The Public Health Dimensions of California Wildfire and Wildfire Prevention, Mitigation and Suppression

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Bringing science to energy policy

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Physicians, Scientists, and Engineers (PSE) for Healthy Energy is a multidisciplinary, nonprofit research institute dedicated to supplying evidence-based scientific and technical information on the public health, environmental, and climate dimensions of energy production and use. We put our mission into practice by integrating scientific understanding across multiple disciplines, including engineering, environmental science, and public health. We conduct original research, translate existing research for nontechnical audiences, and disseminate scientific information and analyses to inform policy at the local, state, and federal levels. We focus on the overlap of energy production, public health, and the natural environment and produce vetted scientific analyses.

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Executive Summary

In recent years, California experienced the largest, most destructive and deadliest wildfires in its history.[1] Wildfires can cause fatalities and injuries, impair air quality for nearby and distant populations, and devastate the immediate area, leaving communities with often burned and hazardous landscapes and infrastructure. Over the last half-century, California has experienced a five-fold increase in annual burned acreage from wildfires.[2] Atmospheric aridity and fuel-drying, extended drought, and pathogen-impacted forests — all of which are driven and compounded by anthropogenic climate change — increase risks posed by wildfires.[3] Additionally, increased development at the wildland-urban interface (WUI) puts more individuals at risk of harm from these disasters.

Increased wildfire risks are driving California to re-evaluate its strategies to both prevent and suppress wildfires and to mitigate wildfire impacts. These strategies include, but are not limited to, prescribed burning, the use of chemical fire suppression and, more recently, the implementation of public safety power shutoffs (PSPS). However, various approaches to prevent and suppress wildfire and mitigate wildfire-related impacts in California also hold near- and long-term implications for public health, and may shift health burdens to different populations, geographies and timescales. To date, the public health implications of various wildfire prevention and mitigation strategies have not been thoroughly characterized and synthesized.

In this report we summarize and integrate scientific information on the public health dimensions of both wildfire and approaches to wildfire prevention, mitigation and suppression into a synthetic framework. Our approach consists primarily of 1) a review of the peer-reviewed literature, government reports, grey literature and news media and 2) interviews with local and State agency staff. The aim of this project is to better equip California agencies, researchers and risk managers to effectively manage wildfire-related risks in ways that incorporate data-driven public health information into decision-making.

Key findings, conclusions and recommendations

Below, we provide the key findings, conclusions and recommendations (FCRs) from our review of the literature, organized under overarching principles. The aim of these FCRs is to inform efforts to integrate public health into decision-making regarding wildfire emergency response and recovery and wildfire prevention, mitigation and suppression efforts in California. Additional detailed report findings, including specific examples and policy models aimed to mitigate potential health risks and identified research gaps and limitations, are summarized below in Table ES-1.

[1] CAL FIRE, 2020. *Stats & Events*. https://www.fire.ca.gov/stats-events/.

[2] Williams et al., 2019. Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*, *7*(8), 892–910. https://doi.org/10.1029/2019EF001210.

[3] IPCC, 2019. Summary for Policymakers: In: Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf.

Principle #1. Integrated, dense, resilient, and rapidly deployable air quality surveillance is beneficial to assess smoke exposure during wildfires and prescribed burns.

Increase resolution of air quality monitoring

Finding 1.1. Existing stationary air monitoring networks are distributed across California with low spatial density, in particular in high wildfire risk areas. As such, real-time air quality data during wildfire and prescribed burn events are often not readily available.

Conclusion 1.1. While current stationary air monitoring networks support assessments of regional air quality, these networks may not reflect local air quality, introducing uncertainty to the information necessary to estimate wildland smoke exposure and engage in enhanced risk communication and management efforts. Rapid deployment of air quality monitors may be necessary to capture air quality data during wildland fire smoke events in areas that lack air quality monitors. Efforts underway pursuant to Assembly Bill 617 (AB 617) are forming a model of how spatial intensity of this coverage could expand.

Recommendation 1.1. Agencies with jurisdiction should integrate or support the integration of air quality data from disparate air quality networks throughout the State of California and support additional air quality surveillance in high wildfire risk areas and in areas of high population density. These efforts could build upon the AB 617 community air quality monitoring program as a model to expand geo-spatial intensity of air quality data. Researchers, as well as local and state air quality agencies should be prepared to capture air quality data in real-time as wildfires occur and build these data into publicly accessible and real time reporting tools. Emerging efforts by the California Air Resources Board may help to address some of these air quality monitoring needs.

Ensure zero-emission backup energy sources for air quality monitors

Finding 1.2. Air quality monitoring networks largely rely on power provided by utility-scale electricity transmission infrastructure to collect and transmit air quality data and this infrastructure is vulnerable to failure and de-energization during wildfires and public safety power shutoffs (PSPS), respectively.

Conclusion 1.2. In the event of PSPS and other unexpected power outages, air quality monitoring networks may fail to collect air quality data to inform decision-making, risk communication and risk management.

Recommendation: 1.2. Air monitoring networks should be supported by zero-emission back-up energy sources (e.g., solar arrays, battery power, or other distributed energy resources) to provide power in the event of unexpected or utility-initiated loss of access to electricity.

Characterize the chemical composition of wildfire and prescribed fire smoke

Finding 1.3. The chemical composition of wildfire smoke is highly variable and is dependent on multiple factors, including but not limited to the materials that burn and the temperature of combustion. Wildfires directly and indirectly, through atmospheric transformation, emit criteria air pollutants and various toxic air contaminants. Existing characterizations of wildfire smoke composition and associated exposures often focus on criteria air pollutants, primarily particulate matter and ozone. Air pollutant emissions from prescribed burns may differ from air pollutant emissions from wildfires, particularly wildfires that result in the combustion of structural materials (e.g., homes, cars, businesses, etc.). Relatedly, few studies evaluate the differences in smoke composition between prescribed burns and wildfires.

Conclusion 1.3. While studies have investigated the patterns and concentrations of particulate matter and tropospheric ozone associated with wildfire smoke, these studies are limited by the exclusion of a wider range of health-damaging air pollutants that may also be present (e.g., toxic air contaminants). Expanded information regarding the concentration and distribution of chemicals in wildfire smoke and prescribed fire smoke will help inform risk communication and management efforts aimed to protect populations from the impacts of both wildfire and prescribed burn activities.

Recommendation 1.3. Agencies with jurisdiction should support air quality and exposure surveillance that includes a broader array of health-damaging air pollutants beyond criteria pollutants including, but not limited to VOCs and ultrafine particles. This information should be integrated into risk communication and management efforts. Further, agencies with jurisdiction could support air quality monitoring and research that identifies and characterizes the drivers of wildfire smoke composition. Future exposure and risk assessments should consider multiple pollutant exposures associated with smoke from wildfire and further research is also needed to assess chronic (repeated) exposure to prescribed fire smoke and potential health risks.

Principle #2. Detailed and integrated health outcome surveillance during and following wildfire is necessary to support epidemiological investigations, identify disproportionate health risks and impacts, and implement effective public health interventions.

Evaluate additional health outcomes and chronic (repeated) exposures and outcomes

Finding 2.1. The existing peer-reviewed literature indicates a positive association between wildfire smoke exposure and various adverse health outcomes, including eye irritation, respiratory outcomes (asthma exacerbation, bronchitis, dyspnea and chronic obstructive pulmonary disease, and increased hospital admissions for respiratory illness); adverse birth outcomes; out-of-hospital cardiac arrests, and premature mortality. Commonly used public health metrics (deaths, hospitalizations, emergency department visits) do not comprehensively measure the total public health impact of wildfire smoke exposure, as these measures exclude subclinical or asymptomatic effects and impacts that take time to manifest.

Conclusion 2.1. The literature focused on associations between wildfire smoke exposure and various health outcomes is expansive for some health outcomes, and limited for others. For instance, health studies in populations repeatedly exposed to wildfire fire smoke have not been undertaken. A comprehensive health surveillance system would help to quantify the magnitude of health effects that result from wildfires and could result in more effective public health interventions.

Recommendation 2.1. Future research on health impacts associated with wildfire smoke exposure should assess understudied health outcomes including, metabolic disorders, pediatric cognitive development, cognitive decline among older adults, maternal health, as well as mental health outcomes and health outcomes with long latency (e.g., cancer). Long-term surveillance of populations repeatedly exposed to wildland fire smoke can help to evaluate the effects of repeated exposures. Additionally, stress should be examined for its role in the relationship between wildfire smoke exposure and various health outcomes.

Support mental health surveillance and mental health services

Finding 2.2. Events associated with wildfires (e.g., destruction of home and community, the process or threat of evacuation, and perception of risk) may contribute to mental health burdens or exacerbate existing mental health conditions in affected communities.

Conclusion 2.2. Mental health impacts can be mitigated by ensuring sufficient services are available to meet the needs of populations undergoing traumatic events. Mental health research may be informed by recent wildfire events and other natural disasters.

Recommendation 2.2. Additional studies are needed to evaluate wildfire smoke exposure and mental health outcomes, as wildfire smoke events may increase in frequency and intensity for certain populations due to climate change and other drivers. Mental health outcomes should be included in health surveillance during and after wildfire events, as well as an exploration of other factors tied to wildfires that influence mental health (e.g., the potential increase in experiences of homelessness in communities where properties have been damaged by fire). Studies can additionally evaluate more widespread mental health impacts associated with wildfires on broader populations via vicarious traumatization.

Principle #3. Strategic deployment of distributed clean energy resources can provide backup power to support critical services during wildfires, public safety power shutoffs (PSPS) and other natural disasters and grid outages.

Finding 3.1. PSPS – or the de-energization of electricity transmission infrastructure – is a critical tool to prevent wildfires. However, the continuity of electricity in communities is also fundamental to support critical public health services during wildfires and other natural disasters. During the 2019 wildfire season, public safety power shutoffs (PSPS) for wildfire prevention resulted in numerous documented impacts to public health and safety.

These health and safety implications of PSPS are noted at various settings, including residential (e.g., the inability to refrigerate medications and food, breast milk, pump water, filter indoor air, and regulate indoor temperature, power medical devices, and access emergency information via the internet); community (e.g., inability to pump and deliver water through distribution systems, traffic accidents due to traffic light outages; lack of cellular network for communication); and healthcare settings (e.g., rescheduling of medical procedures). Distributed clean energy resources (e.g., solar+storage systems) provide electricity and can serve as backup power options that, unlike diesel-powered generators, do not contribute to the cumulative burden of climate-forcing and health-damaging air pollutants.

Conclusion 3.1. PSPS should remain a tool available to reduce risk of wildfires. However, creating resilient and reliable electric power systems and preparing communities for power outages are critical to address decrease public health impacts of PSPS. PSPS also present health hazards, risks and impacts for populations both within and outside of wildfire risks areas. Distributed clean energy resources (e.g., solar and battery storage) can provide essential electricity to residences, critical facilities, and communities at large during wildfires, PSPS and other emergencies and natural disasters.

Recommendation 3.1. Agencies with jurisdiction should support advanced grid solutions to monitor for wildfire risk and implement targeted, rather than widespread, PSPS, when possible. Agencies with jurisdiction should support the development and siting of distributed clean energy resources to provide backup power and support critical services during wildfires, PSPS and other natural disasters and grid outages. Approaches to support the proliferation of these energy resources could be in the form of market-based incentives (e.g., rebates and financial incentives), power procurement requirements, or energy requirements during post-disaster community rebuilds.

Principle #4. Small-scale biomass-to-energy facilities should be evaluated further in the context of energy reliability, wildfire risk mitigation, and impacts to air quality compared to other vegetation management practices.

Finding 4.1. Vegetation management is an important pillar of wildfire risk management. Wood biomass in wildfire prone areas of the state may either be burned by wildfire, combusted via prescribed or pile burns or burned to generate electricity, all of which contribute to degraded air quality. Traditional direct combustion biomass facilities in California are among the highest sources of particulate matter (PM) and nitrogen oxides (NO_X) on the California electric grid. Small-scale gasification technologies (e.g., biochar) result in lower NO_X emissions, but in the United States these technologies are less mature and more expensive, and therefore less common. The health implications of wood biomass utilization for electricity generation are largely dependent on the quantity of fuels used, technology used to generate electricity or heat, the location of these facilities, the timing of use with respect to air quality and atmospheric conditions and the proximity, density and demographic characteristics of nearby populations.

Conclusion 4.1. Approaches to vegetation management should take air quality and public health factors into consideration. Strategic siting of future small-scale, distributed biomass facilities and ongoing operation of existing facilities should consider potential air quality and health impacts and key tree mortality and vegetation management zones.

Recommendation 4.1. Additional research should be undertaken to evaluate human health, energy reliability, air quality, ecological, and other implications associated with approaches to vegetation management. Research should evaluate the differential impacts to air quality between vegetation management techniques including but not limited to wildfire, prescribed and pile burns, and the siting of small (e.g., 5 MW), distributed biomass-to-energy facilities in key vegetation management zones to provide simultaneous benefits of fuel reduction and more resilient access to power in places that may also be likely to experience wildfire and PSPS. Detailed tracking of biomass from fuel reduction efforts can be used to verify that biomass is combusted in settings that prioritize reducing air quality impacts (e.g., biomass-to-energy facilities vs. open pile burns). Additional research and investment into cost reduction for emerging, distributed and lower-emission biomass gasification systems could also be explored.

Principle #5. While chemical fire suppressants are critical to protect human life and infrastructure from wildfire, numerous uncertainties remain regarding potential health risks associated with the use of these compounds.

Finding 5.1. While some ingredients in chemical fire suppressants are well-characterized, complete chemical formulations of fire retardants and foams are considered trade secrets and are not publicly disclosed.

Conclusion 5.1. Public disclosure of chemical formulations in chemical fire suppressants is essential to assess potential risks to human health and the environment.

Recommendation 5.1. Chemical formulations of fire suppressants should be publicly disclosed. Compounds in chemical fire suppressants that pose risks to human health or the environment or have unknown toxicological profiles should be replaced by substances with known toxicological profiles that pose little to no toxicity to human health and the environment. Alternatives assessments should require that alternatives have well-characterized chemical compositions, are evaluated for ecotoxicity and toxic potential in humans, and are tested to ensure performance standards are met.

Principle #6. Wildfire response and wildfire-related public health interventions need to be re-evaluated and adapted amid the COVID-19 global pandemic.

Finding 6.1. COVID-19, an infectious disease caused by an emergent coronavirus (SARS-CoV-2), is now a global pandemic affecting the global human population with no known treatment or vaccine. Key wildfire mitigation strategies including evacuations (e.g., transport and indoor sheltering of displaced populations) and clean air spaces (e.g., indoor public spaces that provide filtered air to reduce wildfire smoke exposure) present physical conditions that are clear risk factors for transmission of COVID-19, particularly if additional precautionary measures are not undertaken.

Conclusion 6.1. Strategies to mitigate health and safety risks associated with wildfire through existing wildfire emergency response efforts (e.g., evacuations and indoor shelters) and proposed public health interventions (e.g., clean air spaces) may increase risk of COVID-19 transmission among wildfire-impacted populations.

Recommendation 6.1. Multiple agencies have already begun efforts to re-evaluate typical wildfire emergency response activities in the context of COVID-19, and these efforts should continue to adapt to evolving circumstances. Agencies with jurisdiction should follow current and future CDC, WHO, and state and local health department guidance to reduce the spread of COVID-19 during wildfire emergency response activities and wildfire smoke exposure interventions, such as wearing face coverings, in particular when adequate physical distancing may not be possible.

In Table ES-1 below, we provide a summary of our report findings, including the health hazards risks and impacts associated with wildfire and approaches to wildfire prevention, mitigation and suppression; strategies and policy models to mitigate potential public health risks; and identified research gaps and limitations. It is important to note that this summary table aims to provide different policy models and examples aimed to mitigate potential human health risks associated with wildfire and approaches to wildfire prevention, mitigation and suppression, but it is not meant to be comprehensive.

Table ES-1. Summarized report findings, including health hazards risks and impacts associated with wildfires and approaches to wildfire prevention, mitigation and suppression; strategies and policy models to mitigate potential public health risks; and identified research gaps and limitations. (Note: This summary table aims to provide different policy models and examples aimed to mitigate potential human health risks associated with wildfire and approaches to wildfire prevention, mitigation and suppression, but it is not meant to be comprehensive).

<table>
<tr><th></th><th>Summary of health hazards, risks and impacts</th><th>Strategies to mitigate potential health risks</th><th>Policy model(s) / example(s)</th><th>Research gaps and limitations</th></tr>
<tr><td colspan="5">The Public Health Dimensions of Wildfire (Section 2.0)</td></tr>
<tr><td rowspan="6">Air quality
(Section 2.1)</td><td rowspan="6">• Wildfires emit numerous health-damaging air pollutants, including criteria air pollutants, toxic air pollutants, ultrafine particulate matter, and ozone precursors.
• The composition of wildfire smoke is dependent on the size and intensity of the fire, the chemical composition of materials combusted and oxygen availability. As such the composition of wildfire smoke plumes can vary greatly across geographies and even within a single fire event.
• Exposure to wildfire smoke is associated with: eye irritation; respiratory illnesses (asthma exacerbation, bronchitis, dyspnea and chronic obstructive pulmonary disease); adverse birth outcomes; cardiovascular disease, and premature mortality.
• Certain population subsets may be disproportionately impacted by wildfire smoke exposure. These populations include: children, pregnant women, older adults, outdoor workers, people with underlying respiratory or cardiovascular conditions; socioeconomically disadvantaged populations,
• Children, pregnant women, older adults, outdoor workers, people with preexisting respiratory and cardiovascular conditions, people experiencing homelessness, and socioeconomically disadvantaged populations are disproportionately impacted by exposure to wildfire smoke.
• Wildfire smoke can be transported vast distances, in many cases increasing the number of people exposed. High $PM_{2.5}$ concentrations during California wildfire events often extend beyond California air basins, traveling from the basin where the active burn occurs and into neighboring regions.</td><td>Offering public access to forecasted local air quality and real-time air quality data shared in a public health context. Ideal air monitoring networks would include data with high spatial and temporal resolution, equipped with resilient back-up power (e.g., solar+storage) in the case of power outages.</td><td>• Air Quality Index (AQI) – index placing air quality in a health context.
• AirNow - Real- time and daily forecasts.
• PurpleAir- Global network of low-cost sensors.
• California Air District websites (e.g., BAAQMD).
• AB 617 Community Air Monitoring Networks (CARB AQview).</td><td rowspan="6">Further characterization of wildfire smoke exposure is needed. Future investigations should consider:
• pollutants beyond $PM_{2.5}$, such as VOCs, PAHs, ultrafine PM, speciated PM.
• evaluating pollutants relevant to structural fires.
• multiple pollutant exposures.
• additional air monitoring in high wildfire-risk communities.
Studies evaluating the relationship between wildfire smoke exposure and health outcomes:
• commonly use public health metrics (deaths, hospitalizations, ED visits) that do not represent the total public health impact of wildfire smoke exposure as they exclude, subclinical or asymptomatic effects.
• should evaluate metabolic disorders, childhood development, cognitive decline, maternal health, as well as mental health outcomes and health outcomes with long latency.
• should investigate repeated exposed to wildfire smoke and the influence of stress in relationship between wildfire smoke exposure and various health outcomes.
Evaluations should address effectiveness of public health interventions in reducing wildfire smoke exposure in different settings. For example:
• N95 respirator use among outdoor worker, vulnerable populations, and the general population.
• AQI interpretation and use among general populations, especially sensitive receptors
• reach and effectiveness of smoke response emergency response and planning and translated materials for hard to reach populations (e.g., non-English speaking populations).
• optimal conditions for clean air community spaces (e.g., duration of availability).</td></tr>
<tr><td>Incentives for indoor air purification technologies and provision of clean air community spaces. Incentives (e.g., cost reduction, rebates) can bolster the use of air purification technologies in residential and community settings. Public access to community spaces (e.g., libraries, youth centers, shopping malls) with air filtration during wildfire smoke events can reduce wildfire smoke exposure.</td><td>• During the 2018 Camp Fire, San Francisco Department of Emergency Management maintained and provided access to a list of clean air spaces on an online map.
• AB 836: Wildfire Smoke Clean Air Centers for Vulnerable Populations Incentive Pilot Program.</td></tr>
<tr><td>Respiratory protective equipment: Recommended when outdoor and low-intensity activity cannot be avoided. Proper use of N95 masks can significantly reduce exposure to particulate matter in wildfire smoke.</td><td>• CDPH Wildfire Smoke: Guide for California Public Health Professionals (CDPH) provides detailed respirator guidance.</td></tr>
<tr><td>State-issued regulations to protect worker health during wildfires: Requires employers to communicate wildfire smoke hazards, train employees about the health effects of wildfire smoke and how to find the current AQI for $PM_{2.5}$, provide respirators and implement engineering controls or change workers' schedules to reduce exposures.</td><td>• Cal/OSHA §5141.1: Protection from Wildfire Smoke.</td></tr>
<tr><td>Inclusive educational materials, emergency planning and response for wildfire smoke events: Public access to air quality emergency notification alerts and accessible, translated materials regarding wildfire smoke exposure, respirators and in-home air filtration options. Local health departments can also coordinate with community-based organizations to identify vulnerable individuals that may benefit from additional outreach and/or wellness checks during poor air quality events.</td><td>• Bay Area Regional Air Quality Messaging Toolkit.
• Alerts from local agencies (e.g., via Nixle).
• AB 661: Wildfire Smoke Air Pollution Emergency Plan: Sacramento Metropolitan Air Quality Management District.
• SB 160: Emergency services: cultural competence.</td></tr>
<tr><td>Coordinated health surveillance during wildfire smoke events: Comprehensive surveillance system of the health effects from wildfires and wildfire smoke events, including public and private healthcare providers.</td><td>• San Mateo County Health, Council of State and Territorial Epidemiologists (CSTE) Climatic Exposures and Respiratory Health Outcomes Pilot (CERHOP).</td></tr>
</table>

