specific pages on the "Wildfires and Air Quality" website I created for UCSD.

Bay Area

The Bay Area Air Quality Management District covers the counties of Alameda, Contra Costa, Marin, San Francisco, San Mateo, Santa Clara, Napa, and parts of Solano and Sonoma. Throughout these counties, there are 34 air monitoring stations. Their website has information on current air quality and monitoring data, a "spare the air" program, and information about how to reduce exposure to high levels of PM2.5. During a phone interview with Aaron Richardson who works in the communications department at the Bay Area Air Quality Management District, I learned that the spare the air program has been in place since the early 90s and that they are currently revising the program to include a wildfire response plan to address the increasing incidence of wildfires in California.

The spare the air program is similar to the action days from AirNow, and began in 1991 to reduce air pollution and provide notice when air quality is forecast to be unhealthy (BAAQMD: Get the Facts). By using air alerts, the employer program, and community resource teams, Spare the Air focuses on educating the public and promoting changes in behavior to prevent unhealthy air quality (BAAQMD: Get the Facts). Air alerts are initiated when PM2.5 or ozone levels exceed the federal standard - when the AQI exceeds 100. If the alert is called due to high levels of ozone in the summer, residents are asked to reduce their driving, and if the alert is called in the winter, usually because of high levels of PM2.5, the use of wood-burning devices is prohibited. People can sign up for alerts through email on the EnviroFlash AirNow website or text messaging alerts on the Spare the Air website and will receive alerts the day before they go into effect based on the air quality forecast. Every alert is also shown on the website and shared with the media where it is announced through television and radio stations.

Because of the recent large fires that have affected the Bay Area, the air quality management district is working with county health departments to create a wildfire response plan that includes detailed school guidance. They are also applying for grants to help school and public facilities install new filtration equipment in their buildings. Even with the spare the air alert program they currently have in place, during the 2017 wildfires, many people thought that alerts did not go out soon enough and the AQI did not update fast enough to reflect real-time conditions (McKinnon 2017). By creating a response specific for wildfires, the Bay Area Air Quality Management District will be able to warn residents sooner about poor air quality conditions from wildfires smoke, health effects associated with this, and specific actions to take.

The Bay Area air quality website has information about high levels of PM2.5, associated health effects, and recommended actions, similar to the AirNow website. In addition to recommendations like staying indoors and reducing outdoor activity levels, the Bay Area website identifies vulnerable populations and some specific actions for them. This includes taking steps to reduce exposure earlier and making a plan with your doctor.

The Bay Area Air Quality Management District is a great example of an air pollution control district providing appropriate tools and guidance for protecting their residents' health. Their spare the air program was created to both reduce air pollution and inform bay area residents when air pollution is forecasted to be high so they may take appropriate actions. The District is taking steps to prepare for climate change and improve their messaging by creating a wildfire response plan. Their website provides information on current air quality and community health in addition to the typical rules and compliance pages. Although the page on reducing exposure to PM2.5 is dense, and there is a lot of information scattered throughout the District's website and Spare the Air site, it is useful for those looking for more information about air quality.

Oregon

Oregon has created the "Wildfire Response Protocol for Severe Smoke Episodes" guidance document for state and federal agencies to provide a coordinated response to wildfire smoke events. The document outlines agency actions, desired outcomes, and recommended public health actions (Oregon Response Protocol, 2017). It is an all-inclusive response plan for wildfire smoke events and includes the creation of the "Oregon Smoke Blog" where the public can get the information they need.

The Protocol has a table of recommended public health actions based different AQI levels and anticipated duration of smoke exposure. It includes actions such as cancelling outdoor public events and opening clean-air shelters for sensitive groups during AQI levels that are very unhealthy. The Protocol also contains templates and examples for public announcements and news releases. Inter-agency coordination is highly encouraged and often required for many of the responses outlined in this document.

The Oregon Smoke blog is a resource for the public to get information about current air quality and health information. The home page has a map of air quality based on the EPA's AQI designations and blog announcements about current and past air quality advisories. Other tabs within the website include smoke and health, air quality now, air quality forecasting, fire info, local contacts, webcams, and because you asked (Oregon Blog). These tabs are mostly links to outside sources of information and are a little overwhelming for someone looking for basic information about actions to take. There is also the ability to post public comments within the site, and based on these comments it doesn't seem like the website is updated very often. Oregon has made a good first step with the Wildfire Response Protocol, involving many different agencies, but it's associated website blog is lacking in organization and usability.

Canada

With its vast forests and extensive wildland, Canada also deals with frequent wildfires and the associated health problems from smoke inhalation. AirNow contains a page dedicated to air quality in Canada with its own map and resources. Public weather alerts, including air quality alerts, are mainly managed by the Canadian government. Although the AirNow page uses the EPA's AQI system of reporting air quality, Canada also has their own Air Quality Health Index (AQHI) that they use for health messaging. The AQHI is a scale from 1-10+ indicating low, moderate, high, and very high risk. Potential sensitive groups at higher risk are indicated based on the AQHI level, with recommended actions to take at every level. Different provinces and cities also have specific air quality information for their locations, but they all use the same air quality health index.