	Summary of health hazards, risks and impacts	Strategies to mitigate potential health risks	Policy model(s) / example(s)	Research gaps and limitations
The Public Health Dimensions of Wildfire *(Section 2.0)*				
Water quality *(Section 2.2)*	• California forested lands contain numerous key watersheds. 60% of the California water supply originates in the Sierra Nevada alone. • Wildfire events often increase erosion and subsequent sediment loads in surface waters, which can lead to impaired infrastructure, increased treatment demands, and increased formation of disinfection byproducts, some of which have been found to be toxic. • Water quality impacts can occur during wildfire events and for months and years after. • Recent California wildfires have resulted in volatile organic compound (VOC) contamination in water distribution systems. • Small, single source water systems in high wildfire risk areas may be at greatest risk of devastating wildfire-related impacts.	**Watershed quality assurance post-wildfire:** Erosion controls and silt collection devices are used on fire damaged properties. Potential sources of water contamination, including animal carcasses, hazardous waste and other debris are removed from landscapes and disposed of.	• California **Debris Management Task Force** led by CalEPA. • **Debris Management Teams** aim to limit impacts to water resources (e.g., response following the 2018 Woolsey Fire, Consolidation Debris Removal Program). *(For additional information on debris and hazardous waste removal, see Section 2.3, Soil and Crops.)*	• Toxicological profiles of unregulated disinfection byproducts, which have been detected in treated water post-wildfire, are not fully elucidated. • The mechanism(s) driving recent VOC contamination of water distribution systems post-wildfire are currently being explored. • Best practices need to be developed for: 1) mitigating VOC contamination in water distribution systems post-wildfire (e.g., consider materials used in distribution components and ways to isolate contamination); 2) testing throughout wildfire-impacted distribution systems; and 3) handling and disposing of VOC contaminated materials (e.g., contaminated water, contaminated water distribution infrastructure).
		Potable and drinking water management: Water providers take steps to re-pressurize systems, repair source intakes and leaks, conduct water quality testing throughout water treatment and distribution systems, and replace portions of systems, if warranted. Water advisories may be issued including Boil Water orders or Do-Not-Drink and Do-Not-Boil orders, depending on contaminants of concern.	• **Paradise Irrigation District** response following the 2018 Camp Fire (e.g., Water System Recovery Plan). • **City of Santa Rosa Water** response following the Tubbs Fire (e.g., Post-Fire Water Quality Updates).	
Soil and Crops *(Section 2.3)*	• Soil and vegetation burn can release nutrients and contaminants (e.g., PAHs, mercury) and inhibit the ability of water to infiltrate into soils. • Wildfire also can cause soil destabilization, particularly along steep slopes, increasing the risk of debris flows that may damage or destroy nearby buildings and infrastructure and result in loss of life. • Agricultural soils and crops may also be impacted by wildfires and wildfire-associated debris and ash.	**Debris and hazardous waste removal:** Includes coordinated handling, removal and disposal of burned and otherwise damaged materials in wildfire-affected areas, including burned structural materials (e.g., homes, vehicles, household items. other infrastructure).	• **Los Angeles County Department of Public Works** response following the 2018 Woolsey Fire (e.g., Consolidation Debris Removal Program). • **CA DTSC** Emergency Guidance on Wildfires #1: Handling Ash, Debris, and other Hazardous Materials from Burned Structures. • **CA DTSC** Emergency Guidance on Wildfires #2: Management Options for Expedited Collection of Hazardous Wastes from Burned Areas.	• More detailed characterizations of soils in developed wildfire-affected areas could further inform future remediation efforts. • Additional research is needed to assess uptake of wildfire-associated contaminants into a variety of crops.
		Post-fire debris-flow hazard assessments: Characterizes risk of soil destabilization and debris flow in wildfire-affected areas given local conditions (e.g., slope gradient, extent of reduced infiltration capacity of soils).	• **USGS** Emergency Assessment of Post-Fire Debris-Flow Hazards.	
		Soil testing in agricultural soils: Soils used for agricultural — from backyard gardens to large-scale farms — may need to be tested in areas directly impacted by wildfire or wildfire ash.	• **University of California Cooperative Extension Sonoma County**: Produce Safety after Urban Wildfire.	

	Summary of health hazards, risks and impacts	Strategies to mitigate potential health risks	Policy model(s) / example(s)	Research gaps and limitations
The Public Health Dimensions of Wildfire *(Section 2.0)*				
Mental health *(Section 2.4)*	• Events associated with wildfires including destruction of homes and forced evacuation of communities may contribute to mental health burdens or exacerbate existing mental health conditions. • While more research is required to understand the potential mental health impacts on populations exposed to wildfire smoke, studies evaluating associations between mental health outcomes and $PM_{2.5}$ exposure broadly indicate increased depressive and anxiety symptoms, increased emergency department visits for psychiatric concerns, and higher perceived stress. • Limited studies evaluating the direct and indirect experiences associated with wildfires also show evidence of related mental health impacts, including grief, acute stress, exacerbation of underlying disorders, symptoms of depression and symptoms of vicarious traumatization or secondary trauma. • Additionally, wildfires and other natural disasters can interrupt provision of mental health services for those that require additional services and for the general population during and after a fire.	**Mental health surveillance:** Data on mental health outcomes included in broader health surveillance during and after wildfire can inform allocation of resources to support mental health services and can inform efforts to anticipate needs of future wildfire events. **Provision of support services during and after wildfire:** An adequate supply of mental health professionals is necessary to respond to wildfires and other emergencies and natural disasters. Resources and staff are particularly needed to address the mental health needs of children and adolescents following disasters.	• **Healthcare Foundation Northern Sonoma County** Wildfire Mental Health Collaborative. • PsySTART Rapid Mental Health Triage and Incident Management System.	• Additional studies are needed to evaluate wildfire smoke exposure and mental health outcomes, as wildfire smoke events may increase in frequency and intensity for certain populations due to climate change and other drivers. Future studies evaluating wildfire smoke exposure should also assess impacts on mood and cognition, especially among vulnerable populations such as children and the elderly. • Mental health outcomes should be included in health surveillance during and after wildfire events, as well as an exploration of other factors tied to wildfires that influence mental health (e.g., the potential increase in experiences of homelessness in communities where properties have been damaged by fire). • Studies can additionally evaluate more widespread mental health impacts of wildfires on the broader populations that may experience secondary trauma, including those living in close proximity to wildfire-affected areas and those living in communities that absorb displaced populations after wildfire. • Future evaluations are needed to anticipate delivery of mental health services to guide preparation and response efforts for future wildfire events.

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<table>
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<tr><td colspan="5">The Public Health Dimensions of Wildfire Prevention, Mitigation and Suppression (Section 3.0)</td></tr>
<tr><td rowspan="6">Public safety power shutoffs
(Section 3.1)</td>
<td rowspan="6">Within the home, lack of electricity limits one's ability to:
• Safely store and refrigerate food, medication and breastmilk;
• Run pumps for water wells or septic systems;
• Power or charge electric or battery-operated medical devices;
• Charge electric bikes or cars;
• Filter indoor air and regulate indoor temperatures; and
• Access emergency information via the internet.

In a community setting, lack of electricity can cause:
• Inability to pump water throughout water distribution systems;
• Increases in traffic accidents on roads due to traffic light outages;
• Closures of schools, offices, businesses, and community spaces which may result in lost wages; and
• Limited or lack of cellular network for communication; and
• Limited or lack of air quality monitoring data.

In medical settings, lack of electricity can result in:
• Rescheduling of medical procedures;
• Transporting patients to other facilities;
• Placing burden on those individuals and facilities with various electricity-dependent requirements (e.g. comorbidities, elderly care facilities).</td>
<td colspan="2">Strategies to reduce fire risk from power lines</td>
<td rowspan="6">• Development of a formalized process for documenting potential health and safety impacts associated with public safety power shutoffs.
• Comprehensive identification of medical baseline customers and other at-risk and vulnerable populations is needed.
• Investigations into disproportionate impacts of PSPS events is warranted.
• Identification of resilient sites for strategic deployment of distributed energy resources statewide, with an emphasis on communities that may be disproportionately impacted by wildfire, natural disasters, PSPS and other grid outages.
• Effectiveness of utility and State agency efforts to mitigate public safety power shutoffs risks and impacts need to be evaluated, with particular focus on vulnerable and hard to reach populations.</td></tr>
<tr><td>Grid inspections and vegetation management: Transmission and distribution power infrastructure require ongoing inspection and maintenance to remove tree branches and other vegetation growing too close to electric lines.</td>
<td>• Monitoring technology for inspections, including drones and video cameras, as well as physical inspections (e.g., SoCal Edison recently installed weather stations, high-resolution cameras, etc.)
• SB 167: Electrical corporations: wildfire mitigation plans.</td></tr>
<tr><td>Burying wires: Undergrounding electric wires significantly reduces risk of ignition, but can be prohibitively expensive and time-consuming.
Grid hardening: Hardening grid infrastructure includes covering exposed wires and replacing poles and transformers with more fire-resistant alternatives.</td>
<td>• As Paradise (CA) rebuilds following the 2018 Camp Fire, PG&E commits to put all electric distribution power lines underground.
• SB 70: Electricity: undergrounding of electrical infrastructure.</td></tr>
<tr><td colspan="2">Strategies to create a resilient electric power system</td></tr>
<tr><td>Residential solar+storage: Household-level solar+ storage systems can provide resilience during PSPS events and other emergencies while supporting the transition to a clean, low-carbon electric grid.
Islandable solar: Solar photovoltaic systems are typically set up such that they do not provide electricity when the grid at large goes down. However, the inclusion of a separate disconnect on solar systems can allow them to island from the grid and provide electricity while the sun is shining. This would provide less resilience than a solar+storage system, but at a significantly lower cost.
Solar+storage for critical facilities and resources: Solar+storage can provide back-up for critical facilities, including hospitals, clinics, police and fire stations, water treatment facilities, emergency responders and food distribution centers. In addition, solar+storage can help ensure that traffic lights, street lights, communications infrastructure and water distribution systems continue to function during grid outages.
Resilient community centers: Resilient community centers are sites that can be equipped with solar+storage to provide a safe place for community members to receive critical support during grid outages. Potential resilient community sites include cooling centers, gyms, libraries, schools and other public buildings.
Microgrids: Solar, storage, and other generation resources can be integrated across larger regions to island from the electric grid to provide resilience during blackouts.</td>
<td>• Comparative tool for emergency backup power options (CARB Emergency Backup Power Options - Residential).

• AB 1144: Self-generation incentive program: community energy storage system, high fire threat districts.

• City of Fremont Fire Station Microgrids.

• Proposed clean-energy microgrid community for select facilities (e.g., public buildings, schools, community centers) in downtown Berkeley (Berkeley Energy Assurance Transformation, BEAT).

• The Blue Lake Rancheria tribe microgrid equipped to provide power to an estimated 8% of the county's population during the PSPS events in October 2019.
• Montecito Community Microgrid Initiative.</td></tr>
</table>

<table>
<tr><th></th><th>Summary of health hazards, risks and impacts</th><th>Strategies to mitigate potential health risks</th><th>Policy model(s) / example(s)</th><th>Research gaps and limitations</th></tr>
<tr><td colspan="5">The Public Health Dimensions of Wildfire Prevention, Mitigation and Suppression (Section 3.0)</td></tr>
<tr><td rowspan="6">Public safety power shutoffs
(Section 3.1)</td><td rowspan="6">Within the home, lack of electricity limits one's ability to:
• Safely store and refrigerate food, medication and breastmilk;
• Run pumps for water wells or septic systems;
• Power or charge electric or battery-operated medical devices;
• Charge electric bikes or cars;
• Filter indoor air and regulate indoor temperatures; and
• Access emergency information via the internet.

In a community setting, lack of electricity can cause:
• Inability to pump water throughout water distribution systems;
• Increases in traffic accidents on roads due to traffic light outages;
• Closures of schools, offices, businesses, and community spaces which may result in lost wages; and
• Limited or lack of cellular network for communication; and
• Limited or lack of air quality monitoring data.

In medical settings, lack of electricity can result in:
• Rescheduling of medical procedures;
• Transporting patients to other facilities;
• Placing burden on those individuals and facilities with various electricity-dependent requirements (e.g. comorbidities, elderly care facilities).</td><td colspan="2">Strategies to create a resilient electric power system (continued)</td><td rowspan="6">• Development of a formalized process for documenting potential health and safety impacts associated with public safety power shutoffs.
• Comprehensive identification of medical baseline customers and other at-risk and vulnerable populations is needed.
• Investigations into disproportionate impacts of PSPS events is warranted.
• Identification of resilient sites for strategic deployment of distributed energy resources statewide, with an emphasis on communities that may be disproportionately impacted by wildfire, natural disasters, PSPS and other grid outages.
• Effectiveness of utility and State agency efforts to mitigate public safety power shutoffs risks and impacts need to be evaluated, with particular focus on vulnerable and hard to reach populations.</td></tr>
<tr><td>Diesel generators: Diesel generators can supply critical power during outages. However, diesel combustion releases criteria pollutants such as particulate matter as well as greenhouse gases.</td><td>During 2019 PSPS events:
• Caltrans used diesel generators to support the Caldecott Tunnel (Oakland).
• Portable generator was deployed at pump station to provide water for the City of Vallejo.</td></tr>
<tr><td>Advanced grid infrastructure: Modernization of grid infrastructure, including smart meters, synchrophasors, flexible electric loads, and other forms of grid flexibility and demand management, can allow the utility to identify outages and other problems and shut off and restart portions of the grid remotely.</td><td>SDG&E has integrated technologies to remotely turn off parts of the grid.</td></tr>
<tr><td colspan="2">Additional strategies to prepare and support communities</td></tr>
<tr><td>Support telecommunications and emergency notifications during PSPS events: Includes preparation for power outages in communities that may be isolated during PSPS and development of protocols for rapid response to outages that may impact communication.</td><td>• SB 670: Telecommunications: community isolation outage: notification.
• SB 560: Wildfire mitigation plans: deenergizing of electrical lines: notifications: mobile telephony service providers.</td></tr>
<tr><td>Preparation to mitigate health and safety impacts associated with PSPS for vulnerable populations: Develop protocols related to mitigating public safety impacts of power shutoffs on vulnerable populations, including those receiving medical baseline allowances.</td><td>• SB 167: Electrical corporations: wildfire mitigation plans.
• During 2019 PSPS, the City of Vallejo in partnership with Touro University and Solano County, performed wellness checks on those with medical needs.</td></tr>
</table>

	Summary of health hazards, risks and impacts	Strategies to mitigate potential health risks	Policy model(s) / example(s)	Research gaps and limitations
The Public Health Dimensions of Wildfire Prevention, Mitigation and Suppression *(Section 3.0)*				
Forest management strategies *(Section 3.2)*				
Wildland-urban interface policies *(Section 3.2.1)*	• An estimated 4.46 million homes are located and 11.2 million people live within the WUI in California, more than any other state. • Increased development at the WUI represents the introduction of fuel and the alteration of local fire regimes, which may affect fuel loading and exacerbate wildfires and their associated impacts. • WUI policies include wildfire risk identification, creation of defensible space, vegetation management, home hardening, disincentivizing development within the WUI and managed retreat. • WUI policies overwhelmingly protect public health and safety.	**Risk communication for all residing in the WUI:** Clearly communicating risk to those living in the WUI, including permanent residents, as well as seasonal or temporary residents.	• **AB 38**: Fire safety: low-cost retrofits: regional capacity review: wildfire mitigation	• Detailed tracking of populations movement to and from WUI areas in California could inform current WUI policies and future projections of wildfire risk among populations in the WUI. • Local and regional planning departments could evaluate managed retreat strategies from high risk WUI areas and the capacity to promote urban infill to reduce wildfire risk for populations in proximal WUI regions in California.
		Utilize safe fire-resistant building materials: This includes the further development, evaluation, and implementation of safe fire-resistant building materials. These materials may include wood treated with flame retardants, or foams used in combination with concrete. Fire-resistant building materials should be well-characterized and evaluated to ensure that they pose little to no risk to human health and the environment under normal conditions and in the event of conflagration.	• Designated fire-resistant materials include ignition materials listed by the State Fire Marshal and materials that have been tested in accordance with SFM Standard 12-7A-5 (CAL FIRE).	
		Re-evaluate local zoning and land-use policies for new development in the WUI: Future zoning policies could limit construction of new homes in very high fire hazard severity zones. Current construction standards exist for fire-resistant homes, but there are regions of the state where development still occurs in high fire hazard regions. While new development is required to meet certain standards, modifications and retrofitting should also be considered for existing development.	• Policy examples and recommendations provided in the Office of Planning and Research Fire Hazard Planning: General Plan Technical Advice Series .	
		Promote development of dense urban infill: The cost and scarcity of housing in urban areas is driving the increased development in the WUI. A partial solution to reducing the number of residents living in the WUI is to construct more housing in urban areas. Urban infill policies can promote healthy, active lifestyles and provide access to healthy food, affordable housing, and quality jobs by directing development in underutilized urban areas.	• Examples of urban infill policies throughout California are outlined by Planning for Healthy Places, a program of Public Health Law & Policy (Healthy Planning Policies: A Compendium for California General Plans).	