Source: https://www.alberta.ca/about-the-air-quality-health-index.aspx
Figure 12: Canada's air quality health index risk (AQHI) levels

Health Risk	Air Quality Health Index	Health Messages	
		At Risk Population	General Population
Low Risk	**1 - 3**	**Enjoy** your usual outdoor activities.	**Ideal** air quality for outdoor activities.
Moderate Risk	**4 - 6**	**Consider** reducing or rescheduling strenuous activities outdoors if you are experiencing symptoms.	**No need to modify** your usual outdoor activities unless you experience symptoms such as coughing and throat irritation.
High Risk	**7 - 10**	**Reduce or reschedule** strenuous activities outdoors. Children and the elderly should also take it easy.	**Consider** reducing or rescheduling strenuous activities outdoors if you experience symptoms such as coughing and throat irritation.
Very High Risk	**Above 10**	**Avoid** strenuous activities outdoors. Children and the elderly should also avoid outdoor physical exertion.	**Reduce or reschedule** strenuous activities outdoors, especially if you experience symptoms such as coughing and throat irritation.

Source: https://www.alberta.ca/about-the-air-quality-health-index.aspx
Figure 13: Health messaging associated with each AQHI level

There is one literary study that tried to determine the effect of air quality alerts on human health, although it did not focus on wildfire smoke events but rather smog days (Chen et al., 2018). Studying seven health outcomes including cardiovascular and respiratory mortality and hospital visits for cardiovascular and respiratory conditions, they found alert announcements in Toronto, Canada reduced asthma-related emergency department visits by 25% (Chen et al., 2018). There were no other significant reductions in other health outcomes, and the authors concluded that air quality alerts alone had only a limited effect on public health, and more should be done to enforce air pollution reduction measures (Chen et al., 2018). Although this study was not looking directly at wildfire smoke, it has important implications for how effective air quality alerts might be and what more we could do to protect public health.

San Diego

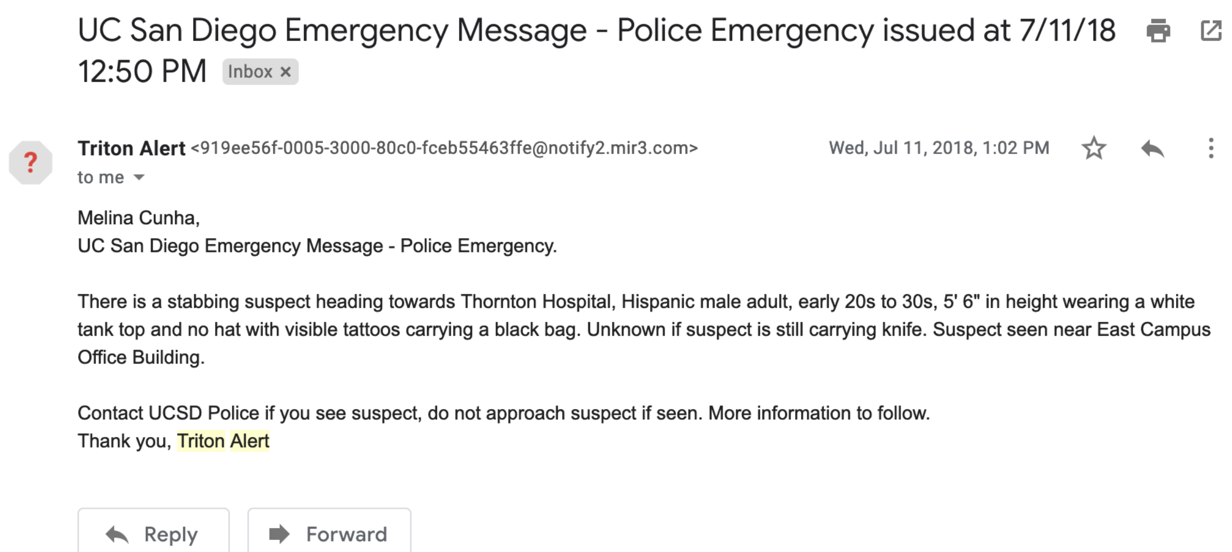
San Diego and UCSD are part of San Diego County, where air quality is monitored by the Air Pollution Control District (APCD), similar to the Bay Area Air Quality Management District. Current air quality is displayed on their home page in the form of an AQI chart and you can enter your zip code to find the AQI closest to you. There are only a few air monitoring stations within San Diego that are managed by the APCD: Kearny Mesa, El Cajon, Carmel Mountain Ranch, Alpine, Chula Vista, and on the border at Otay Mesa. The monitor furthest west and closest to UCSD is Kearny Mesa, which is a good distance away and not always indicative of air quality on campus. The APCD does have a map displaying these monitors along with the AQI, but it is not easy to find on the website, and the default air quality forecast information is displayed in chart format, which is much harder to read.

There is no page on the APCD website dedicated to wildfire smoke or particulate matter and health effects. The only mention of health is a link to an EPA brochure on AQI, found under related links on the “current air quality” page. I also could not find any information about action days in San Diego, and when I called the San Diego Air Pollution Control District, they confirmed that they did not have a program like that, and they do not analyze air quality data themselves. When I asked how they inform the public during wildfire smoke events or other days with poor air quality, they did not have an answer and suggested if you smell smoke, to go indoors. Because there is no action day or similar program in place for San Diego, it is unclear whether signing up for EnviroFlash alerts will lead to an actual alert. The AirNow website has no contact information other than a mailing address, so I was not able to get an answer to this question. This interview with San Diego APCD was extremely disappointing and highlights the lack of preparedness we have in San Diego for wildfire smoke events.