	Summary of health hazards, risks and impacts	Strategies to mitigate potential health risks	Policy model(s) / example(s)	Research gaps and limitations
The Public Health Dimensions of Wildfire Prevention, Mitigation and Suppression *(Section 3.0)*				
Forest management strategies *(Section 3.2)*				
Prescribed burns *(Section 3.2.2)*	• Prescribed burning of the forested helps to reduce biomass fuels that may otherwise contribute to risk of incidence and intensity of wildfire. However, simultaneously, this type of vegetation management emits health-damaging pollutants. • The composition of pollutants emitted to the atmosphere during prescribed burns is often similar to wildfire smoke (e.g. $PM_{2.5}$ and other Criteria and Hazardous air pollutants), and are well-known to be associated with various adverse health outcomes. • Chronic exposure to these pollutants can occur for populations living downwind of landscapes with ongoing prescribed burn activities. • Similar to populations vulnerable to wildfire smoke exposure, various population subsets, including people with underlying cardiovascular and respiratory conditions, children and older adults may also be susceptible to smoke from prescribed burns.	**Air quality monitoring during prescribed burns:** Current smoke management guidelines require districts to evaluate air quality when determining a permissive burn day. Air quality monitoring during prescribed burns could produce useful data to assess potential health impacts in nearby populations.	SB 1260: Fire prevention and protection: prescribed burns.	• Emissions from prescribed burns should be further quantified and characterized. • Additional research on exposure to smoke from prescribed burns is needed, particularly focused on repeated smoke exposures. • Future research should explore the differences between smoke from prescribed burns and smoke from wildfires, focusing on the implications for public health.
		Prescribed burn reporting: Smoke Management Guidelines require reporting of prescribed burn activities. **Notification systems:** Notify communities nearby prescribed burn areas, particularly nearby sensitive receptor facilities (hospitals, elderly care facilities, schools, day care centers).	• **Smoke Management Plan** (implemented by CARB and Air Districts). • **California Prescribed Fire Information Reporting System** (PFIRS).	
Biomass waste to energy production *(Section 3.2.3)*	• Health implications of wood biomass utilization for electricity are largely dependent on the quantity of fuels used, technology used to generate electricity or heat, the location of these facilities, and the proximity, density and characteristics of nearby populations. • Traditional direct combustion biomass facilities in California are among the highest sources of PM and NO_X on the California electric grid. • However, biomass facilities tend to be located in less densely populated areas (median population living within 1 mile is 1,400).	**Siting, developing and upgrading biomass facilities using best available technologies:** Biomass facilities should be sited and designed to minimize both air pollutant emissions, the distance biomass fuel travels to reach the plant (e.g., considering locations of key tree mortality zones), and undergrounding electrical infrastructure to reduce wildfire risk.	**Resources relevant to evaluating potential health implications of biomass facilities:** • California Power Map (PSE Healthy Energy) • California Biomass Residue Emissions Characterization (C-BREC) tool models air pollutant emissions from biomass energy systems (*under development).* • The best use of California's biomass to meet air quality and climate goals (CARB, pending publication) • Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California (Carreras-Sospedra et al., 2015; prepared for CARB)	• Additional research about biomass facility operations, associated emissions, and local dispersion patterns is critical to understanding the potential public health implications of biomass facilities. • Future investigations should evaluate and compare individual biomass facility operations and emissions. • Tracking pre-fire fuel treatments, such as forest thinning, could aid researchers and policy-makers in understanding the success of management strategies. These metrics could include data about biomass utilization, such as how much fuel is diverted as waste to energy facilities. • Additional research and investment into cost reduction for emerging, distributed and lower-emission biomass gasification systems could also be explored.

<table>
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<tr><td colspan="5">The Public Health Dimensions of Wildfire Prevention, Mitigation and Suppression (Section 3.0)</td></tr>
<tr><td rowspan="4">Chemical fire suppression
(Section 3.3)</td><td rowspan="4">• While some ingredients in fire retardants and foams are well-known, complete chemical formulations of fire retardants and foams are considered trade secrets and are not publicly disclosed.
• Chemicals historically used in firefighting foams, such as per- and poly-fluoroalkyl substances (PFAS), are persistent in the environment, bioaccumulate in the body, and have been found to be toxic at lower concentrations than current federal drinking water standards.
• Fluorine-free fire suppressants are utilized in Europe and are being considered in certain industries in the United States (e.g., at airports).</td><td>Safer chemical fire suppressants: Transparency and public disclosure of chemical formulations in chemical fire suppressants. Compounds that pose risks to human health or the environment or have unknown toxicological profiles may be replaced by substances with known toxicological profiles that pose little to no toxicity to human health and the environment.</td><td>• Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), fluorine-free foams.
• Removing requirements for fluorinated fire suppressants from industry or federal standards (e.g., FAA Authorization Act of 2018, H.R. 302).
• SB 1044 (Proposed): Firefighting equipment and foams: PFAS chemicals.</td><td rowspan="4">• Chemical formulations of fire suppressants used historically and currently in California are not well characterized.
• Additionally, many unknowns remain regarding the toxicological profiles of past and present chemical fire suppressants.
• Fluorine-free fire suppressant alternatives need verification, full characterization to determine if toxicological profiles pose little or no risk to human health or the environment.
• In California, PFAS source investigations and drinking water well sampling in recent wildfire-affected urban areas are being conducted. Research is needed to determine the extent of population exposure to PFAS compounds associated with wildfire suppression activities.
• Additional research is needed regarding the potential health impacts associated with PFAS exposure, specifically low dose and long-term exposure over time in human populations.</td></tr>
<tr><td>Safe application of fire suppressants: Existing fire suppressants are noted for aquatic toxicity and persistence in the environment, and are generally prohibited from being applied 300 feet from surface water and in areas with threatened, endangered and sensitive species (unless public safety and human lives are threatened).</td><td>• US Forest Service designated avoidance areas.</td></tr>
<tr><td>Drinking water standards for known toxic chemicals in firefighting foams: Adoption of notification and response levels and drinking water standards for PFAS used currently and historically in firefighting foams.</td><td>• SWRCB notification and response levels for PFOS and PFOA
• OEHHA public health goals and maximum contaminant level for PFOS and PFOA (in progress).</td></tr>
<tr><td>Environmental monitoring for toxic chemicals in firefighting foams and common household items: Ongoing environmental monitoring at health-relevant levels of detection, particularly in wildfire-affected areas where exposure pathways are likely.</td><td>• SWRCB PFAS Investigation.</td></tr>
</table>

AB– Assembly bill; AQI– air quality index; Cal/OSHA– California Occupational Safety and Health Administration; CA DTSC – California Department of Toxic Substances Control; CalEPA – California Environmental Protection Agency; CARB – California Air Resources Board; ED– emergency department; NO_x – nitrogen oxides; PAH– polycyclic aromatic hydrocarbons; PFAS– per- and poly- fluoroalkyl substances; PFOA– perfluorooctanoic acid; PFOS– perfluorooctanesulfonic acid; PG&E – Pacific Gas and Electric; PM– particulate matter; SB– Senate bill; SDG&E – San Diego Gas and Electric; USGS – United States Geological Survey; VOC– volatile organic compound.

1.0 Background and approach

In recent years, California has experienced the largest,[1] most destructive[2] and deadliest[3] wildfires in its history. Wildfires can cause death and injury, impair air quality for nearby and distant populations, and devastate the immediate area, leaving communities with often hazardous remains of burned landscape and infrastructure. Evacuations and recovery efforts as a result of wildfires can have lasting impacts on individuals and communities. Over the last half century, California has experienced an increasing trend in annual burned acreage from wildfires (Williams et al., 2019). Atmospheric aridity and fuel-drying, extended drought, and pathogen-impacted forests — all of which are driven and compounded by anthropogenic climate change — increase risks posed by wildfires (IPCC, 2019). Additionally, increased development at the wildland-urban interface (WUI) puts more individuals at risk of harm from these natural disasters.

In light of increased wildfire risks compounded by climate change and land-use decisions, the State of California is re-evaluating its strategies to both prevent wildfires and mitigate wildfire impacts. These strategies include, but are not limited to the deployment of prescribed burns to control vegetation, chemical fire suppressants and, most recently, public safety power shutoffs (PSPS). While these strategies do help to control the frequency, intensity and duration of wildfire, to date, the public health dimensions of these wildfire prevention and mitigation strategies have not been thoroughly characterized and synthesized, especially within the California context.

This report integrates information about the public health dimensions of wildfire, wildfire prevention and approaches to impact attenuation into a synthetic framework. The aim is that this will assist the State of California, researchers and risk managers in the development of effective wildfire risk management, while ensuring that public health information is embedded into decision-making to help to minimize unintended consequences. In this report, we review the human health hazards, risks, and impacts of California wildfires, as well as the impacts of policies aimed to prevent and mitigate wildfire intensity and impact.

This report includes three primary components:

1. **The public health dimensions of active wildfire (Section 2.0):** This section first provides a brief background on California wildfire trends over time, followed by a summary of the various environmental pathways (air, water soil, and crops) through which humans can be exposed to chemical hazards during and after active wildfire. Mental health impacts associated with wildfire are also discussed. Community- and individual-scaled approaches to address public health implications of wildfire and related research gaps and limitations are discussed.

[1] **Mendocino Complex Fire**, July 2018. 459,123 acres. https://www.fire.ca.gov/media/5510/top20_acres.pdf.

[2] **Camp Fire**, November 2018. 18,804 structures. https://www.fire.ca.gov/media/5511/top20_destruction.pdf.

[3] **Camp Fire**, November 2018. 85 deaths. https://www.fire.ca.gov/media/5512/top20_deadliest.pdf.

2. **The public health dimensions of California's approach to wildfire prevention, mitigation and suppression (Section 3.0):** In this section we discuss the public health dimensions of various wildfire prevention, mitigation and suppression strategies, including public safety power shutoffs, forest management strategies (e.g., prescribed burns) and chemical fire suppression. Current, proposed and recommended policy models and approaches to address public health implications of these wildfire prevention, mitigation and suppression strategies are discussed. Existing research gaps and limitations are also discussed.

3. **Addressing California wildfires in a public health context: discussion and next steps (Section 4.0):** This section includes a synthesis of (1) the public health implications of wildfires and wildfire prevention, mitigation, and suppression strategies, (2) policies and approaches aimed to address the health hazards, risks and impacts posed by both, and (3) associated research gaps and limitations. Emerging areas of concern, including the compounding risks posed by climate change and implications of the COVID-19 pandemic are discussed. This section also outlines detailed research and policy recommendations to guide next steps in California.

Approach

In this report, our approach consists primarily of 1) a review of the peer-reviewed literature, government reports, and grey literature and 2) interviews with local and State agency staff. Below we provide details on each of these components.

Literature review

We searched the peer-reviewed literature for publications on the health hazards, risks and impacts associated with wildfires and wildfire prevention, mitigation and suppression strategies using the publication databases Web of Science, PubMed, and Google Scholar. Search terms included, but were not limited to, combinations of the following: *wildfire, fire, California, water, water quality, groundwater, drinking water, air quality, smoke, particulate matter, ozone, soil, crops, agriculture, debris flow, mental health, outdoor worker, health, toxicity, epidemiology, wildland urban interface, WUI, prescribed burn, controlled burn, biomass, biomass processing, fire retardant, firefighting foam, chemical fire suppression, perfluoroalkyl and polyfluoroalkyl substances, PFAS,* and *power outage*.

We also gathered federal and state governmental reports, white papers, news articles and other grey literature to summarize and discuss wildfire prevention, mitigation and suppression approaches and the associated health hazards, risks and impacts. California agencies from which we acquired reference materials include the Department of Forestry and Fire Protection (CAL FIRE), the Governor's Office of Emergency Services (CalOES), the Department of Industrial Relations (DIR), the Air Resources Board (CARB), and the California Public Utilities Commission (CPUC), among others. Materials applicable to Section 2.0 and Section 3.0 of this report (described above) were gathered through June 1, 2020. Given that circumstances amid the

COVID-19 pandemic are constantly evolving, materials related to COVID-19 and wildfire preparedness and response (see Section 4.2) were gathered through July 15, 2020. Of note, as we focus on public health more broadly in our review, occupational wildfire-related exposures of firefighters and emergency responders are beyond the scope of this report.

Stakeholder and government interviews

We conducted qualitative, informational interviews with relevant stakeholders and government agencies to address questions that arose from our review of the available literature. We interviewed staff at the following agencies:

- California Air Resources Board (CARB)
- California Department of Toxic Substances Control (DTSC)
- California Department of Public Health (CDPH)
- San Francisco Department of Public Health (SF DPH)

Defining terms: hazard, risk, and impact

The terms ***hazard***, ***risk*** and ***impact***, while often used interchangeably, have different implications in the field of risk assessment, which includes health risk assessment. Briefly, a *hazard* is defined as any biological, chemical, mechanical, environmental or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control (Sperber, 2001). For example, hazards related to wildfires can include fire and air pollutants known to be detrimental to human health. *Risk* is the probability that a given hazard plays out in a scenario that causes a particular harm, loss or damage (National Research Council, 2009). Determining risk, or the probability of harm, requires a receptor (e.g., human population) to be exposed to the hazard, and often depends on the vulnerability of the population (e.g., lifestage, pre-existing conditions) (Shonkoff et al., 2015). Living in close proximity to areas where wildfire is likely (e.g. arid, heavily forested landscapes) may increase the likelihood of populations coming into contact with various hazards, including fire and air pollutants emitted during wildfires that are known to be hazardous to human health. *Impact* is defined as a particular harm, loss or damage that is experienced if the risk-based scenario occurs (National Research Council, 2009).

2.0 The public health dimensions of active wildfire

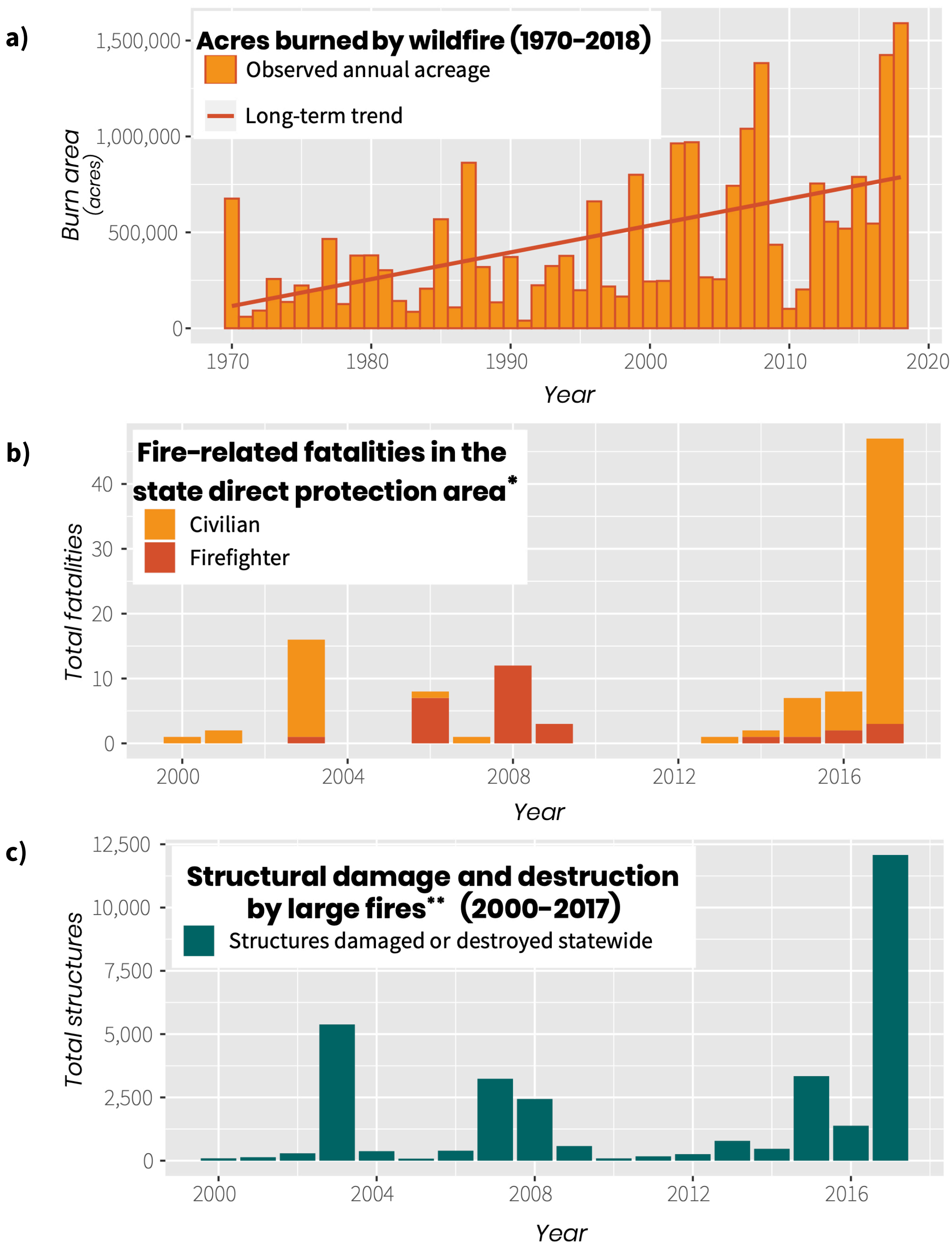
In this section, we discuss trends associated with California wildfire activity. We then review the human health hazards, risks and impacts associated with wildfires through relevant environmental and exposure pathways including air (Section 2.1), water (Section 2.2), soil and agricultural crops (Section 2.3). We also discuss wildfire-related health hazards, risks and impacts related to mental health (Section 2.4). In each subsection, policies aimed to address these health hazards, risks and impacts are discussed and research gaps and limitations are identified. California-specific case studies and examples regarding wildfires and health are discussed throughout.

California wildfires in context

Wildfires have increased in size, frequency and intensity over the last several decades across many regions of the world. In California, there has been an upward trend in annual acreage burned by wildfires over the last 50 years (Figure 1a), with a fivefold increase in annual burned acreage between 1972 and 2018 (Williams et al., 2019). Moreover, individual fires have grown more damaging, with several of the State's largest, deadliest and most destructive wildfires occurring in the last decade (Figure 1b; Figure 1c).[4]

In 2018, both Northern California and Southern California experienced above-average acreage burned based on regional ten-year averages (385% and 118%, respectively), and California experienced record-breaking wildfires (NIFC, 2018; CAL FIRE, 2020a). The largest wildfire in California's history — the 2018 Mendocino Complex Fire — burned 459,123 acres in Colusa, Lake, Mendocino, and Glenn counties in Northern California (CAL FIRE, 2020b). Also in 2018, the Camp Fire — the most destructive and deadliest wildfire in California's history — destroyed 18,804 structures in Butte County and resulted in 85 deaths (CAL FIRE, 2020b). The Camp Fire was the costliest natural disaster globally in 2018, resulting in an estimated 16.5 billion in total losses (Reyes-Velarde, 2019; Munich RE, 2019). While long-term trends over time indicate increases in larger and more destructive fires, in 2019, both in California and across the United States, fewer wildfires were reported and fewer acres burned when compared to corresponding ten-year averages (NIFC, 2019). Wildfires and their associated evacuation, emergency response and recovery efforts present ever-increasing direct and indirect public health and safety implications for Californians.

[4] **PSE online interactive data visualization tool:** California's largest, deadliest, and most destructive wildfires, 1923 - 2018.



Source data: (a) CAL FIRE Open Data Hub: Fire Perimeters After 1950, National Interagency Fire Center 2019 Annual Report, (b, c) CAL FIRE 2000-2017 Redbooks. *Non-inclusive of fire-related fatalities in the local or federal direct protection area. Actual fatalities may be higher. **Definition of “large fire” may vary by source Redbook.

Figure 1. Direct impacts of California wildfires: **(a)** acreage burned, 1970 - 2019; **(b)** firefighter and civilian fatalities, 2000 - 2017; and **(c)** structures damaged or destroyed, 2000 - 2017.

2.1 Wildfires, air quality and health

It is well understood that wildfire smoke can cause significant and widespread air quality impacts. Wildfire smoke is composed of numerous health-damaging air pollutants that can be transported through the atmosphere downwind of active burn zones. This section describes the composition of wildfire smoke, its atmospheric transport and dispersion, the known adverse health outcomes associated with wildfire smoke exposure, and populations that are particularly vulnerable to wildfire smoke exposure (Section 2.1.1). Policies aimed to reduce health risks and impacts associated with wildfire smoke exposure (Section 2.1.2) and research gaps and limitations are also discussed (Section 2.1.3).

2.1.1 Wildfires and air quality: implications for public health

Composition of wildfire smoke

Wildfire smoke is composed of various constituents known to be hazardous to human health. Criteria air pollutants, which are regulated under the Clean Air Act, contribute to the health-damaging fraction of wildfire smoke (U.S. EPA, 2019). Criteria air pollutants include particulate matter (PM), carbon monoxide, nitrogen dioxide, sulfur dioxide, lead and ground-level ozone — all of which may be emitted or secondarily formed from a wildfire (U.S. EPA, 2018a). For example, burned biomass can emit PM and nitrogen dioxide, with carbon monoxide emitted as a result of incomplete combustion; sulfur dioxide and lead may be released from burned synthetic materials; and ozone precursors emitted during wildfires (e.g., nitrogen oxides and volatile organic compounds) can result in secondary formation of ozone in the presence of sunlight (Fabian et al., 2010; U.S. EPA, 2020). Exposure to criteria air pollutants is associated with various adverse respiratory and cardiovascular outcomes, among other health and environmental impacts (U.S. EPA, 2018a).

Perhaps the most widely studied criteria air pollutant associated with wildfire is particulate matter (PM), which consists of microscopic particles that can penetrate deep into the lungs. PM with particles that are 2.5 micrometers in diameter or less ($PM_{2.5}$) can travel deep into the respiratory tract and enter the bloodstream, and pose an even greater risk to health compared to larger particles (e.g., 10 micrometers in diameter, PM_{10}), which tend not to travel past the upper respiratory tract (U.S. EPA, 2018b). PM exposure is associated with adverse respiratory outcomes (exacerbated asthma, increased respiratory symptoms and decreased lung function), cardiovascular outcomes (heart attacks, irregular heartbeat), and premature mortality for those with existing lung or cardiovascular disease (U.S. EPA, 2016a). PM can be directly emitted during a wildfire during combustion or, similar to ozone, can form secondarily from chemical interactions in the atmosphere. In 2018, California wildfires emitted an estimated 598,000 and 507,000 short tons of PM_{10} and $PM_{2.5}$, respectively (CARB, 2019). While ambient concentrations of PM are elevated during wildfire events, wildfires also influence the chemical composition of PM by increasing the organic carbon and elemental carbon fraction, which may influence toxicity (Liu and Peng, 2019; Bell and HEI Health Review Committee, 2012).

Although smoke is mostly composed of water vapor and carbon dioxide (a greenhouse gas), the toxicity of carbon dioxide is relatively low (Reinhardt and Ottmar, 2004). The remaining components in smoke are a complex mixture of hundreds of gases and particles, which include compounds designated as toxic air contaminants (TACs) by the California Air Resources Board (CARB) and hazardous air pollutants (HAPs) by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act (e.g. acrolein, benzene, formaldehyde). The gaseous pollutants in smoke include volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), many of which are directly hazardous to human health and some of which are also ozone precursors. Wood smoke also contains many of the same toxic and carcinogenic substances as cigarette smoke, including benzene, benzo[a]pyrene and dibenz[a,h]anthracene (Balmes, 2018). During smoldering (a form of incomplete combustion), a wildfire emits health-damaging pollutants such as carbon monoxide, ammonia, and various VOCs including acrolein and formaldehyde (Urbanski et al., 2009).

Wildfire smoke composition can vary greatly between fires and even within a single fire event. Combustion products and air pollutant concentrations emitted from a wildfire are largely dependent on the fire-specific conditions, including the size and intensity of the fire, the chemical composition of materials ignited and available ventilation (Fabian et al., 2011). Different combustion processes that occur within the perimeter of a wildfire (e.g., flaming, smoldering, and glowing) are distinct from one another, which also contributes to the range of combustion products (Ward and Hardy, 1991). Adding to the complexity of smoke composition, wildfires may ignite structure fires, which are defined as any fire that occurs in or on a structure such as a residential or commercial building (Ahrens, 2013). For the purposes of this report, we distinguish a *structure fire* as including *structural materials,* such as household products, residential and commercial buildings, vehicles and other infrastructure of the built environment which, when combusted, can release an array of hazardous compounds, including asbestos, heavy metals, and other chemical or biological hazardous materials (Fabian et al., 2010; CITRIS Policy Lab et al., 2019). A selection of the known chemicals emitted during fires are listed in Table A-1 by type of material burned, either biomass or structural (Aurell et al., 2017; Fabian et al., 2011, 2010).

Examples of structural materials burned in fires include polystyrene plastics, which produce benzene, phenols, and styrene; vinyl compounds that emit acid gases, hydrogen cyanide, hydrogen chloride, and benzene; treated wood products that emit formaldehyde, formic acid, hydrogen cyanide, and phenols; and roofing materials which produce sulfur dioxide and hydrogen sulfide. Fires involving vehicles have been observed to emit ethylene, ammonia, acetylene, methanol, and butanol (Fabian et al., 2010). For wood products, researchers have found that smoke production increased when the proportion of synthetic compounds increased in a wood product (Fabian et al., 2011). The compounds emitted from burned structural materials have been shown to affect health as human carcinogens, asphyxiants, respiratory irritants, and reproductive developmental toxicants (Adetona et al., 2016; Fabian et al., 2011; Purser, 2010; OEHHA 2020; Table A-1).

Dispersion and transport of wildfire smoke

Understanding the atmospheric dispersion of wildfire smoke and its health-damaging constituents is essential to assessing wildfire smoke exposure and associated health impacts among populations. Numerous scientific investigations have demonstrated long-range transport of wildfire smoke using methods such as satellite imagery, back trajectory analysis, and direct reading instruments. For example, smoke plumes released from wildfires in Quebec, Canada caused increased levels of PM in Baltimore, Maryland (Sapkota et al., 2005). Following the Camp Fire in Northern California in November 2018, satellite imagery from the National Oceanic and Atmospheric Administration (NOAA) showed distinct plumes of smoke from the wildfire reaching New York after traveling across the southwest and through the Appalachian states (Dowd, 2018). In 2020, National Aeronautics and Space Administration (NASA) scientists detected smoke from wildfires in Australia circumnavigating the Earth (Jenner, 2020).

Figure 2 below illustrates the regional nature of wildfire smoke air quality impacts in California. Across a two-year span, there was a relatively high degree of synchrony between large wildfires and high $PM_{2.5}$ events, including numerous exceedances of national 24-hr $PM_{2.5}$ standards (35 micrograms per cubic meter, $\mu g/m^3$). Notably, high $PM_{2.5}$ concentrations during wildfire events often transcended air basins, traveling from the basin where the fire was burning into neighboring regions. For example, during the Camp Fire in 2018, coastal Northern California air basins experienced a large spike in $PM_{2.5}$ concentrations while the fire burned in inland Butte County. For additional reference, a map of California air basins aggregated by region is included in the appendix (Figure A-1).

Secondary formation of ozone following the transport of ozone precursors (e.g., nitrogen oxides) presents additional concerns about wildfire smoke distribution. Wildfire smoke can contribute to local ozone increases as well as increases in areas geographically removed from the source of air pollution (Black et al., 2017). Wildfires can impact ground-level ozone both nearby and potentially downwind from the source of a fire, and intense wildfires have contributed to ozone levels that exceed health standards (Pfister et al., 2008; Chalbot et al., 2013).

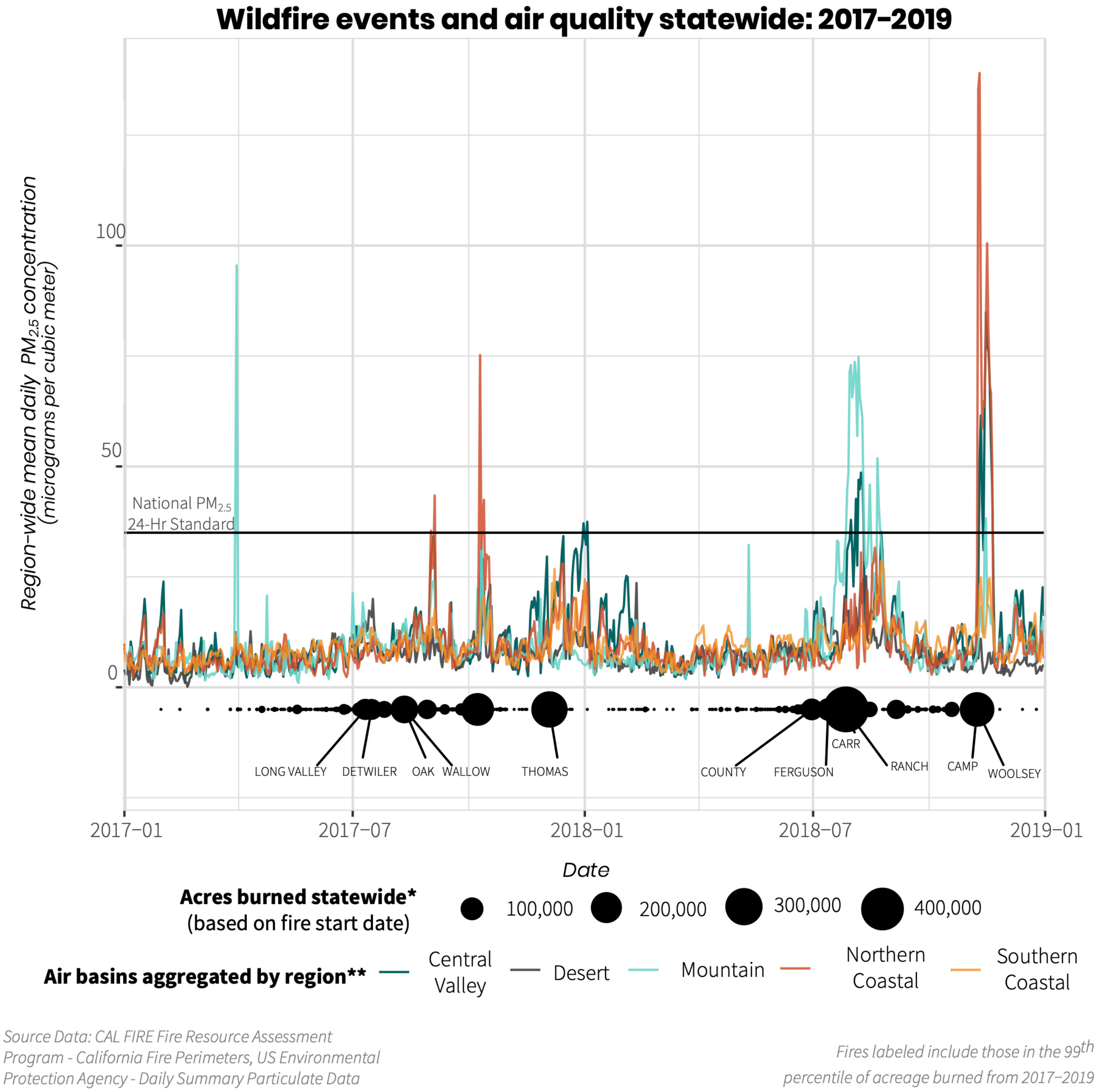


Figure 2. Wildfire events and 24-hr average $PM_{2.5}$ concentrations by region in California, 2017-2019. Regions represent aggregated air basins shown in Appendix A, Figure A-1.

Health impacts associated with wildfire smoke exposure

Numerous adverse health impacts are associated with wildfire smoke exposure. In this section, we (1) discuss the potential underlying mechanisms for health impacts from wildfire smoke exposure; (2) summarize the epidemiological literature evaluating the health risks and impacts associated with exposure to wildfire smoke; and (3) describe populations that may be particularly vulnerable to wildfire smoke exposure.

Toxicological mechanisms underlying wildfire smoke health impacts

Toxicological investigations using cell-lines and animal assays can be used to explain the underlying mechanisms of disease etiology, and can support causality between an exposure and a health outcome by extrapolating findings to human physiological systems. Numerous toxicological studies have identified pathways through which wildfire smoke exposure impacts respiratory and cardiovascular health. Briefly, inhalation of smoke from wildland fires can cause oxidative stress (an imbalance between free radicals and antioxidants) in the airways which leads to inflammation. Additionally, small particles (e.g., $PM_{2.5}$) that cross into the bloodstream can cause systemic inflammation in the body (Adetona et al., 2016). In animal studies, exposure to coarse PM from wildfire smoke showed evidence of cell death, markers of increased inflammation, and reduced immune function in mice (Reid et al., 2016; Wegesser et al., 2009, 2010; Williams et al., 2013). Evidence from additional animal studies shows that wood smoke exposure can result in inflammation of neutrophil white blood cells in the lungs and bronchoconstriction in the airways (Adetona et al., 2016).

Health outcomes associated with wildfire smoke exposure

Overall, peer-reviewed studies provide evidence of associations between wildfire smoke and the following health outcomes: eye irritation; respiratory outcomes including asthma exacerbation, bronchitis, dyspnea and chronic obstructive pulmonary disease, and increased hospital admissions for respiratory illness; adverse birth outcomes; out-of-hospital cardiac arrests, behavioral and cognitive impacts, and fatality and premature mortality. Studies evaluating the relationship between wildfire smoke exposure and health outcomes are summarized below.

Eye effects: Eye effects associated with wildfire smoke exposure can include eye irritation and superficial scratches on the surface on the eye. During numerous 1987 Northern California wildfires, few patients visited emergency departments across six counties for eye irritation (Duclos, 1990). Following the 1991 Oakland Hills fire (Oakland, CA), in a region with a dense population, 13% of patients with fire-related presentations to the emergency department in the week post-fire reported corneal abrasions (Shusterman et al., 1993), likely attributable to exposure to coarse PM. Additionally, numerous constituents found in wildfire smoke are noted eye irritants (e.g., PM, acrolein, formaldehyde). Acute eye effects due to exposure to these compounds can include redness, swelling, and irritation.

Respiratory effects: There is consistent evidence of associations between wildfire smoke exposure and general respiratory morbidity, specifically for exacerbations of asthma and chronic obstructive pulmonary disease (COPD) (Finlay et al., 2012; Morrison et al., 2014; Adetona et al., 2016). Elevated particulate matter concentrations as a result of wildfire have been associated with increased emergency department visits for asthma, bronchitis, dyspnea, and COPD (Black et al., 2017; Reid et al., 2019). Additionally, individuals previously diagnosed with asthma or COPD are more susceptible to adverse health outcomes associated with wildfire smoke exposure (Reid et al., 2016).

Birth outcomes: Studies in California and throughout the United States have evaluated the association between wildfire smoke exposure and various adverse birth outcomes. In October 2003, large urban populations in Los Angeles and Orange counties experienced elevated air pollutant concentrations from nearby wildfires. Pregnancy during these wildfires was associated with slightly reduced average birth weight among infants exposed *in utero* (Holstius et al., 2012). Among a cohort of pregnant women exposed to wildfire-associated $PM_{2.5}$ from 2007 to 2015 in Colorado, researchers observed increased odds of preterm birth associated with *in utero* exposure during the second trimester of gestation and during the full gestation period, as well as increased odds of gestational diabetes and gestational hypertension in pregnant women without pre-existing disease when exposure occurred during the first trimester and full gestation period (Abdo et al., 2019). Observations from the Colorado cohort may be relevant at a much greater scale during wildfires in California, given the larger fires in recent years and greater population density in affected areas.

Cardiovascular effects: More recent investigations have evaluated the associations between wildfire smoke exposure and cardiovascular events (e.g., cardiac arrest). Wildfire-related PM in California between 2015 and 2017 was associated with varied impacts of out-of-hospital cardiac arrests (OHCA) across populations by socioeconomic status (SES) (Jones et al., 2020). OHCA increased with the presence of heavy smoke (>22 $\mu g/m_3$ $PM_{2.5}$) across populations regardless of socioeconomic status; however, during periods of medium (10.5-21.5 $\mu g/m_3$ $PM_{2.5}$), OHCA were elevated for those of lower SES only. Previous studies of OHCA support these findings and reported an association with exposure to wildfire $PM_{2.5}$ (Dennekamp et al., 2015; Haikerwal et al., 2016). Another investigation of modeled smoke density in eight California air basins during the 2015 wildfire season revealed that basins with greater wildfire smoke exposure were associated with increased ED visits for ischemic heart disease, dysrhythmia, heart failure and pulmonary embolism (Wettstein et al., 2018). Despite significant findings for associations of wildfire smoke exposure with OHCA, there is mixed evidence about hospital admissions and emergency department visits for cardiovascular events during wildfires, with several previous studies reporting no significant increase (Hanigan et al., 2008; Henderson et al., 2011; Johnston et al., 2007; Martin et al., 2013; Morgan et al., 2010; Schranz et al., 2010).

Fatality and premature mortality associated with wildfire smoke exposure: In the most serious cases, close proximity to fire and subsequent wildfire smoke exposure can be fatal. Fatalities from fire are caused in part by asphyxiant gases, specifically CO and hydrogen cyanide, which can displace oxygen in body tissues (Purser, 2010). The time between wildfire smoke exposure and fatality from asphyxiation during a fire is typically between a few minutes and an hour, depending on the concentration of CO and the susceptibility of the person exposed (National Research Council, 2010). Additionally, CO_2 emitted as a result of combustion can displace oxygen and contribute to increased breathing rate which in turn promotes the inhalation of toxic gases. Carbon dioxide concentrations above ten percent can cause the loss of consciousness (Langford, 2005). Intense heat associated with direct exposure to smoke at the fire can also cause physical damage along the respiratory pathway (Rehberg et al., 2009). In recent years, California fire seasons have resulted in significant numbers of fatalities — with

47 fatalities in 2017 and 100 fatalities in 2018 (CAL FIRE, 2020a; Figure 1b). These fatalities may be related to direct contact with fire, but individual fatalities may be caused in part by exposure to wildfire smoke.

At the population scale, there is increasing evidence of associations between all-cause mortality and wildfire smoke exposure (Reid et al., 2016). It is well-established in population-based epidemiological studies that chronic exposure to $PM_{2.5}$, a primary constituent in wildfire smoke, is associated with all-cause mortality (Hoek et al., 2013; Krewski et al., 2009; Tamura-Wicks et al., 2018). Using simulations of smoke transport and dispersion during the 2017 fire season in the Pacific Northwest, researchers estimated 85% of the total $PM_{2.5}$ ambient concentrations and 95% of the resultant multiple-cause mortality in the region was contributed by wildfire emissions (Zou et al., 2019). Those with pre-existing medical conditions may be particularly susceptible to PM from wildfire smoke; for example, in a recent study examining end-stage renal disease patients requiring hemodialysis, wildfire smoke exposure was positively associated with all-cause mortality (Xi et al., 2019).

Wildfire smoke exposure and vulnerable populations

Wildfire smoke impacts vary based on an individual's susceptibility, which may be related to one's age current health status, occupation and additional socioeconomic vulnerabilities. Categories of vulnerability are described in Table 1 (Adapted from Wildfire Smoke: A Guide for Public Health Officials, U.S. EPA, 2019). Vulnerable individuals may be a member of multiple at-risk lifestages or subpopulations described in Table 1, a consequence which may compound vulnerabilities and further increase an individual's susceptibility to wildfire smoke. For instance, socioeconomically disadvantaged populations, older adults, and children may experience additional factors of vulnerability, such as transit dependence, which may hinder their ability to evacuate wildfire-smoke impacted areas and spaces and access clean air (Raval et al., 2019).

Outdoor workers may also be at greater risk of wildfire smoke exposure. Approximately 800,000 outdoor workers support California's agricultural economy alone (Martin et al., 2016). During the Woolsey Fire in 2018, an estimated 36,000 farm workers worked outside picking produce during periods of poor air quality caused by wildfire smoke and had limited access to personal protective equipment or medical care (Simon et al., 2018). In 2019, the Kincade Fire in Sonoma County occurred during the wine country grape harvest; even as neighborhoods were evacuated, workers stayed behind to continue the harvest (Barry-Jester, 2019; Ho and Koran, 2019). Many agricultural workers face financial insecurity, language barriers and immigration status uncertainties, all of which represent additional constraints that can result in employees working during hazardous air quality conditions (Barry-Jester, 2019; Ho and Koran, 2019).

Table 1. Summary of lifestages and populations potentially at risk of health effects from wildfire smoke exposures (Adapted from Wildfire Smoke: A Guide for Public Health Officials, U.S. EPA, 2019).