UCSD Air Quality Alert System

A relatively large part of the population of San Diego comes from its universities. UCSD alone has around 75,971 students, faculty, and staff - 38,798 students, 2,535 faculty, and 34,638 staff employees as of Fall 2018 (UCSD Campus Profile). The campus is so large that it has its own microgrid supplying electricity, heating and cooling (Berkeley Lab, UCSD Microgrid). Although the total population of San Diego is around 1.42 million, UCSD represents an important subpopulation consisting of permanent residents, students from San Diego and around the world, and visitors constantly coming and going. At Scripps Institution of Oceanography, scientists are conducting pioneering research on climate change. The resources available here make it a perfect starting point for a wildfire smoke alert system in San Diego.

When considering the best platform for this alert system, I first thought of Triton Alert Emergency Notifications, run by the Emergency Management and Business Continuity Division of Environment, Health, and Safety. During emergency situations like an active shooter on campus or an outbreak of a contagious illness, a Triton Alert is sent out to students, faculty, and staff by text message and email. Everyone with a UCSD email address receives the notification, but you have to add your phone to your profile to receive the text messages. The content of the notification includes a brief description of the situation and instructions about what to do (EH&S Triton Alert Emergency Notification Policy, 2017). This information is also be posted on the UCSD homepage or emergency status website.


UC San Diego Emergency Message - Police Emergency issued at 7/11/18 12:50 PM Inbox ×

Triton Alert <919ee56f-0005-3000-80c0-fceb55463ffe@notify2.mir3.com> Wed, Jul 11, 2018, 1:02 PM
to me

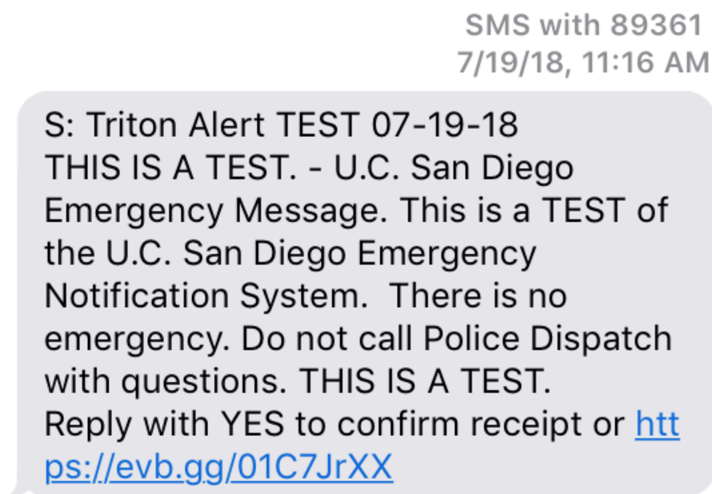
Melina Cunha,
UC San Diego Emergency Message - Police Emergency.

There is a stabbing suspect heading towards Thornton Hospital, Hispanic male adult, early 20s to 30s, 5' 6" in height wearing a white tank top and no hat with visible tattoos carrying a black bag. Unknown if suspect is still carrying knife. Suspect seen near East Campus Office Building.

Contact UCSD Police if you see suspect, do not approach suspect if seen. More information to follow.
Thank you, Triton Alert

Reply Forward

Source: Melina Cunha's email
Figure 14: This is a real example of a Triton Alert that I received by email last July 2018 informing students of a police emergency taking place near campus. When they resolved the situation, a follow up email was sent.



Source: Melina Cunha's text messages
Figure 15: EH&S sends test triton alert messages at least once per year. This is a real example of a test text message alert that was sent to me last July 2018.

My initial contact with UCSD EH&S EM&BC was a phone call with Matt Hussmann, an employee in the department. He provided me with information about the Triton Alert notification system and whether it was the right platform for my wildfire smoke alert. He was open to the possibility, and we set up a meeting with his supervisor, Dismas Abelman, me, and my capstone chair, Tarik Benmarhnia. Dismas was very enthusiastic about helping me with the implementation of the air quality alert and we began to discuss the logistics. Because Triton Alerts are reserved for emergency situations, we decided that a community information message by email was the better route for the air quality alert. These types of messages are still sent to all students, faculty, and staff, similar to the Triton Alert. In addition, I would create content for a webpage that would go on the EH&S website.

Email

After further discussion about the email alert and the information it would contain, we decided that multiple email templates would be required: an initial email detailing the wildfire situation and air quality at UCSD, a follow-up email for if the air quality worsens but the campus remains open, a separate follow-up email for if the air quality worsens and classes are cancelled/campus is closed, and a final email for when air quality improves and campus operations return to normal. The full text of these four emails are included in the Appendix. The steps for sending these emails are included in a flow chart in the appendix. The main content of the emails includes current AQI level, some information about the fire that is causing poor air quality, a few suggested actions to take, information about campus operations, and a link to our Wildfires & Air Quality website for more information.