At-risk lifestage/ population	Rationale and potential health effects from wildfire smoke exposure
People with asthma and other respiratory diseases	**Rationale:** Underlying respiratory diseases result in compromised health status that can result in the triggering of severe respiratory responses by environmental irritants, such as wildfire smoke. **Potential health effects:** Breathing difficulties (e.g., coughing, wheezing and chest tightness) and exacerbations of chronic lung diseases (e.g., asthma and COPD) leading to increased medication usage, emergency department visits and hospital admissions.
People with cardiovascular disease	**Rationale:** Underlying circulatory diseases result in compromised health status that can result in the triggering of severe cardiovascular events by environmental irritants, such as wildfire smoke. **Potential health effects:** Triggering of ischemic events, such as angina pectoris, heart attacks, and stroke; worsening of heart failure; or abnormal heart rhythms could lead to emergency department visits, hospital admissions, and even death.
Children	**Rationale:** Children's lungs are still developing and there is a greater likelihood of increased exposure to wildfire smoke resulting from more time spent outdoors, engagement in more vigorous activity, and inhalation of more air per pound of body weight compared to adults. **Potential health effects:** Coughing, wheezing, difficulty breathing, chest tightness, decreased lung function in all children. In children with asthma, worsening of asthma symptoms or heightened risk of asthma attacks may occur.
Pregnant women	**Rationale:** Pregnancy-related physiologic changes (e.g., increased breathing rates) may increase vulnerability to environmental exposures, such as wildfire smoke. In addition, during critical development periods, the fetus may experience increased vulnerability to these exposures. **Potential health effects:** Limited evidence shows air pollution-related effects on pregnant women and the developing fetus, including low birth weight and preterm birth.
Older adults	**Rationale:** Higher prevalence of pre-existing lung and heart disease and decline of physiologic process, such as defense mechanisms. **Potential health effects:** Exacerbation of heart and lung diseases leading to emergency department visits, hospital admissions, and even death.
Socioeconomically disadvantaged populations	**Rationale:** Less access to health care could lead to higher likelihood of untreated or insufficient treatment of underlying health conditions (e.g., asthma, diabetes). Less access to measures to reduce exposure (e.g., air conditioning) could lead to higher levels of exposure to wildfire smoke. **Potential health effects:** Greater exposure to wildfire smoke due to less access to measures to reduce exposure, along with higher likelihood of untreated or insufficiently treated health conditions could lead to increased risks of experiencing the health effects described above.
Outdoor workers	**Rationale:** Extended periods of time exposed to high concentrations of wildfire smoke. **Potential health effects:** Greater exposure to wildfire smoke can lead to increased risks of experiencing the range of health effects described above.
People experiencing homelessness	**Rationale:** Individuals who may not have access to clean air spaces, including those who spend extended periods of time in informal settlements and living outdoors, may have higher levels of exposure to wildfire smoke. Less access to health care could lead to higher likelihood of untreated or insufficient treatment of underlying health conditions (e.g., asthma, diabetes). **Potential health effects:** Greater exposure to wildfire smoke due to less access to measures to reduce exposure, along with higher likelihood of untreated or insufficiently treated health conditions could lead to increased risks of experiencing the health effects described above.

By focusing on the most susceptible populations, interventions to reduce wildfire smoke exposure are likely to achieve the greatest health benefits. In the United States, the overall population experiencing wildfire smoke will continue to increase due to projected increases in wildfires. Considering climate change projections through 2050, it is estimated that more than 82 million people will be subject to greater than a 50% increase in the frequency and an estimated 30% increase in the intensity of 'smoke waves,' or periods of high wildfire-specific $PM_{2.5}$ for two or more consecutive days (Liu et al., 2016). In California an increasing number of susceptible people will be at risk from wildfire smoke as the population over 60 is projected to increase by 81% (CA Department of Aging, 2017). Additionally, an estimated 151,000 people experienced homelessness in 2019 in California, an increase of 16% from the previous year; these individuals are at particular risk due to limited access to clean air spaces and other factors including socioeconomic vulnerabilities (HUD, 2020).

2.1.2 Addressing and mitigating potential health and safety risks associated with wildfires and air quality

As addressed in Section 2.1.1, wildfires can have significant and widespread impacts on air quality, and wildfire smoke exposure is associated with a variety of adverse health outcomes. State and local agencies have established protocols and implemented public safety campaigns to advise on ways to reduce exposure to wildfire smoke. Numerous existing and proposed public health interventions aim to reduce exposure to wildfire smoke during an air quality emergency, including air quality surveillance and public outreach; indoor air filtration, and respiratory protective equipment. Recent California policies have aimed to address wildfire smoke exposure among outdoor workers and how emergency response protocols can better serve vulnerable and diverse populations. Additionally, continued and expanded public health surveillance and epidemiological research can further improve our understanding of the impacts of wildfire smoke on human health.

Air quality surveillance and public outreach

Through spatially distributed, air monitoring networks, real-time and time-averaged air quality data are readily available to decision makers and the public, providing additional guidance for reducing exposure during periods of poor air quality related to wildfire smoke or otherwise. The Air Quality Index (AQI) is used to place air pollutant concentrations in a public health context, providing guidance for the general population, as well as sensitive receptors. AQI is designed as an indicator of potential acute health effects experienced by exposed populations within a few hours or days after breathing polluted air. The U.S. EPA calculates the AQI for the five major regulated air pollutants— ground-level ozone, PM_{10} and $PM_{2.5}$, carbon monoxide, sulfur dioxide, and nitrogen dioxide —and reports the associated health effects of concern for a given air quality threshold (AirNow, 2020; Table 2). AQI provides the current federal standard interpretation of air quality, but may not be protective enough given the limited pollutants included in AQI and uncertainties of wildfire smoke composition. Furthermore, the 24-hour measurements and multiple pollutants used to calculate AQI values may add unnecessary complexity (National Academies, 2019). This is particularly the case when seeking to understand $PM_{2.5}$, which the AQI does not report linearly. Because some researchers consider the AQI risk bins to be relatively arbitrary, it can be helpful to refer to $PM_{2.5}$ in units of micrograms per cubic meter ($\mu g/m^3$), as this is how concentrations are reported alongside associated health effects in epidemiological literature (National Academies, 2019). As discussed in Section 2.1.1, wildfire smoke composition can vary significantly based on materials combusted and other factors which are not captured by the AQI and the AQI also does not capture ultrafine particles, larger particles (e.g., heavy metals) and toxic gases (Wagner and Chen, 2019).

Despite limitations, AQI provides useful context of wildfire smoke's impact on air quality. During the Camp Fire in November 2018, the Air Quality Index (AQI) for $PM_{2.5}$ reached the "Hazardous" range in Sacramento, and "Very Unhealthy" range in the Bay Area. California regional air districts share air quality alerts regarding wildfire smoke with an AQI value (Table 2). For example, during wildfire events in recent years, the Bay Area Air Quality Management District shared frequent air quality alerts with AQI guidance via text messages over the platform, Nixle.[5]

Table 2. Air Quality Index (AQI) interpretation by range (Sourced directly from AirNow, 2020).

AQI Levels of Health Concern	Numerical value	Interpretation
Good	**0 - 50**	Air quality is considered satisfactory, and air pollution poses little or no risk.
Moderate	**51 - 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 - 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 - 300**	Health alert: everyone may experience more serious health effects.
Hazardous	**301 - 500**	Health warnings of emergency conditions. The entire population is more likely to be affected.

Note: Values above 500 are considered beyond the AQI and recommendations for the 'Hazardous' AQI category should be followed.

[5] Nixle. https://www.nixle.com/.

Regulatory, stationary air monitoring systems provide air quality information throughout the state, but at lower spatial resolution, as monitors are located far from one another and air quality can vary hyperlocally (Apte et al., 2017). Recent air monitoring efforts using low-cost air monitoring supported through AB 617 (Garcia, 2017) Community Air Grants have increased spatial coverage of air quality data in California communities (e.g., the Richmond Air Monitoring Network).[6] Air quality datasets that include both regulatory stationary air monitors and low-cost air monitors (e.g., Purple Air) provide air quality data available at more refined temporal and spatial scales. For example, AirNow — developed by the U.S. EPA, NOAA, National Park Service, and tribal, state and local agencies — provides hourly-averaged AQI using stationary regulatory monitors and temporary monitors throughout the United States.[7] AirNow also includes a spatial depiction of current fire activity throughout the United States.[8] PurpleAir, on the other hand, includes a global network of low-cost monitors that provide minute-by-minute $PM_{2.5}$ concentrations and associated AQI levels and can provide greater spatial resolution of air quality information depending on the density of these monitors in a given area.[9] AQI information from AirNow and Purple Air platforms are incorporated into additional platforms provided by state and local agencies, including regional air district webpages, and other entities such as Weather Underground.[10]

In an effort to crowdsource information through citizen science, the U.S. EPA National Health and Environmental Effects Research Laboratory developed the Smoke Sense application (National Academies, 2019). The app makes wildfire smoke and health resources easily available and is designed to emphasize the importance of changing behaviors during smoke events. In the past, epidemiology has concerned itself with overall measures such as 24-hour averaged exposures, but more recent questions are concerned with acute exposures. To this end, one aim of the Smoke Sense app is to help researchers understand the subclinical health impacts of wildfire smoke.

In sum, air quality surveillance can be used to inform real-time public health interventions and decision-making regarding wildfire smoke exposure, and retrospective exposure assessment and epidemiological investigations.

Indoor air filtration and clean air spaces

Air filtration can be used in enclosed spaces to remove particles and other air pollutants from indoor air, thus reducing inhalation exposure to air pollutants. Filtration is most effective in well-sealed spaces (Elliott et al., 2014). Filtration generally involves a centralized air filtration system or portable air filters which largely rely on physical filters to remove particles from indoor air. Air filtration systems and portable air filters that use high-efficiency particulate air

[6] Richmond Air Monitoring Network. https://www.psehealthyenergy.org/our-work/richmond/.

[7] AirNow. https://www.airnow.gov/.

[8] AirNow - Wildfires. https://airnow.gov/index.cfm?action=topics.smoke_wildfires.

[9] PurpleAir. https://www2.purpleair.com/.

[10] Weather Underground. www.wunderground.com.

(HEPA) filters have been shown to reduce residential $PM_{2.5}$ and exposure to wildfire smoke (Barn et al., 2016). In a case study of public health interventions during a 1999 wildfire near the Hoopa Valley National Indian Reservation in northwest California, researchers found that HEPA cleaners were effective approaches to reducing reported respiratory symptoms during periods of high wildfire smoke. The odds that those with HEPA cleaners reported respiratory symptoms was nearly half of those without HEPA air cleaners (Mott, 2002). CARB certifies all portable indoor air cleaners sold in California, and provides a list of approved air cleaners on their website (CARB, 2020a).

Public facilities equipped with centralized air filtration systems can provide access to cleaner air to a greater number of individuals in areas with wildfire smoke. In the San Francisco Bay Area, the San Francisco Museum of Modern Art, as well as several other museums, offered free admission when smoke from the Camp Fire caused unhealthy air quality in 2018, and again during the Kincade Fire in 2019 (Wells, 2019). Other types of facilities typically featured as clean air shelters are public libraries, senior centers, movie theaters and malls. During the Camp Fire, the San Francisco Department of Emergency Management maintained a designated website to display a map of locations with clean air (Ioannou, 2018).

Considerations that should be made when determining policy about clean air shelters include the duration of shelters' availability for public use, the effectiveness of the heating, ventilation and air conditioning (HVAC) system, and the ability of buildings to accommodate high efficiency filters. However, clean air shelters are not a solution that addresses the 24-hour exposures of residents, who may live in older, poorly insulated homes, or have to travel through wildfire smoke to reach the community spaces. For longer and more severe smoke events, creating policies that promote clean air spaces within the home may have greater benefits than clean air shelters. At the national level, U.S. Senators Ron Wyden and Jeff Merkley, both from Oregon, have introduced legislation that would provide federal funding to assist communities experiencing air quality emergencies, allowing state and local governments to access resources for wildfire smoke mitigation efforts, resiliency assistance, smoke shelters, air purifiers and additional air monitoring sites (Merkley, 2019a; 2019b). In California, Assembly Bill 836 (AB 836; Wicks, 2019) established a program for retrofits of air ventilation systems to create community clean air centers, prioritizing areas with high cumulative smoke exposure burden.

Respiratory protective equipment

Respirators are types of personal protective equipment used to protect an individual against the inhalation of hazardous substances. Unlike surgical masks, respirators are designed to create a complete seal between the outdoor air and the personal breathing zone to effectively filter particles and, in some cases, gases. N95 masks are commonly used in construction and industrial settings and may be recommended to certain individuals to reduce wildfire smoke exposure. When properly fitted and used, N95 masks filter out at least 95 percent of small particles (≥0.3 microns) (FDA, 2020). While certain individuals may be advised to wear N95 masks during poor air quality events such as wildfire smoke, there are numerous additional variables necessary to consider for the general public. For instance, N95 masks may not be able to be properly fitted for children or individuals with facial hair (Hodenfield, 2018; FDA, 2020). Generally, other ways to reduce exposure (e.g., limiting time outdoors and reducing activity) are recommended before using a respirator (CARB, 2020b).

There is still controversy about the effectiveness of respirators during periods of poor air quality, as respirators may not be helpful for all populations (e.g., those with reduced respiratory function) and as respirator masks can easily be used incorrectly. It has been argued that debates about respirator safety are based on incorrect information, and that for most people there is no increased risk from wearing respirators because the work of breathing does not increase substantially (National Academies, 2019). In a case study of public health interventions in response to a wildfire near the Hoopa Valley National Indian Reservation in northwest California, the researchers found evidence that use of N95 masks was not associated with reduced reports of respiratory symptoms; rather, mask use was associated with outdoor exposure, likely a result of inconsistent use and improper fit (Mott, 2002). However, other studies have indicated that individuals who used face masks during wildfires or severe air pollution episodes reported experiencing fewer respiratory symptoms (Kunii et al., 2002; Künzli et al., 2006). A respirator education program may increase the effectiveness of respirators. Education campaigns could include information about who should use respirators and how to wear them (Sbihi, 2014). Additionally, only widespread proper mask use would successfully prevent a small number of acute healthcare events. For example, one estimate determined that 370,000 people would need to wear masks to prevent one health event; and for those without preexisting cardiopulmonary diseases, 1 million people would have to wear N95 masks to prevent one health event (National Academies, 2019).

Worker protection from wildfire smoke

Outdoor workers are at greater risk of exposure to wildfire smoke. Following recent wildfire events where outdoor workers, such as agricultural workers, were observed in heavy wildfire smoke conditions (Paquette, 2018), additional occupational health-protective policies have been implemented. In July 2019, the California Division of Occupational Safety and Health (Cal/OSHA) issued an emergency regulation (§5141.1) to outline specific worker protections from wildfire smoke when AQI for $PM_{2.5}$ is 151 or greater (i.e., Unhealthy; see Table 2) (Cal/OSHA, 2019). The emergency regulation makes California the first state to set a safety standard for workers exposed to wildfire smoke (Paluch, 2019). Section 5141.1 requires employers to: (1) identify harmful exposures related to wildfire smoke using AQI forecasts and/or measuring $PM_{2.5}$ at the worksite; (2) communicate information about these exposures and protective measures that employees can take; (3) provide trainings and instruction about health effects associated with wildfire smoke and methods to protect employees from wildfire smoke; and (4) control harmful exposures related to wildfire smoke through measures including evacuation, engineering controls (e.g., air filtration), administrative controls (relocating worksite or adjusting work schedules), and the provision of respiratory protective equipment, such as N95 masks (Cal/OSHA, 2019). The emergency regulation is effective through September

22, 2020, an expiration date which has been extended several times as Cal/OSHA works to make the regulation permanent.[11]

Emergency response planning for vulnerable populations during wildfire smoke events

As described in Table 1, specific populations are more susceptible to the adverse health impacts associated with wildfire smoke exposure than others based on factors such as lifestage and socioeconomic vulnerabilities. *Ad hoc* initiatives have occurred during past episodes of poor air quality due to wildfire smoke. For example, in Oakland, shelter beds were available at the city's year-round shelter, St. Vincent de Paul, during the air quality emergency resulting from the Camp Fire. This information was featured on the City of Oakland website and through Alameda County Health Care for the Homeless (HCH)[12], which provides a list of local centers for accessing cleaner air indoors during the day. During the Camp Fire, over 5,500 N95 respirators provided by the City of Oakland were distributed through a network of city and community partners, including HCH which distributed masks to informal encampment sites (City of Oakland, 2018).

Following the 2018 record-breaking wildfire season, numerous Bay Area stakeholders developed the Bay Area Regional Air Quality Messaging Toolkit,[13] including individuals from the Bay Area Regional Air Quality Messaging Steering Committee, the Bay Area Joint Information System, the Association of Bay Area Health Officials (ABAHO), the Bay Area Air Quality Management District (BAAQMD), and regional public health, emergency and local government staff. The toolkit, released in October 2019, includes guidance for the public on preparedness actions prior to and during air quality events and includes information on available community resources. As a result of ample coordination between local organizations and agencies, the toolkit includes information about air quality messaging, including templates in six languages and guidance for communicating with hard-to-reach populations, including immigrant populations, people with disabilities, and people with limited English proficiency. In addition, San Francisco Department of Public Health (SF DPH) works to develop and maintain relationships with various local community-based organizations to help identify vulnerable individuals that may require wellness checks during emergency events, such as days with high heat and poor air quality.[14] Additionally, CDPH developed a guidance document for California public health officials regarding wildfire smoke.[15,16]

[11] California Department of Industrial Relations. Protection from Wildfire Smoke - Rulemaking Documents. https://www.dir.ca.gov/oshsb/Protection-from-Wildfire-Smoke-Emergency.html.

[12] Alameda County Health Care for the Homeless. www.achch.org.

[13] Bay Area Regional Air Quality Messaging Toolkit. http://www.bayareauasi.org/aqi.

[14] Personal communication with San Francisco Department of Public Health (SF DPH). January 14, 2020.

[15] Wildfire Smoke: Considerations for California's Public Health Officials. https://www.cdph.ca.gov/Programs/EPO/CDPH%20Document%20Library/Wildfire%20Smoke%20Considerations%20for%20California's%20Public%20Health%20Officials%20(August%202019)_508.pdf#search=wildfire%20smoke%20public%20health%20guidance%20document.

[16] Personal communication with California Department of Public Health (CDPH). April 8, 2020.

Recent legislation has prompted the considered development of emergency response planning for wildfire smoke events. Assembly Bill 661 (AB 661; McCarty, 2019) requires the Sacramento Metropolitan Air Quality Management District to prepare a wildfire smoke air pollution emergency plan to serve as an informational source for local agencies and the public during an air pollution emergency caused by wildfire smoke (McCarty, 2019). Policies for equitable emergency response to wildfires (beyond poor air quality interventions) are discussed below in Box 1.

Coordinated health surveillance during wildfire smoke events

A surveillance system is beneficial for quantifying the magnitude of health effects resulting from wildfires and guiding adequate public health interventions. Linking air quality data to health monitoring data would create an essential dataset for establishing thresholds of public health response and subsequent evaluation of interventions (Morrison et al., 2014). The Center for Disease Control (CDC) National Syndromic Surveillance Program maintains the nationwide syndromic surveillance data, which includes patient encounter data from emergency departments, urgent care, ambulatory care, and inpatient healthcare settings, as well as pharmacy and laboratory data (Pfister, 2019). These data can be used in combination with other data (e.g., environmental monitoring), to identify unusual activity or, retrospectively, to examine health effects during specific events, such as wildfire smoke days. For example, in response to the Camp Fire in 2018, the San Mateo County Health department relied on syndromic surveillance to determine the potential scale of health impacts associated with wildfire smoke exposure (Pfister, 2019).

Box 1. Equitable wildfire emergency planning and response

Given the diversity of California's population across race, ethnicity, gender, income, age, language, disability, and citizenship effective wildfire emergency response operates through an equity-oriented lens. Given that an estimated 9% of households in California speak limited English, wildfire emergency communications should be translated into multiple languages. A challenge in translating emergency communications is having sufficient time and staff during an emergency as up-to-date information quickly changes (National Academies, 2019). During the Thomas Fire that affected parts of Ventura and Santa Barbara counties in 2017, it took ten days for the counties to translate information into Spanish. It then became the burden of a community-based organization, the Mixteco/Indigena Community Organizing Project, to translate information into indigenous languages spoken by migrants from southern Mexico and Guatemala.

The impacts from natural disasters can compound existing inequities, so comprehensive disaster planning should address equity concerns to build preparedness and resilience (National Academies, 2019). For instance, some resources for wildfire recovery are restricted by citizenship status. Resources through FEMA require social security numbers, and some philanthropic groups have restrictive documentation requirements, thus exacerbating underlying vulnerabilities faced by undocumented immigrants impacted by wildfires. Following the Tubbs Fire in 2017, community-based organizations supporting immigrant groups in Sonoma County recognized resource restrictions and created "UndocuFund," a resource dedicated to the undocumented community (National Academies, 2019).

Income inequality impacts the ability of households to evacuate and recover from a wildfire. In the case of a proximate wildfire causing smoky conditions but not directly threatening a home or life, low-income households may not have the financial means to transport themselves away from the evacuation zone or stay somewhere outside their own home, leaving these households exposed to wildfire smoke. Similarly, low-income households who lose a home in a wildfire have fewer means with which to recover, whether that means renting a home in their wildfire-afflicted community where rents may have increased due to a decrease in housing stock, or meeting needs not covered by insurance (if they have insurance). Acknowledging the web of vulnerabilities that currently exist in communities is central to achieving the equitable wildfire emergency response measures suggested here, as well as promoting community resilience following any type of disaster. Future wildfire response that establishes clean air spaces and cooling centers should make equity foundational to this resource network.

Recent legislative efforts aim to address equity in wildfire emergency planning and response. AB 1877 (Limón, 2018) establishes greater language access for emergency information by requiring the Office of Emergency Services to create a library of translated emergency notifications and a translation style guide. AB 1877 also requires designated alerting authorities to consider using the library and translation style guide when issuing emergency notifications to the public. SB 160 (Jackson, 2019) requires a county to integrate cultural competence into its emergency plan, and to engage with culturally diverse communities in the process.

2.1.3 Wildfires, air quality, and human health: research gaps and limitations

There are numerous challenges related to the evaluation of health risks and impacts associated with wildfire smoke exposure, including accurately characterizing and estimating wildfire smoke exposure, getting access to data on various health outcomes in the exposed population, as well as implementing and evaluating the effectiveness of public health interventions. Through review of materials featured in this report, we identify and discuss research gaps in assessing health risks and impacts associated with wildfire smoke exposure.

Characterization and estimation of wildfire smoke exposure

Challenges in exposure assessment introduce challenges to assess a dose-response relationship between wildfire smoke exposure and specific health outcomes. These challenges primarily include uncertainties regarding the composition of wildfire smoke and the distribution and atmospheric transport of smoke plumes across geographic space.

Most studies that evaluate air quality and health impacts during wildfires estimate smoke exposure through proxies, such as quantifying the number of days that smoke is present, or using local or regional air quality monitoring for $PM_{2.5}$. It should be noted that some studies have found evidence that PM in wildfire smoke impacts human health differently than non-wildfire PM (Wagner and Chen, 2019).

While numerous studies observe associations between exposure to $PM_{2.5}$ in wildfire smoke and the development of various adverse health outcomes, the limited research on the concentrations and atmospheric transport of other chemical constituents in wildfire smoke (e.g., hazardous air pollutants and toxic air contaminants) introduces challenges when evaluating the full scale of health hazards, risks and impacts of wildfire smoke. What is known about the composition is that wildfire smoke contains volatile organic compounds, polycyclic aromatic hydrocarbons, and ultrafine particulate matter, and that ozone forms downwind from the precursor constituents present in wildfire smoke. It is also known that a range of toxic chemicals are emitted when household items, residential and commercial structures, cars, and other infrastructure of the built environment burn. Emissions can include asbestos, heavy metals, and chemically or biologically hazardous materials.

To address the unknowns regarding emissions of chemical constituents other than $PM_{2.5}$, air quality monitoring could include chemical speciation of the samples using EPA TO-15 via GC/MS or other approaches. Additionally, epidemiological studies could include evaluations of cumulative or multiple-pollutant exposures, rather than individual compounds ($PM_{2.5}$) to better evaluate risk and impact.

Variables such as fire intensity, smoke plume rise, and the type of materials burned can influence the profile of wildfire emissions (Sever, 2020). The unpredictable nature of these variables makes it difficult to anticipate and assess emissions from wildfires in ways that inform human health risk assessment and communication. For instance, a fire's intensity is driven by fluctuating conditions such as incomplete combustion and the amount of fuel burned. When a wildfire smoke plume moves through an area, it does not affect all portions of that area equally; smoke plumes are usually not well mixed and exposure can vary. For example, under a plume, exposure can be very high, while nearby it is much lower. Factors such as fire temperature and smoke plume injection heights also influence the amount of air pollution emitted from fires.

Denser air quality monitoring networks, with higher spatial and temporal resolution, may allow for better estimation of exposure to $PM_{2.5}$ and other pollutants during wildfire smoke events. In certain settings, the targeted distribution of personal monitors to individuals may also help more accurately measure wildfire smoke exposure in select geographic areas and among select populations. Improved air quality surveillance on geographic and air pollution composition bases could also be used to communicate and manage risk, in particular for vulnerable populations (Stares et al., 2014). A current challenge to air monitoring and assessment is that wildfires frequently occur in more rural geographies which, compared to urban areas, typically lack comprehensive air pollution monitoring networks (Reid, 2016). To address this challenge, air quality surveillance should be increased in areas with limited monitors and that are prone to wildfires.

Health outcomes associated with wildfire smoke exposure

The peer-reviewed literature suggests that adverse health outcomes associated with exposure to wildfire smoke primarily include respiratory outcomes, birth outcomes, and premature mortality. As outlined in Figure 3 (Adapted from Cascio, 2018), data on deaths, hospitalizations, and visits to emergency departments, urgent care, and physicians may be the more accessible information to obtain on health outcomes during wildfire smoke events. However, these metrics do not represent the total public health impact of wildfire smoke exposure, which also includes subclinical or asymptomatic effects (e.g., reduced lung function or heart rate variability) and respiratory or cardiovascular outcomes that do not require further medical assistance.

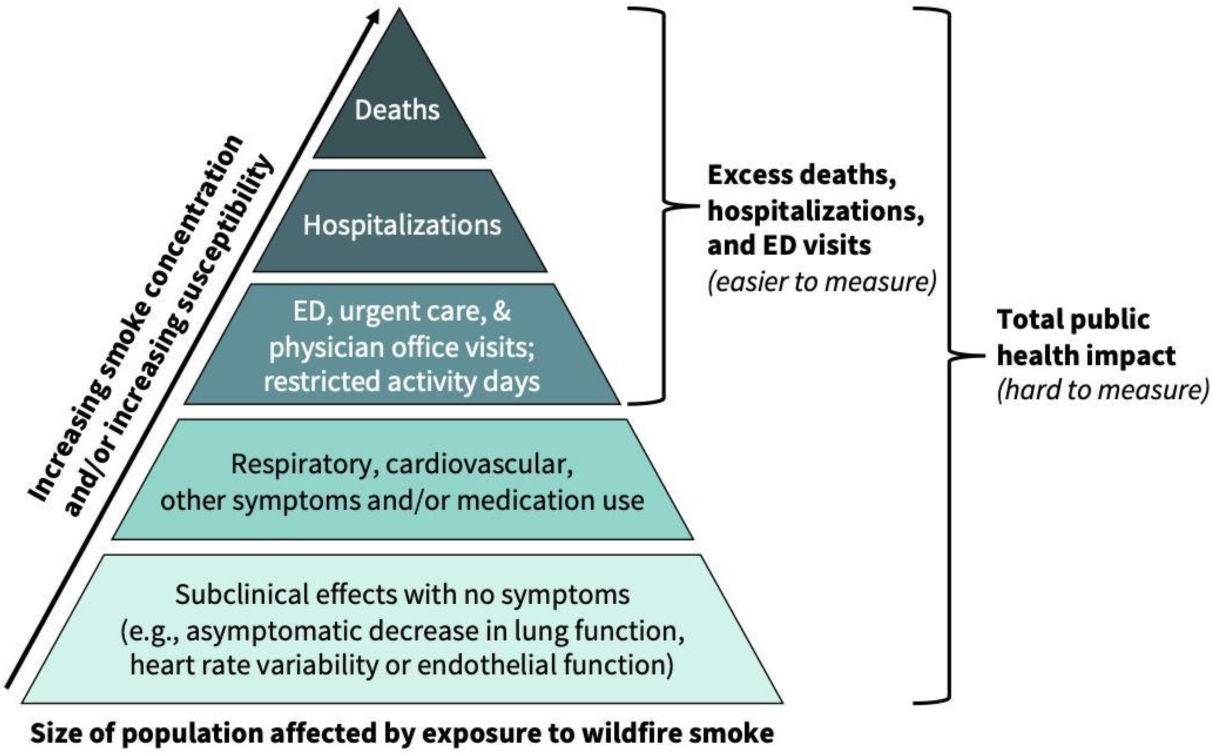


Figure 3. Public health impacts of wildfire smoke or $PM_{2.5}$ exposure (Adapted from Cascio, 2018). *ED - emergency department.*

Numerous understudied health endpoints related to wildfire smoke exposure include metabolic disorders, pediatric cognitive and motor development, cognitive decline, and maternal health (National Academies, 2019). Nevertheless, the literature on $PM_{2.5}$ exposure can be leveraged to understand potential health impacts associated with wildfire smoke exposure that have yet to be addressed directly in the literature. Additional research on mental health outcomes following California wildfires is also warranted. Further, findings differ across studies regarding the impact of wildfire smoke on cardiovascular disease and further investigation is needed to better elucidate the potential exposure-response relationship regarding cardiovascular outcomes.

The duration of exposure is also key to consider when assessing the relationship between a given pollutant and a health outcome. Whereas immediate or acute health impacts associated with wildfire smoke exposure may be well characterized, studies typically do not address the potential long-term health impacts of repeated exposures to wildfires or disease that occurs after a long latency period following a single or multiple exposure events. This may also be applicable in communities that experience frequent prescribed burns. One challenge in determining evidence of chronic health outcomes is that endpoints, such as cancer, have longer latency periods. Another constraint is the extensive financial and time requirements to conduct long-term surveillance of populations exposed to wildfire smoke.

Given the known vulnerability and susceptibility of particular populations to wildfire smoke exposure, targeted research could further evaluate the health impacts for these population subsets to better inform public health interventions.

Furthermore, there may be significant influence of additional confounders or effect modifiers, such as stress, on the relationship between wildfire smoke exposure and various health outcomes. Additionally, wildfires occur during parts of the year with elevated temperatures which are associated with various adverse health outcomes, including, but not limited to heat stress. Finally, climate change introduces compounding risks of heat and wildfire smoke events. As such, these heat and wildfire exposures should be evaluated and mitigated together.

Public health interventions to mitigate wildfire smoke exposure

Ultimately, research evaluating health impacts associated with wildfire smoke exposure can be used to inform the development of or promote existing policies aimed at reducing wildfire smoke exposure. Given known vulnerabilities of particular population subsets, these public health interventions can be targeted and their effectiveness evaluated. For instance, outdoor workers may be a prime population to evaluate effectiveness of certain interventions such as N95 respirator masks.

Another area that merits further study is risk communication. While the California public has become accustomed to interpreting the AQI in a health context during severe wildfires in recent years, the ways in which the public receives information about air quality and health risk are still unclear. Future initiatives may include applying models used in other parts of the country, such as the Smoke Sense app developed by the U.S. EPA. Studies could also examine the reach and effectiveness of translated materials among non-English speaking populations.

Wildfire smoke events may also be accompanied during high heat days, compounding risks for particularly vulnerable individuals. These climate-related exposures should be considered and interventions should be developed that address the potential for both of these exposures to occur in tandem (e.g. clean air community spaces with centralized cooling).

Additionally, there are unknowns about the implementation costs and best approaches for using portable filtration, such as how to plan filtration capacity in HVAC systems to create conditions for clean air shelters (Keefe et al., 2014). Research is needed to determine best practices for establishing clean air shelters, as the mitigating effects of clean air shelters on acute respiratory health is understudied (National Academies, 2019). Research is also needed to elucidate how clean air community spaces can alleviate the cumulative impacts from wildfires that occur during warmer months when heat waves are more likely. The multiple stressors of high heat, poor air quality, and lack of electricity may lead to negative health impacts, particularly for vulnerable populations.

2.2 Wildfires, water quality and health

In this section, we discuss wildfire impacts on watersheds, drinking water quality and drinking water systems in the context of ecological and public health (Section 2.2.1). Wildfire-related impacts on water include polluted source water, impaired water treatment infrastructure, reduced water treatment capabilities and contaminated water distribution infrastructure. Policies aimed to reduce health risks associated with wildfire-related water quality impacts (Section 2.2.2) and research gaps and limitations are also discussed (Section 2.2.3).

2.2.1 Wildfires and water quality: implications for public health

Wildfire impacts on watersheds and surface water

In the United States, approximately 80 percent of freshwater resources originate in forested land (US Forest Service, 2006). Approximately one-third of the State of California is forested, including the majority of watersheds that serve as originating water sources for millions of Californians (California Legislative Analyst's Office, 2018). Forested landscapes affected by wildfire include watersheds that support local ecosystems and provide water used for agricultural, municipal, and domestic purposes. Figure 4 below illustrates the extent to which California's surface waters are adjacent to, originate in, or traverse land with high fire risk, much of which is forested. This is particularly true throughout Northern California and in the Sierra Nevada. These regions serve important roles in California's water system, with 75% of the State's precipitation occurring in watersheds north of Sacramento and 60% of the State's water supply originating in the Sierra Nevada (Department of Water Resources, 2020; Sierra Nevada Conservancy, 2020).

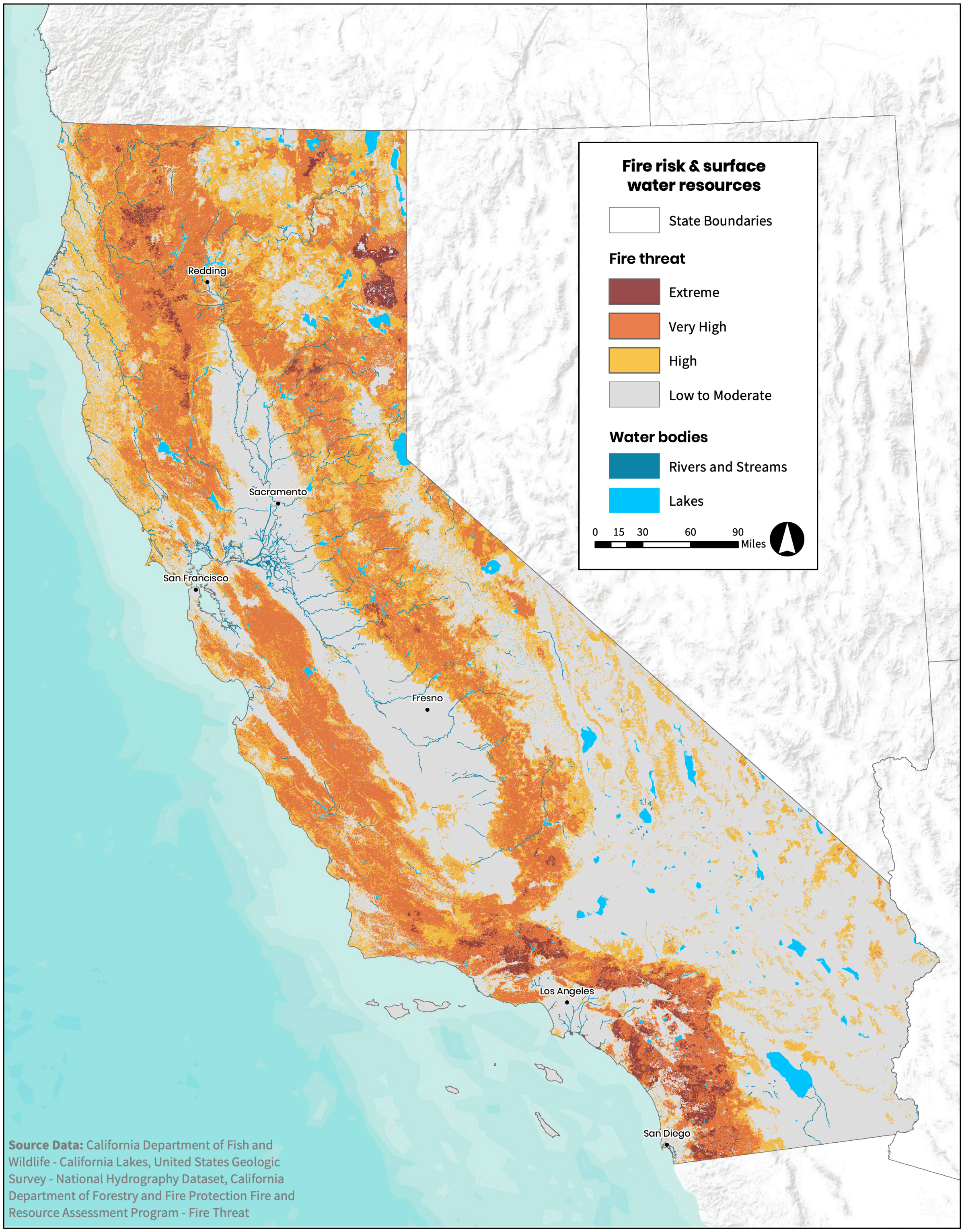


Figure 4. Fire risk and surface water resources in California.

Localized wildfire impacts on watersheds include loss of vegetation and soil burn, which can increase runoff and reduce the ability of water to infiltrate soils and recharge underlying groundwater sources (US Forest Service, 2011a). Following wildfires and subsequent rainfall events, small streams and tributaries may experience very high and sudden flows. Increased runoff can impact surface freshwater resources by causing changes to annual river flows; increasing flows post-wildfire have been observed in western states with warmer temperatures and humid climates as well as in drought-prone semi-arid regions (Hallema et al., 2018). Furthermore, wildfire smoke can reduce surface water temperature which may impact aquatic ecosystems and specific aquatic species (David et al., 2018).

In areas impacted by wildfires, burned wildland vegetation can contribute additional nutrients (nitrogen and phosphorus), organic carbon and carbon combustion products, and agricultural chemicals to surface water systems. Additionally, burned structures such as buildings, homes and other infrastructure, can introduce various contaminants to surface water, including heavy metals (lead, aluminum, mercury, arsenic) and organic carbon and carbon combustion byproducts. Ash produced from wildfires further contributes to pH changes in water and increases overall sediment loads and turbidity (Macler, 2019). Increases in sediment load may impact ecological health by overwhelming habitat for aquatic organisms and other organisms that rely on surface water for reproduction or early life (e.g., insects, amphibians). Furthermore, altered nutrient loads in surface water may cause species changes in localized aquatic ecosystems (USGS, 2018).

Wildfire impacts on drinking water systems and water treatment

In the United States, approximately 180 million people in over 68,000 communities rely on forested lands to capture and filter their drinking water (US Forest Service, 2019). Wildfires increase watershed susceptibility to flooding and erosion, which then can impair water supplies. Notably, wildfires can impact water quality both during active burning (e.g. ash settling at the surface of reservoirs), and from storm events for months and years after a fire has been contained (USGS, 2018; Hohner et al., 2019).

Wildfires can adversely impact drinking water through various pathways. Reservoirs, infiltration basins and treatment facilities may be filled, damaged or impaired by sudden increases in sediment loads from rainfall and snow melt following wildfire events. Elevated sediment loads can increase pre-treatment filtration and processing needs and costs for removing suspended sediments such as soil and ash. Wildfires may also contribute toxic metals and organics to water supplies used for drinking water, which may lead to drinking water standard (e.g., maximum contaminant level, MCL) violations. Increased algal growth and algal organic matter also increase the needs for filtration and pH adjustment, and may impact the taste and odor of drinking water (Macler, 2019). Increased organic carbon loads requires increased coagulation and chlorine demand and may expedite membrane fouling (Cawley et al., 2018). Water quality impacts are most significant in areas immediately adjacent to fires, but in some cases can be widespread. For example, after the 2003 wildfires in Southern California, treatment works and reservoirs as far as 100 miles from the fire were affected by the increase in suspended sediment loads (SAWPA, 2003).