The initial email alert is triggered when AQI passes 100. This corresponds to the national air quality standard for pollutants. At this level, PM2.5 is at 35.4 $\mu g/m^3$, and air quality levels beyond this number are deemed unhealthy for sensitive groups. It is important to remember that this is not a hard threshold, and there may be higher or lower concentrations of PM2.5

where people experience adverse health effects. Live AQI Data from AirNow will be used to monitor air quality and automatically trigger an alert within the EH&S department when the AQI passes 100 in San Diego. The next step after this will be to confirm this AQI level by making a call to the Air Pollution Control District. After this confirmation, the initial alert email may be sent out, with subsequent emails depending on the situation. The steps for this are outlined in detail below, as well as in the flow chart located in the Appendix: Flow Chart for Alert Messaging.

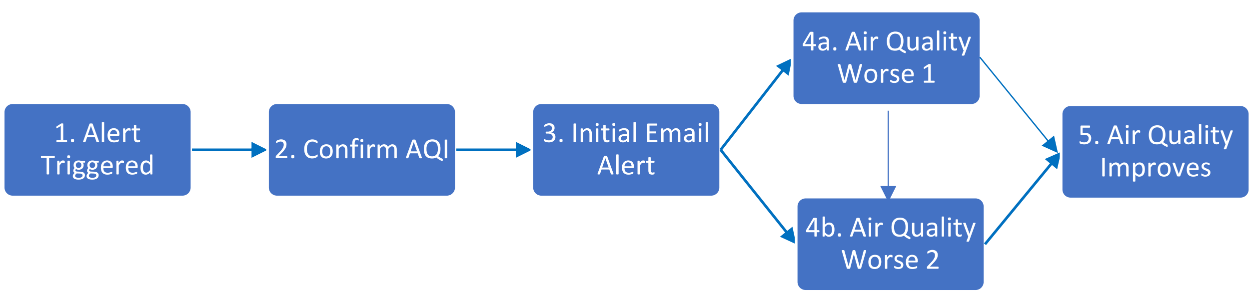
Steps for UCSD EH&S to follow for air quality email alert dissemination:

1. Internal alert triggered when AQI passes 100
2. Phone call made to the San Diego Air Pollution Control District (858) 586-2650 to confirm AQI is due to wildfire smoke and is not an anomaly
3. Initial alert email sent out to entire campus - students, faculty, and staff

4a. If air quality remains above 100 for the next two days, send second email for air quality worsened, but school remains open

4b. OR If air quality further worsens to AQI 200 (very unhealthy), consider cancelling classes and partially closing the campus. Send second email for air quality worsened, school closed, dependent on the decision of Campus leadership

5. When air quality improves, send final email, air quality improved



Website

When thinking about everything I wanted to include in the air quality alert for UCSD, I realized that not everything could be covered in an email. Therefore, I decided to create a website with additional information about air quality, sensitive groups, and recommended actions. The natural place to host the website seemed like a page within the EH&S department, where information about Triton Alert and emergencies is already hosted. Dismas Abelman put me in contact with Eric Delucien, who creates and manages the EH&S web pages. He agreed to help me create the website I was envisioning, and we got to work on putting the page together.

Based on the air quality management websites I had researched, I wanted this website to contain critical information about current air quality with information about sensitive populations and recommended actions, while still keeping it simple, succinct, and user-friendly.

The website contains a map of current air quality in San Diego, recommended actions for everyone and specific actions for sensitive groups, and a few links for resources on fire conditions, health information, and more. It can be seen at [Wildfires and Air Quality] and in the Appendix: Website.

There are a few different maps of air quality available online, with the most well-known one on the AirNow website. However, this map only has a few air quality monitors in San Diego, and none close to the UCSD campus. The closest monitor is in El Cajon, 22 miles away from UCSD. When looking for other options, I came across PurpleAir. This organization uses and sells its own sensors to track particulate matter levels across the United States and the world. They have both inside and outside sensors, with values of PM2.5 and PM10 shown on the map, averaged every 20 seconds. The map itself displays many more sensors than the AirNow map, especially for the San Diego region. There are six sensors located just around UCSD. Because of this and the user-friendly map interface, I chose to use the PurpleAir map for the website. The embedded map is zoomed into San Diego so that visitors to the page can see the air quality that affects them right away. The map updates automatically with new air quality information, so no maintenance is needed for the website.

Based on the research done on sensitive groups/vulnerable populations, on the website I listed sensitive groups as older adults, children, those with heart or lung disease, and pregnant women. Because the main target for this website is students at UCSD, I specifically indicated that those with asthma and pregnant women should follow all recommended actions immediately. The recommended actions included on the website for everyone and sensitive groups were chosen based on what was most common across researched air quality alert systems. For everyone, this includes staying indoors, limiting outdoor activity, using an air purifier, and using a respiratory mask only if recommended by a physician. For sensitive groups, it is recommended to follow these recommendations earlier (when AQI passes 100) as well as the following: relocate to an area with better air quality and seek medical care if needed. For each of these recommendations, a few bullet points were added for clarity and explanation.

An additional resource I wanted to provide for the students was a list of buildings on campus that had proper air filtration systems so they could go there to ensure they were in a clean building. I designated these areas "clean air zones." After attempting to contact several different people in the facilities department, I was unable to get any information about the filtration systems in the buildings at UCSD. It was also mentioned to me that there may be a liability for UCSD if we list these locations on the website and are ultimately unable to provide access during a wildfire event. Therefore, this will be an area of future discussion and opportunity beyond the scope of this project.