Elevated levels of organic matter in drinking water sources post-wildfire can also lead to the increased formation of toxic water disinfection byproducts (DBPs) (Cawley et al., 2018), which form when disinfectants (e.g., chlorine) react with organic matter. Numerous studies have found increased concentrations of DBP precursors (e.g., dissolved organic matter) in source water intakes post-wildfire (Wang et al., 2015; Wang et al., 2016; Cawley et al., 2018; Hohner et al., 2019). Additionally, increases in concentrations of both regulated and unregulated DBPs have been observed in treated waters post-wildfire (Hohner et al., 2019).

California wildfires resulting in VOC-contaminated drinking water systems

Severe wildfires in close proximity to water systems also may cause severe damage to water distribution infrastructure. Recent California wildfires — the 2017 Tubbs Fire in Sonoma and Napa County and the 2018 Camp Fire in Butte County — resulted in compromised drinking water systems in affected communities due to volatile organic compound (VOC) contamination. Individuals may be exposed to VOCs in potable water via ingestion of water or inhalation during cooking and/or showering.

Wildfire-driven VOC contamination of water distribution systems is an evolving area of research. VOC contamination of water systems can result in concentrations of hazardous compounds that exceed health-based drinking water standards. One of the most common VOCs found in wildfire-contaminated water systems, benzene, is a known human carcinogen and reproductive and developmental toxicant that is regulated by numerous federal and state agencies in air and water. Two primary mechanisms considered for post-wildfire VOC contamination in distribution systems include 1) the leaching of burned of water distribution infrastructure or other materials that come in direct contact with water in the distribution system, and 2) as water distribution systems are depressurized to support fire-fighting activities, gaseous VOCs produced from burned biomass and structural materials (including water distribution-related infrastructure, i.e. piping) may be drawn into the water distribution system. VOCs may adsorb onto or absorb into the walls of water distribution system pipes and then desorb or leach from the pipes over time (Paradise Irrigation District, 2019). A recent investigation of VOC emissions from polyvinyl chloride (PVC) pipes indicated that benzene and other VOCs were detected at health-relevant concentrations in the combustion emissions, but were minimally detected or went undetected in water leachate, supporting the theory that gaseous VOCs, from burned PVC or other emission sources (e.g., biomass) may contribute to post-wildfire VOC contamination in water distributions in recent California wildfires (Chong et al., 2019).

The 2017 Tubbs Fire resulted in 36,807 acres burned, 5,638 structures destroyed and 22 deaths (CAL FIRE, 2020b). In the impacted City of Santa Rosa, benzene was detected for the first time in the Santa Rosa Water system and contamination was isolated in the Fountaingrove neighborhood, where 13 of approximately 350 homes remained after the Tubbs Fire (City of

Santa Rosa, 2018a; City of Santa Rosa, 2020). In a post-fire water quality investigation at various points throughout the distribution system underlying the affected Fountaingrove neighborhood, benzene was detected at upwards of 500 parts per billion, 500-times higher than the California health-based regulatory drinking water standard (maximum contaminant level, MCL) of 1 ppb. Methylene chloride was also detected at concentrations exceeding the MCL in the Santa Rosa water distribution system after the Tubbs Fire (Whelton, 2019).

At a much larger scale of destruction, the 2018 Camp Fire burned 90 percent of structures in Paradise, California, significantly impacting water distribution infrastructure and more than 2,400 private wells (National Academies, 2019). One year following the Camp Fire in Paradise, California, benzene contamination still lingers in the water supply (Peterson, 2019). As of April 2019, Paradise Irrigation District officials reported they had collected 500 water samples and detected benzene concentrations in one-third of samples. The average detected benzene concentration was 31 ppb with the highest concentration observed being 923 ppb, significantly exceeding the benzene MCL of 1 ppb. In some cases, other VOCs have been detected in Paradise water post-fire in the absence of benzene (Whelton, 2019). For example, methylene chloride, another known human carcinogen, was detected in tap water samples at levels exceeding the MCL (Whelton, 2019). It is not known if these compounds are associated specifically with the Camp Fire, and limited testing of these additional VOC compounds raises questions about the level of contamination and the focus on benzene as the primary contaminant of concern (Whelton, 2019). It will take an estimated two years and $300 million to restore drinking water quality for Paradise residents (Bizjak, 2019). Ongoing investigations aim to accurately determine the mechanism for water contamination in Paradise and to develop strategies to improve water quality (PHI, 2019). Remediation and recovery efforts related to these two cases of VOC contamination of California water distribution infrastructure are discussed further in Section 2.2.2.

2.2.2 Addressing potential health and safety risks associated with wildfires and water quality

To mitigate the impacts of wildfire on watersheds, state and local agencies have taken protective actions. To minimize impacts to rivers, streams, and aquifers, the State's Debris Task Force and its Debris Management Team (DMT) use erosion controls and silt collection devices on fire damaged properties (Los Angeles County Department of Public Works, 2019). Another watershed concern following wildfire is the presence of animal carcasses, increasing risks of exposures to waterborne pathogens. The State Water Resources Control Board and Regional Water Quality Control Boards address this concern by recommending disposal of carcasses through rendering, cremation or disposal in a permitted landfill (SWRCB, 2003). Additional information on debris and hazardous waste removal is discussed below in Section 2.3.

In the event that drinking water is contaminated or a fire has damaged potable water distribution, wastewater and sewage treatment infrastructure, local officials may take various steps depending on the severity of the damage. Recent cases of water system contamination following California wildfires are discussed in Section 2.2.1. Following the 2017 Tubbs Fire in the affected City of Santa Rosa, Santa Rosa Water conducted initial water testing throughout the water distribution system to identify chemical contaminants of concern. Upon detection of benzene, Santa Rosa implemented a do-not-drink and do-not-boil water advisory in the Fountaingrove neighborhood to protect public health (City of Santa Rosa, 2018a). These water quality advisories considered the potential volatilization of benzene and other volatile compounds with low boiling points and high vapor pressure during boiling and showering. Over 7,000 water quality samples were collected and tested to identify the sources of chemical contamination within the system. In certain cases, contaminated water service infrastructure including hydrants, blow-off valves, and water mains was removed and replaced at an approximate cost of $8 million (City of Santa Rosa, 2018b). The water quality advisories were lifted approximately one year following the Tubbs Fire.

Following the Camp Fire in Paradise, the water distribution system had been contaminated, extensively damaged and drained (Paradise Irrigation District, 2019). In response, the Paradise Irrigation District repressurized the systems, repaired leaks, and began water quality testing. When initial testing showed VOC contamination, the district issued a “do not drink” advisory. During testing and repair, the district provides a temporary customer supply of non-potable water. To return the system to full operating capacity, the irrigation district developed a Water System Recovery Plan.[17] As of September 2019, the Paradise Irrigation District stated that 70 percent of mains and hundreds of service connections were cleared of VOC contamination (Peterson, 2019). However, a large proportion of service laterals serving homes and businesses that have burned have fire-related VOC contamination (Paradise Irrigation District, 2019). Given the extent of the damage and contamination, further testing, decontamination and research are underway.

2.2.3 Wildfires, water quality and health: research gaps and limitations

While recent record-breaking wildfires have offered opportunities for increased understanding and data collection related to water quality impacts associated with wildfires, there are many areas that require further research and investigation. Publicly available datasets on water sources and water systems in the State of California do not allow for connectivity. Therefore, it is difficult to identify water sources and systems at risk of impairment from wildfires. Identification of small, single source water systems in high wildfire risk areas is key to improve the resilience of these systems in the case of wildfire impacts, by sharing guidance on best practices and/or by directly providing resources to support watersheds and water treatment.

Additionally, numerous disinfection byproducts can form upon treatment of water sources that have been contaminated by wildfire-related debris and sediment. While some disinfection byproducts are noted for their toxicological properties that pose risks to human health, many

[17] Paradise Irrigation District. Draft Water System Recovery Plan. April 12, 2019. https://pidwater.com/docs/district-operations/capital-projects/camp-fire-recovery/1623-draft-water-system-recovery-plan/file.

additional unregulated and regulated disinfection byproducts do not have well elucidated toxicological profiles. Further research is needed to identify disinfection byproducts resulting from treatment of wildfire-impacted water sources, and the toxicity of these compounds for aquatic species and potential impacts to human health.

As discussed above, recent California wildfires have resulted in significant contamination in water distribution systems, most recently in Paradise, California. The mechanism(s) that cause VOC contamination of these local water distribution systems is currently under evaluation, and may provide insight for other water distribution systems in the future to mitigate contamination associated with wildfire events. More research is needed regarding more resilient water distribution systems, such as those that may allow for isolating contamination or contain materials that allow for easier decontamination of distribution components. Additionally, further research and formalization is needed to guide future investigations into wildfire-associated VOC contamination of water distributions systems. These efforts could include formalized protocols for testing data reproducibility, the development of best practices, and standard operating procedures to provide guidance on how samples should be collected, stored, and tested from various points in the distribution systems (e.g., hydrant to tap) (National Academics, 2019). Finally, further research is needed to determine the best ways to handle and dispose of contaminated materials (e.g., contaminated water, contaminated water distribution infrastructure) to inform wildfire recovery efforts.

2.3 Wildfires, soil, crops and health

In this section, we discuss wildfire impacts on soil health, soil destabilization, and agricultural crops in the context of ecological and public health. Wildfires can impair soil health, destabilize landscapes increasing the risk of debris flows, and impact crops and soils used to grow crops for human consumption (Section 2.3.1). Policies to address health hazards and risks posed by wildfire-related impacts on soils and crops (Section 2.3.2) and research gaps and limitations are discussed (Section 2.3.3).

2.3.1 Wildfires, soil and crops: implications for public health

Soil health and soil destabilization

Soils supply air, water, nutrients and mechanical support for the sustenance of plants, including agricultural crops. Soils burned during wildfires can have reduced infiltration capacity (i.e., water absorption) and repel rather than absorb water. When the infiltration capacity of the soil is exceeded, organic and inorganic soil materials are eroded and become major sources of sediment, nutrients and pollutants in surface waters (Larson-Nash et al., 2018). Wildfire impacts on soils depend on a variety of factors including, but not limited to, soil composition and wildfire intensity and severity (Neary et al., 2005).

After a wildfire, charred soils may contain a variety of compounds hazardous to human health. Burned soils post-wildfire can contain various polycyclic aromatic hydrocarbons (PAHs), many of which are toxic, persistent in the environment, and bioaccumulative (Chen et al., 2018). Additionally, mercury is stored naturally in vegetation and soils and can be released during wildfires (Burke et al., 2010); exposure to small concentrations of mercury can cause serious health effects on the nervous, digestive and immune systems; on lungs, kidneys, skin and eyes; and during fetal development *in utero* (WHO, 2017). Compared to average soils in the United States, samples of soil and ash from wildfire activity in residential areas contained elevated concentrations of various metals, including arsenic, lead, antimony, copper, zinc and chromium (Plumlee et al., 2007). Due to increased runoff potential, these heavy metals, PAHs and other hazardous constituents in soils can be transported into rivers or reservoirs where they can impact the food web and drinking water.

Wildfire impacts to soils can also result in significant threats to physical safety and infrastructure. By reducing infiltration and destroying plants with root structures that stabilize soil, wildfire-affected landscapes can become destabilized, increasing the susceptibility of steep slopes to debris flow. After the Thomas Fire in Montecito, California, rainfall and runoff triggered a massive debris flow that resulted in 23 fatalities, at least 167 injuries and 408 damaged homes.

Soil and agricultural crops

Additionally, wildfires may damage soils that support agricultural crops at various scales, from large farm operations to community gardens and backyard garden plots. California is the largest agricultural producer in the United States, supplying over a third of vegetables and two-thirds of fruits and nuts grown in the United States (CDFA, 2018). Recent wildfires have affected agricultural areas, particularly vineyards and grazing pastures (Hirtzer and Munshi, 2019; Kell, 2019). While crops for human consumption may be damaged or destroyed as a direct result or wildfire, wildfires can also alter the pH and infiltration capacity of soils, inhibiting their ability to be used for ongoing agricultural production and impacting future crop yields. Soils and crops (such as fruit-producing trees) may require time, remedial efforts or complete replacement depending on the severity of damage and scale of agricultural production. After the Thomas Fire in 2017, many avocado trees were burned beyond recovery or damaged, requiring years to fully recover (Johnson et al., 2018).

Soil health is essential to consider when growing crops for human consumption. However, uptake of hazardous constituents associated with wildfire debris and ash into the edible portions of crops varies significantly by individual compound and by crop. After the 2017 Northern California wildfires, soils and produce were sampled in agricultural areas in Sonoma County affected by wildfire smoke and in varying proximity to urban sites. Concentrations of wildfire-related contaminants (e.g., PAHs, polychlorinated biphenyls) observed in produce suggest low health risk, as many monitored hazardous substances were undetected or were only detected at low concentrations in a few samples. While no baseline soil data regarding dioxins and furans were available in these areas, concentrations of these compounds in soils were highest at the sites closest to burned urban areas. Dioxins and furans, noted for carcinogenicity, immunotoxicity, endocrine disruption and persistence in the environment and in the body, were detected at levels that exceeded EPA and OEHHA soil screening levels (UCCE Sonoma, 2019).

2.3.2 Addressing potential health and safety risks associated with wildfires, soil and agricultural crops

There are numerous unknowns about the potential health risks associated with wildfire-impacted soils and agriculture crops, such as soil contamination from wildfire smoke, uptake of wildfire-related contaminants into the edible portions of crops, and how soils in areas directly affected by wildfires may become destabilized, resulting in debris flow. In each case, site-specific, case-by-case assessments are necessary to evaluate potential health and safety risks.

While there are many unknowns, past endeavors to understand the impact of wildfire on soils and crops can inform harm reduction. Along with soil and crop sampling after the 2017 fire season, University of California Cooperative Extension in Sonoma outlined suggested best practices for local food growers where soil and crops may be impacted by wildfires via smoke and ash (UCCE Sonoma, 2019). These practices include avoiding smoke exposure during the wildfire smoke event and thoroughly washing produce before storing, cooking and eating. Food preparation recommendations include removing outer leaves of leafy greens and peeling root vegetables. After a nearby wildfire event, it is recommended to immediately wash hands and clothes after working outdoors. If soil contamination is suspected, soil samples are recommended to be tested first for heavy metals to determine if additional testing is required. If soil contamination is suspected or confirmed, soils can be contained through sheet mulching and using raised bed for growing future produce, or soil may be amended using compost and adding additional soil to dilute certain contaminants (UCCE Sonoma, 2019).

Additionally, as soils become destabilized post-wildfire, debris flows in affected areas can be particularly destructive and dangerous for nearby populations, particularly in areas for steep slopes. In response to this risk, the U.S. Geological Survey (USGS) conducts post-fire debris-flow hazard assessments for specific fires, incorporating data on basin morphometry, burn severity, soil properties, and rainfall characteristics to estimate the risk and character of debris flows (USGS, 2020).

Debris and hazardous waste removal

Counties managing wildfire recovery have established procedures for debris and hazardous waste removal. Following the Woolsey Fire in 2018, the Los Angeles County Department of Public Works (DPW) declared a Local Health Emergency, which effectively prohibited the removal of fire debris until inspections could be conducted by hazardous materials agencies, specifically the U.S. EPA and DTSC. To assist in coordination, LA County DPW set up dedicated Woolsey Fire Disaster Recovery Centers.

In addition to conducting inspections during the first phase of clean-up procedures, DTSC and the U.S. EPA removed household hazardous waste from fire-damaged or destroyed houses and commercial properties. Soil testing, coordinated by the State's Debris Management Team (DMT), ensured all contaminated ash had been removed from a burned area. Erosion control methods were installed before DMT could report that a lot was clear and ready for rebuilding (Los Angeles County Department of Public Works, 2019).

For businesses affected by fires, DTSC advises local household hazardous waste collection programs to accept hazardous waste from businesses that are 1) small quantity commercial sources, and 2) have lost records of hazardous waste generation (CA DTSC, 2019a). This recommendation potentially raises concerns about the capacity of local household hazardous waste collection programs to manage waste when large wildfires impact numerous commercial sources. DTSC allows burned hazardous waste that cannot be removed to be treated as nonhazardous ash and fire debris (CA DTSC, 2019b). Removal of non-household hazardous waste debris to landfills involves participation of OES in coordination with LA County DPW, FEMA, and the State's Debris Task Force and DMT.

2.3.3 Wildfire, soil, agricultural crops and health: research gaps and limitations

Impacts to soils from wildfires and associated ash and debris are largely dependent on site-specific conditions. In developed areas with structural burned materials, further research is needed to assess the variability of ash composition within and between residences in a given neighborhood and variability in ash composition as a function of residence age, type, and setting (such as north- or south-facing slope, proximity to other residences, intensity and duration of fire, and type of construction) (Plumlee et al., 2007). Detailed characterization of debris and ash and soils in wildfire-affected areas is warranted to better understand potential health risks and inform remediation efforts, particularly in developed areas, including residential areas and areas where crops are grown for human consumption.

Additionally, comprehensive soil and landscape frameworks are necessary to assess the potential loss from debris flows following wildfires (Kean et al., 2019). Finally, there are many unknowns about how wildfire-associated contaminants may be taken up by crops. Further research is needed to assess how the various constituents that comprise wildfire smoke and ash may be taken up by a variety of crops.

2.4 Wildfires and mental health and well-being

Emergencies and natural disasters can result in significant acute or long-lasting psychological impacts, such as acute anxiety, depression, increased alcohol and drug use, post-traumatic stress disorder, and survivors' guilt (Ursano et al., 2017). In this section, we review the literature and strategies to mitigate risks specific to mental health impacts associated with wildfire. There are several ways in which wildfires may impact mental health, including extended wildfire smoke exposure, the experience of an evacuation, or the proximate or direct impacts of wildfire damage. Studies evaluating mental health impacts associated with wildfires are discussed below (Section 2.4.1). Strategies to mitigate wildfire-associated impacts on mental health (Section 2.4.2) and research gaps and limitations are discussed (Section 2.4.3).

2.4.1 Wildfires and implications for mental health

Few studies have examined the association between wildfire smoke exposure and various mental health outcomes, and of these studies, no associations have been observed (Moore et al., 2006; Duclos et al., 1990). However, exposure to $PM_{2.5}$ broadly (not specific to wildfire events) is associated with an increase in depressive and anxiety symptoms, an increase in emergency department visits for psychiatric diseases, and higher perceived stress (Gu et al., 2020; Kim et al., 2019; Mehta et al., 2015; Pun et al., 2017). Of note, Gu et al. (2020) found that short-term exposure to ambient air pollution (including $PM_{2.5}$) is associated with increased risk of hospital admission for depression in China. These findings may be particularly relevant in the context of short-term exposures associated with wildfire smoke.

Studies of populations directly impacted by significant events related to wildfire, such as destruction of home or community, have observed evidence of associations with mental health outcomes. A study examining emergency department visits before, during and after a period of frequent wildfires across six California counties in 1987 reported no statistically significant increase in mental health hospitalizations (Duclos et al., 1990). However, hospitalizations serve as only one metric to measure the mental health impacts of wildfire among directly and indirectly affected populations. Meanwhile, patients impacted by the 1991 Oakland-Berkeley Hills firestorm in California presented with acute exacerbations of underlying psychiatric disorders, as well as situational stress or grief reactions (Shusterman et al., 1993). Following a 2016 wildfire in Alberta, Canada, a survey of adolescents revealed those who directly experienced greater impact from the wildfire (i.e. personally had seen the fire or had their home destroyed) reported higher scores on mental health measures of post-traumatic stress disorder (PTSD), depression and anxiety as compared to those who experienced lesser impact from the wildfire. Adolescents that experienced greater impact from the wildfire also reported lower self-esteem and quality of life and scored lower for resilience (Brown et al., 2019a; 2019b).