The last section of the website lists some links to outside resources if users are looking for more information. By providing this information separately, I was able to keep the website succinct so as not to overwhelm the user with too much information. I included useful links that I found during my research of action plans.

Resources

- Current Fire Conditions
- Air quality levels from the Environmental Protection Agency
- Effects of wildfire smoke and health
- Sign up for air quality alerts
- Protecting yourself from wildfire smoke (CDC)
- Fire Weather Zones
- UC San Diego Student Health Services

Source: https://blink.ucsd.edu/safety/emergencies/preparedness/wildfire-air-quality.html
Figure 16: Screenshot from "Wildfires and Air Quality" website displaying useful links

"Current Fire Conditions" links to the AirNow page of that name where people can see where fires are as well as get AQI information. "Air quality levels from the Environmental Protection Agency" is a direct link to AirNow's homepage in case someone needs a secondary source of air quality information or wants to peruse that website. "Effects of wildfire smoke and health" links to the AirNow page that talks about the health dangers of smoke inhalation. This page is difficult to find within the AirNow website, so a direct link here is helpful to find this information. "Sign up for air quality alerts" is a link to sign up for air quality alerts on EnviroFlash. "Protecting yourself from wildfire smoke (CDC)" links to a CDC page of that name that includes more information about actions you can take. "Fire weather zones" displays fire weather watch and red flag warnings in San Diego on a map from the National Weather Service. Finally, "UC San Diego Student Health Services" links to the student health services website where students can make appointments and find information about health care at UCSD.

The creation of the email alerts and "Wildfires and Air Quality" website was a collaborative effort with the Emergency Management & Business Continuity Division of EH&S at UCSD. The webpage is available online now and can be found on the Blink website at Wildfires and Air Quality. The alert system and protocol in this report will be followed in the next wildfire smoke event in San Diego.

Dissemination and Future

This project and alert system were implemented for use at University of California, San Diego. The result of the research and collaboration with the Emergency Management & Business Continuity Division of Environment, Health, and Safety is a plan for the campus that includes a protocol for sending four different email templates and a website called "Wildfires and Air Quality" that is available on Blink EH&S, and included as a resource for students, faculty, and staff during wildfire smoke events.

Because wildfires affect all of California, it is important to continue the efforts of this project and expand its adoption elsewhere. Other University of California campuses can use the same emails and website created here or adapt what has been done to their universities. Other universities outside of the UC system can also use this air quality alert system, but they may have to change it slightly based on their demographics.

The County of San Diego does not have an action plan for wildfire smoke events and should replicate the efforts being made by the Bay Area Air Quality Management District to make a plan. They can also use this report and its findings in their development of an action plan. If they wait until the next large wildfire happens in San Diego, it will be too late.

The UCSD air quality alert system should be used during the next wildfire smoke event in San Diego and evaluated for effectiveness if possible. This can be evaluated by examining the ease of execution for the initial and subsequent email alerts. It would also be beneficial to conduct a formal analysis of the alert system after it is used by using either hospitalization records or surveys from students, faculty, and staff, or both. There is not currently a lot information quantifying the value of these alert systems, and this represents a new opportunity to do this. An evaluation would help inform decisions by policy makers on whether to require an alert system in other jurisdictions.

To improve the UCSD air quality alert system produced in this project, it would be beneficial to use forecasting tools and to include designated clean air zones on campus. Forecasting fire danger and smoke dispersion is useful for emergency preparedness and will allow for earlier alert notifications. This will ensure that everyone is alerted to poor air quality conditions before or as soon as air quality conditions deteriorate. Although designated clean air zones were not included in this report nor the website, it would be useful to pursue this further so that students can have somewhere to go on campus to escape from poor air quality conditions. With these improvements, the air quality alert system at UCSD could become even more effective at protecting the health of students, faculty and staff.

Conclusion

Wildfires have become more frequent, larger, and more destructive in the past few decades in California. Smoke has also become a greater issue due to its ability to affect a large number of people and due to the recent discoveries about negative health effects caused from smoke exposure. Climate change is only going to make wildfires worse. To prepare for this, we need to implement secondary preventative measures to reduce exposure to wildfire smoke. At the minimum, this should be in the form of an alert system that informs residents of poor air quality conditions and recommended actions to take, with specific attention made to vulnerable populations. This can be done by both schools and cities to ensure everyone has proper warning.

More effort should be done to improve existing alert systems by making a specific plan and alert for wildfire smoke events. There should also be an effort to include air quality and smoke forecasting tools within the alert systems to make sure people receive air quality warnings in a proper amount of time, ideally before conditions worsen to hazardous levels.

The UCSD air quality alert system can be used as a model for alert systems at other universities and cities. The adoption of this and other air quality alert systems will allow us to be better prepared for climate change and the health effects that wildfire smoke has on the people in California.

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Appendix

Methods

Literature Review

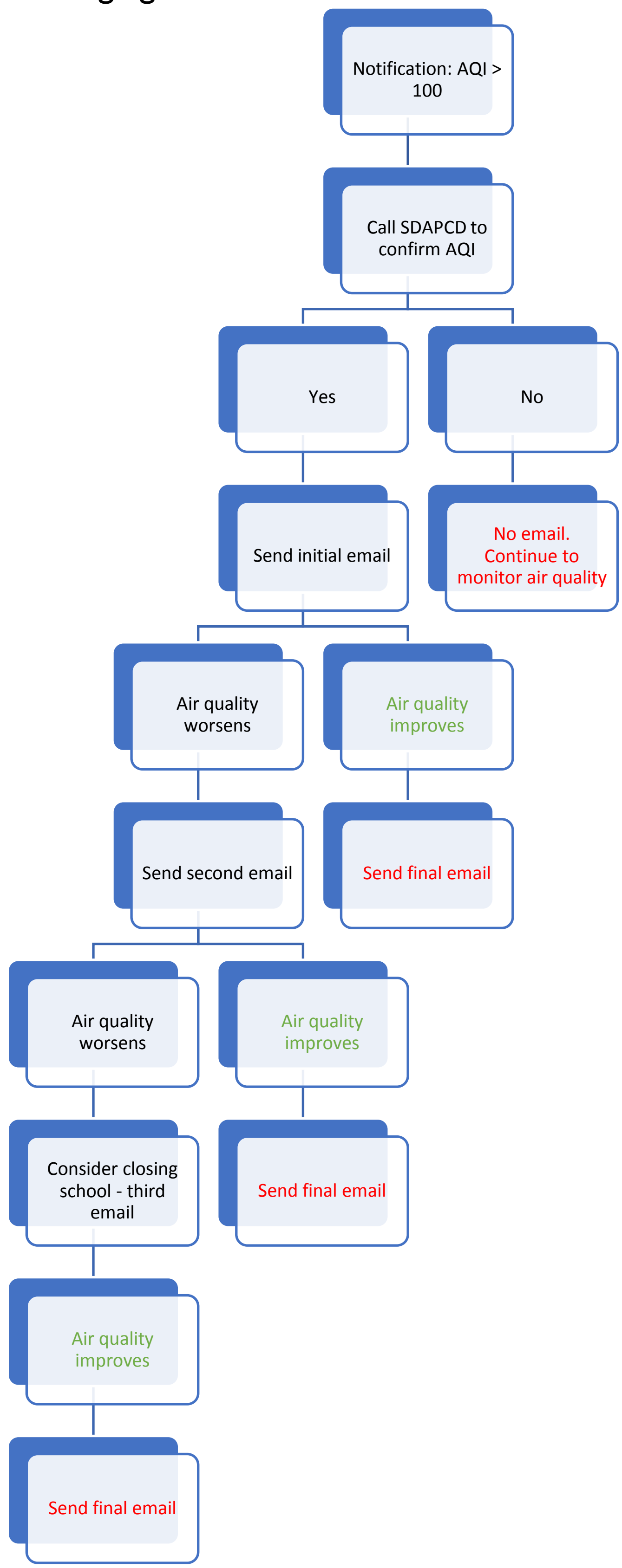
For the background information on wildfires and health impacts, a literature review was conducted using the various keywords and combination of keywords outlined below. Alert systems were also researched in this manner in addition to a general search to find websites related to this topic. A few articles were also sent to me by committee members.

Concept	**Keywords**
Wildfire climate change	wildfire, fire, wildland fire, California, climate change, drought, tree mortality, extreme events, storms, santa ana winds, climate change, beetle bark, modeling, forecast, bushfires
Health Impacts	public health, wildfire, fire, asthma, respiratory, air quality, health impact, health, smoke, cardiovascular, cerebrovascular, PM2.5, PM10, sensitive, vulnerable, groups, populations, susceptibility, pregnant women
Alert Systems	alert, action day, smoke, air quality, wildfire, warning

Databases Used

- Google Scholar
- Google
- Air quality data from AirNow used to create automated alert for EH&S

Flow Chart for Alert Messaging



UCSD Alert Emails

CAMPUS NOTICE
University of California San Diego

OFFICE OF ENVIRONMENT, HEALTH & SAFETY

Month XX, 20XX

ALL ACADEMICS, STAFF AND STUDENTS AT UC SAN DIEGO

Subject: Poor Air Quality at UC San Diego

The current Air Quality Index (AQI) is XX (number and designation i.e. 151 Unhealthy)

Currently there are XX fires near UC San Diego.

Smoke has travelled from inland fires to the UC San Diego Campus and created poor air quality conditions. Everyone may begin to experience health effects from this smoke. Stay indoors as much as possible and seek medical care if you have serious symptoms. Some people may be more sensitive to the smoke than others.

We are closely monitoring air quality and the progression of the fires. The UC San Diego campus is not in immediate danger and remains open. Classes will continue as scheduled. The UC San Diego Health System hospitals and clinics also remain open.

As further updates are available, we will post notifications on Blink. In addition, the Triton Alert system will be activated if we need to issue emergency notifications. You are encouraged to sign up for the Triton Alert system at https://blink.ucsd.edu/safety/emergencies/campuswide/notifications/index.html

For up-to-date information on current air quality, the fires, recommended actions to take, and clean air zones on campus, visit the Wildfires and Air Quality page on Blink.

For campus status updates, visit the UC San Diego Emergency Status website at https://ucsd.edu/about/emergency.html.

If you have any additional questions, please contact Dismas Abelman, UC San Diego Emergency Manager at dabelman@ucsd.edu or 858-534-5451.

Thank you

Corey Singleton
Director of Environment, Health & Safety

CAMPUS NOTICE
University of California San Diego

OFFICE OF ENVIRONMENT, HEALTH & SAFETY

Month XX, 2019

ALL ACADEMICS, STAFF AND STUDENTS AT UC SAN DIEGO

Subject: Update - Worsening Air Quality at UC San Diego

The current Air Quality Index (AQI) is XX (number and designation i.e. 151 Unhealthy)

Currently there are XX fires near UC San Diego.

Smoke from inland fires has continued to affect the air quality at the UC San Diego Campus and created worsening air quality conditions. Everyone may experience more serious health effects. Continue to stay indoors and consider relocating to an area with better air quality.

We are closely monitoring air quality and the progression of the fires. The UC San Diego campus is not in immediate danger and remains open. Classes will continue as scheduled. The UC San Diego Health System hospitals and clinics also remain open.

As further updates are available, we will post notifications on Blink. In addition, the Triton Alert system will be activated if we need to issue emergency notifications. You are encouraged to sign up for the Triton Alert system at https://blink.ucsd.edu/safety/emergencies/campuswide/notifications/index.html

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Thank you

Corey Singleton
Director of Environment, Health & Safety

CAMPUS NOTICE
University of California San Diego

OFFICE OF ENVIRONMENT, HEALTH & SAFETY

Month XX, 2019

ALL ACADEMICS, STAFF AND STUDENTS AT UC SAN DIEGO

Subject: Update - Worsening Air Quality at UC San Diego

The current Air Quality Index (AQI) is XX (number and designation i.e. 151 Unhealthy)

Currently there are XX fires near UC San Diego.

Smoke from inland fires has continued to affect the air quality at the UC San Diego Campus and created worsening air quality conditions. Everyone may experience more serious health effects. Continue to stay indoors and consider relocating to an area with better air quality.

We are closely monitoring air quality and the progression of the fires. Due to the current AQI levels and forecasted levels for tomorrow, classes have been cancelled for the remainder of today through ____. Although most of the campus is now closed, there are a limited number of campus operations that must continue. These include Student Health Services, dining halls and residential facilities, UCPD, and the Office of Environment, Health, and Safety. This is not a comprehensive list. Staff members who are uncertain about whether they should come in should consult with their supervisors.

As further updates are available, we will post notifications on Blink. In addition, the Triton Alert system will be activated if we need to issue emergency notifications. You are encouraged to sign up for the Triton Alert system at https://blink.ucsd.edu/safety/emergencies/campuswide/notifications/index.html

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Thank you

Corey Singleton
Director of Environment, Health & Safety

CAMPUS NOTICE
University of California San Diego

OFFICE OF ENVIRONMENT, HEALTH & SAFETY

Month XX, 2019

ALL ACADEMICS, STAFF AND STUDENTS AT UC SAN DIEGO

Subject: Follow up - Air Quality at UC San Diego

The current Air Quality Index (AQI) is XX (number and designation i.e. 151 Unhealthy)

The inland fires have been contained. Wildfire smoke is no longer affecting the campus.

The air quality at UC San Diego has improved and you should now return to your normal activities. If you continue to experience health effects from the smoke, see your health care provider.

The UC San Diego campus will resume normal campus operations. Classes will continue as scheduled. The UC San Diego Health System hospitals and clinics also remain open.

As further updates are available, we will post notifications on Blink. In addition, the Triton Alert system will be activated if we need to issue emergency notifications. You are encouraged to sign up for the Triton Alert system at https://blink.ucsd.edu/safety/emergencies/campuswide/notifications/index.html

For up-to-date information on current air quality, the fires, recommended actions to take, and clean air zones on campus, visit the Wildfires and Air Quality website on Blink.

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Thank you

Corey Singleton
Director of Environment, Health & Safety

Website

Screenshots of website Wildfires and Air Quality

Wildfires & Air Quality

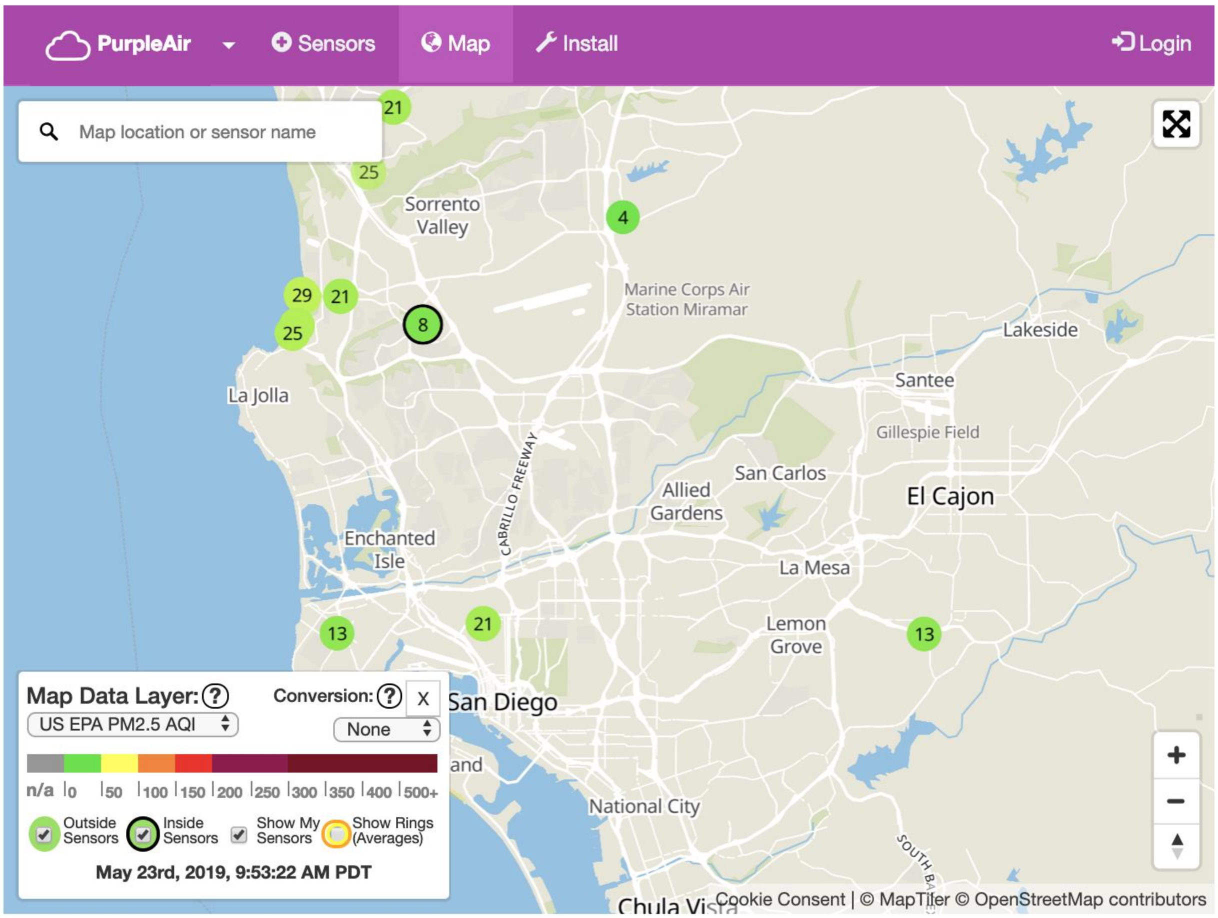
Last Updated: May 22, 2019 3:54:14 PM PDT — Give feedback

Learn how to protect your health during wildfires.

Wildfires and Air quality

Wildfires become more and more prevalent in California every year. Smoke containing a mixture of gases, fine particles, and chemicals travels miles always from the source. Particulate matter from this smoke can enter the bloodstream through the lungs and cause a variety of health problems. Short-term effects include irritation of the eyes, nose, and throat, chest tightness, and shortness of breath. These particles can also exacerbate chronic heart and lung diseases like asthma or Chronic Obstructive Pulmonary Disease (COPD). See below for current levels of air quality and the recommended actions for high pollution days.

Current San Diego Air Quality



Taking Action

Sensitive populations should take the following actions immediately. This includes people with respiratory conditions like **asthma** and women who may be **pregnant.**

Recommended actions for everyone at 'unhealthy' air quality levels above 150:

- Stay Indoors
  - Close doors and windows and recirculate indoor air
  - Reduce indoor pollution - don't use candles, wood stoves or fireplaces, or smoke
- Limit outdoor activity – no exercise
  - Exercise and physical activity cause you to breathe more deeply, allowing more particles to get into your lungs
- Use an air purifier or go to a clean air zone on campus (listed below)
  - Using an air purifier further ensures that the indoor air is clean by removing particles
  - If you don't have an air purifier, you are not sure if your home is properly filtering the air, or you don't have an air conditioner and can't keep the windows closed, consider going to a clean air zone
- Only use a respirator mask (NIOSH N95 or N100) if it has been recommended by a physician and you have been properly fitted
  - Dust masks and bandanas will not protect you from particulate matter and other harmful pollutants
  - Wearing this mask can make breathing more difficult and therefore may not be recommended for those with heart and lung diseases – check with your health care provider

For Sensitive Groups (older adults, children, those with heart or lung disease, and pregnant women):

- Begin taking recommended actions at 'unhealthy for sensitive groups,' levels 101 and above
  - Sensitive groups will start to feel the harmful effects of smoke at lower levels of air pollution so need to take action to reduce their exposure to smoke sooner
- Consider relocating to an area with better air quality
  - When air quality levels remain high for a prolonged period of time, fine particles from smoke can build up indoors so you may need to leave the area
- Seek medical care if needed
  - Follow your doctor's advice and contact your doctor if symptoms persist
  - Seek medical treatment immediately if you experience any heart symptoms.

Clean Air Zones on Campus:

- If resources become available and there is a need, the campus will notify students, faculty, and staff of clean air locations with proper air filtration systems.

Resources

- Current Fire Conditions
- Air quality levels from the Environmental Protection Agency
- Effects of wildfire smoke and health
- Sign up for air quality alerts
- Protecting yourself from wildfire smoke (CDC)
- Fire Weather Zones
- UC San Diego Student Health Services

Contact the EH&S Emergency Team.