Evacuations during wildfires can also exacerbate mental health disorders and related impacts on those currently seeking mental health services. After the 2007 San Diego wildfires, San Diego County Mental Health Services surveyed a high-risk group of patients (Tally et al., 2013). Based on the survey results, researchers found that mental health patients who lived in evacuation areas experienced the effects of disrupted services, including difficulty obtaining and taking medications or finding adequate information about the fires. Patients who evacuated, when compared to patients who did not evacuate, reported increased stress, anxiety, fear, and depression, as well as confusion about evacuation details; these patients also sought additional mental health services. Notably, older clients reported higher levels of depression and sadness as a result of the wildfire. Potential drivers of these reported experiences include loss of control, disruption of normal routines and transportation, proximity to danger and direct experience of losses, possible loss of possessions, and extended exposure to stressors that occur during wildfire and associated evacuations (e.g., lack of information, separation from loved ones). These circumstances may persist over the longer term in cases where loss of housing results in displacement, contributing to homelessness and poverty. Compounding layers of vulnerability may affect individuals managing mental health conditions during a wildfire; people with pre-existing mental illness often have compounded difficulties of poverty, marginal housing, and less access to resources including regular transportation and medical and social support services as compared to those in the general community (Tally et al., 2013). These difficulties may be further exacerbated for particularly vulnerable populations, including children and the elderly.

Mental health disorders, including PTSD, have been well documented in firefighters, given the direct and frequent exposure to traumatic events associated with this occupation (Boffa et al., 2018; Haslam & Mallon, 2003; Heinrichs et al., 2005). Studies also show that indirect exposure to traumatic events can mimic the psychological effects of direct exposure, leading to similar post-traumatic stress symptoms attributed to vicarious traumatization or secondary trauma (Sabin-Farrell and Turpin, 2003). Results of a survey designed to evaluate indicators of vicarious traumatization in individuals in areas unaffected by the 2001-2002 New South Wales bushfires indicated that indirect exposure through viewing media coverage about the bushfires was associated with vicarious traumatization (Byrne et al., 2006).

2.4.2 Addressing potential mental health and safety risks associated with wildfires

Limited studies have evaluated the mental health toll associated with wildfires and related evacuations and recovery activities, but populations struggling with mental health or who are disadvantaged and experiencing compounding burdens, such as homelessness, may be particularly vulnerable to mental health impacts associated with wildfires.

Local and State agencies can establish and coordinate support services for populations impacted by wildfire and support a provider network. One example of such support services is from the Healthcare Foundation Northern Sonoma County, which developed the Wildfire Mental Health Collaborative in response to wildfires in Sonoma County in October 2017. The collaborative organized around the mission of providing trauma skills development for mental healthcare providers and launched a public awareness campaign to help people identify signs of trauma; it also aimed to reduce the stigma of seeking support and informed the community about mental health resources (Healthcare Foundation Northern Sonoma County, 2018). Available resources included a hotline for referral to care, free individual counseling, private group sessions and trauma-informed yoga. Services were available in both English and Spanish. The collaborative also measured outcomes in order to guide future disaster response efforts.

In an effort to address the mental health needs of populations who have experienced a disaster, researchers developed the ‘PsySTART Rapid Mental Health Triage and Incident

Management System’, an evidence-based strategy intended for use by local communities, schools, states, and others to improve response following traumatic events (Schreiber, 2011; Tamsut et al., 2017; Schreiber, 2018). This initiative’s objective is to mitigate long-term mental health impacts by providing services during a key preventative 30-day window. Following wildfires in Napa County, this tool was used to complete 2,700 triage encounters in approximately 4 days, identifying a high-risk subset in order to match available resources with populations in need (National Academies, 2019).

2.4.3 Wildfires and mental health: research gaps and limitations

Future research can help inform efforts to mitigate mental health impacts that stem from experiencing wildfires and their aftermath. A limited number of studies have evaluated wildfire smoke exposure and mental health outcomes, finding no association; however, additional studies are warranted. Evaluations of impacts of brief, frequent and more prolonged exposure to wildfire smoke are needed, especially as wildfire smoke events may increase in frequency and intensity for certain populations due to climate change. Future studies evaluating wildfire smoke exposure should also assess impacts on mood and cognition, especially among vulnerable populations such as children and the elderly.

Health surveillance efforts during and following wildfire events should include mental health outcomes. Additionally, future research should explore other factors tied to wildfires that influence mental health, for example, the potential increase in experiences of homelessness in communities where properties have been damaged by fire and the loss of community cohesion for those remaining in wildfire-affected communities.

Few studies evaluate the indirect impacts of wildfires on the broader population, including those that may not be directly impacted but experience secondary trauma by observing the aftermath in affected communities or due to media coverage. Additional research is also needed to address potential mental health impacts among those living in close proximity to wildfire-affected areas, communities that absorb displaced populations after wildfire, and populations living in high wildfire risk areas.

Policymakers should anticipate that populations affected by wildfires will experience mental health outcomes, and respond by assuring that healthcare providers are able to care for patients with adequate mental health staff. This is a particularly difficult task given the current national and state shortage of mental health professionals — a recent report found that by 2028 California will have less than half the number of psychiatrists required to meet the state’s needs (Coffman et al., 2018). Resources and staff are particularly needed to address the mental health needs of children and adolescents following disasters. Future evaluations are also needed to anticipate delivery of mental health services to guide preparation and response efforts for future wildfire events. Finally, preventative approaches can also be taken at local level in high wildfire risk areas to improve resilience before disasters occur (Doppelt, 2017).

3.0 The public health dimensions of California's approach to wildfire prevention, mitigation and suppression

In this section, we review the existing, proposed, and developing policies and frameworks to address wildfire risks and impacts within the context of public health. These efforts include public safety power shutoffs to reduce wildfire risks (Section 3.1), forest management policies such as prescribed burns (Section 3.2) and the use of firefighting tools such as chemical fire retardants and foams (Section 3.3). Strategies to address health implications of these wildfire prevention, mitigation and suppression strategies, and associated research gaps and limitations are discussed.

3.1 Public safety power shutoffs (PSPS

Electric power lines sparked at least four of California's ten most destructive fires and are considered a potential culprit in a fifth; two more were triggered by failed electrical equipment (CAL FIRE, 2020b). To minimize the fire hazards from power lines, California utilities have begun to implement Public Safety Power Shutoffs (PSPS), during which they de-energize electric lines during high risk wildfire conditions—typically days with low humidity and high wind speeds. These measures have widespread secondary impacts, however, ranging from economic losses for businesses to health risks for individuals dependent on electricity to power home medical equipment (Section 3.1.1). Policies and strategies to address health risks posed by PSPS events (Section 3.1.2) and research gaps and limitations are discussed (Section 3.1.3).

3.1.1 Public safety power shutoffs: implications for public health

In 2019, California utilities implemented power shut-offs on 27 different days, lasting more than five days on some occasions (CPUC, 2020a). The October power shutoffs affected more than one million PG&E customers,[18] equivalent to an estimated two million people, across geographic areas from the North Coast to outside of Bakersfield (Newburger, 2019). On October 9, for example, utilities initiated shut-offs which lasted up to three days and which affected more than 600,000 residential customers, including nearly 30,000 medical baseline customers who rely on electricity to power medical equipment or provide other services critical for their health (Walton, 2019). The broader public health risks of these shutoffs depend on the size and duration of the outage, as well as the number and characteristics of customers left without electricity. Below, we describe the public health concerns related to these shutoffs 1) in the home, 2) in businesses and community-wide, and 3) in medical facilities. Strategies to mitigate impacts associated with PSPS are described in Section 3.1.2.

[18] A customer is any site with its own electrical meter, which may be a building or apartment where multiple people work or reside.

Residential impacts

Public safety power shutoffs have a range of public health implications at homes and residential living facilities. Brief shutoffs may be relatively easy to accommodate, but the longer the shutoff, the greater the potential impact. The most direct public health risk from loss of electricity may fall on those who rely on electricity to power medical equipment. There are numerous home medical interventions that require electricity, including sleep-apnea machines, hearing aids, respirators, motorized wheelchairs, kidney dialysis machines, nebulizers and insulin that needs to be kept cold (Fuller, 2019; Lowrey, 2019). In California, over 170,000 Medicare recipients alone rely on electricity to support medical equipment, along with many other non-Medicare recipients (U.S. DHHS, 2020). Public utilities are typically not permitted to cut off electricity for medical baseline customers who rely on electricity to support this medical equipment, even if they default on bills, but tens of thousands of these customers still lost power during the PSPS in 2019.

Additionally, the California Conference of Local Health Officers has expressed concerns about current barriers that restrict customers from being considered for the medical baseline program, including medical fees, English proficiency, or cognitive and physical capacities required to complete and submit necessary forms (CCLHO, 2019). The result is that only a fraction of the population who may qualify as medical baseline customers are captured. Figure 5 depicts the distribution of electricity-dependent Medicare patients throughout the State, overlaid with probable future PSPS areas and areas that have recently been subject to a PSPS.

Beyond medical equipment, shutoffs put individuals at risk to lose power for heating, cooling and refrigeration. PSPS events caused residents to lose refrigerated food and medicines, and mothers who breastfed scrambled to find a way to continue to pump (which requires electricity) and store breast milk (which requires refrigeration and a freezer, depending on length of storage required) (Caron, 2019). Longer outages can also contribute to food spoilage, leading to either insufficient food supplies or risk of eating contaminated food and developing gastrointestinal illness. Heating and cooling are particularly critical for vulnerable populations, including those with underlying disease and the elderly. In a study of mortality and temperature changes across nine California counties, researchers found that every 10°F increase in same-day mean apparent temperature corresponded to a 2.3% increase in mortality (Basu et al., 2008). Loss of lighting can also lead to safety risks for those moving at night, particularly for those with physical disabilities and the elderly.

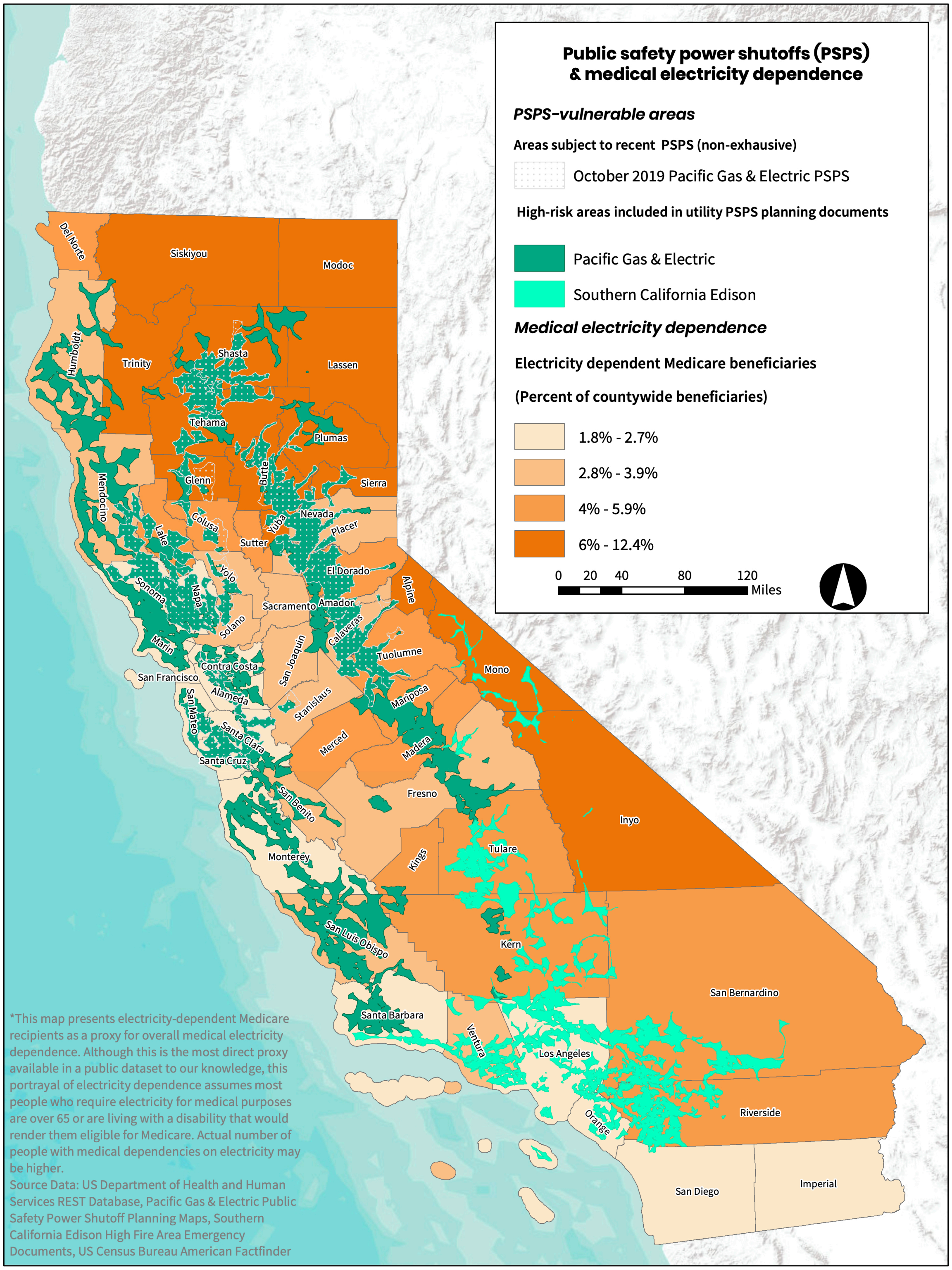


Figure 5. Areas at risk of or have experienced Public Safety Power Shutoffs (PSPS) for wildfire prevention and proportion of countywide Medicare beneficiaries that are medically electricity dependent.

Certain households may also rely on electricity to support clean water supplies and waste disposal, such as water pumps or septic systems. Power shutoffs in fall 2019 impacted households dependent on well water, since many private wells rely on electric pumps (Said, 2019). Loss of electricity can result in limited water supplies for drinking, cleaning and bathing, as well as inability to use toilets or dispose of other wastewater.

Electricity losses can also impact mobility. Critically, those with electric-powered wheelchairs may not be able to charge them. Those dependent on electric vehicles or electric bikes may also be unable to charge them, limiting their ability to travel for food and supplies or evacuate as needed.

All of these risks are compounded by communication failures from the loss of electricity. Loss of access to telephones, cell phones and the internet can limit individuals' ability to determine the length of outages, where to go for backup resources, the need to evacuate in case of a wildfire or the ability to call for emergency services. Cell phone service is an essential lifeline in areas where people are evacuating from wildfires, as well as areas where the general population has come to depend on cell phone service in place of landlines; notably, the Governor's Office of Emergency Services has reported that more than eighty percent of emergency calls to 911 in California in 2018 were made by cellphone (Pogash and Chen, 2019). During the power shutoffs in Sonoma County at the time of the Kincade Fire, one-quarter of the 436 cellphone towers were out of service, and in Marin County more than half of the towers were out of service (Pogash and Chen, 2019). In addition to immediate health and safety concerns from cell phone service being down in areas with wildfire risks, interrupted phone service restricts daily communications in all power shutoff areas, impacting the ability of families, friends and neighbors to check in with one another, and the ability of parents to get information on school closures.

Furthermore, residents, schools, businesses, cities and emergency responders complained about insufficient advisories leading up to the fall 2019 PSPS across PG&E territory. Technical glitches hampered communication when PG&E's website, which provided details about the customers who would be affected by the power shutoffs, crashed repeatedly (Lowrey, 2019; Penn, 2019). On top of this complication, customers received only a few days' notice, if given notice at all, without specific details about when they would lose power and when they could expect it to be restored. During the start of the PSPS events, the utility company also discovered that the systems it used to alert customers that they would lose power didn't work as expected. Information technology specialists from the state had to help restore PG&E's communications systems (Penn, 2019).

Commercial and community-wide impacts

Loss of electricity at businesses can also have public health repercussions, along with loss of electricity for community facilities and systems. Certain businesses, in particular grocery stores and food pantries, may be unable to refrigerate foods if electricity is cut off, leading to food spoilage and food shortages community-wide. Electricity losses at schools, community centers, city buildings and other community facilities may limit the number of places individuals can go to access air conditioning or heating, breathe filtered air, or charge cell phones and other necessary electronics. Resilient cooling centers, which are designed to supply electricity and air conditioning during outages, may have backup generators, but these may be limited by fuel supply and, if reliant on diesel fuel, also emit PM and other health-damaging air pollutants. Prior to October 2019, planned shutoffs had not been a common or large-scale occurrence outside of areas immediately impacted by wildfires, and this circumstance left customers unprepared for the magnitude and longevity of the shutoffs. PG&E established seventy-six Community Resource Centers during the PSPS events, but these proved insufficient. Although these assistance centers provided free electricity, water, snacks and flashlights, residents reported that the hours, locations and staffing at centers were inadequate to serve affected populations (Endicott, 2019; Penn, 2019).

Across communities, electricity supports numerous critical functions which may or may not have backup power. These services include, among others, water distribution, wastewater treatment, street lighting and traffic lights. Wastewater treatment plants, among other facilities, may have backup diesel generators but can also face fuel limitations if there are extended outages. In October 2019, the Caldecott Tunnel in the East Bay nearly had to shut down before Caltrans supplied generators at the last minute, drawing attention to the agency's lack of advanced planning (Swan and Gafni, 2019). The City of Vallejo instituted water restrictions when the City was unable to pump source water for treatment until PG&E provided a generator for the Cordelia Raw Water Pumping Complex (Ramos, 2019). Communities also can support air quality monitoring networks, many of which rely on electricity to collect and transmit air quality data to online platforms. These platforms are used by decision-makers to issue air quality warnings. During the 2019 PSPS, air quality monitoring networks lacked back-up power and were unable to collect and transmit air quality information (Albergotti, 2019).

Medical facilities

Medical facilities and hospitals are highly reliant on electricity to provide critical care for patients, so many have combined heat and power systems or diesel generators to provide backup in the case of power outages. Like any backup source, these can be limited by fuel supply and are at more risk during long-duration outages. Furthermore, systems reliant on natural gas or diesel for fuel supply emit criteria pollutants that can increase atmospheric O_3 and particulate matter concentrations, which have respiratory and cardiovascular health impacts. Notably, these systems have to be cycled and tested even when there is no outage, resulting in emissions throughout the year.

Smaller medical facilities, however, such as outpatient clinics or pharmacies, may not have backup power. Electricity outages can necessitate the postponement of medical procedures. Furthermore, emergency responders may face limited capabilities due to loss of electricity at their bases and communication outages across their territory. Assisted living facilities also lost power during PSPS events, limiting their ability to support vulnerable populations living in their care.

Box 2. A precedent from the 2003 New York City blackout

Previous power outages can provide examples of how sudden loss of electricity may impact human health. In August 2003, a widespread power outage affected the northeastern United States and parts of Canada, including the entire population of New York City during a period of high temperatures and high humidity. During the blackout, mortality rose 28%, resulting in approximately 90 excess deaths (Anderson and Bell, 2012). The risk of accidental deaths (e.g., CO poisoning) increased more than non-accidental deaths (e.g., disease-related), yet the greatest number of excess deaths were from non-accidental causes, particularly related to cardiovascular outcomes. Individuals between the ages of 65 and 74 were particularly vulnerable to mortality risk, and increased exposure to heat during the power outage may have worsened its effects.

During the New York City blackout in 2003, impacts to electricity-dependent public transportation and infrastructure, including subways and elevators, caused difficulties for those actively using or reliant on these resources. These circumstances contributed to the heightened risk of mortality: one mortality occurred when a woman collapsed after she walked down many flights of stairs, with paramedics at the scene not able to get an ambulance for over thirty minutes (Barstow, 2003). An estimated twenty-seven trains and 350,000 people were impacted on the New York City subways when the power went out, with the Transit Authority anticipating services to resume six or eight hours after power was restored (Kennedy, 2003). One Long Island Rail Road train was stuck beneath the East River with 1,000 passengers who waited for two hours with no air conditioning before a diesel-powered train could tow it to Penn Station (Kennedy, 2003). Similar to PSPS events in California, the New York City power outage impacted refrigerators and freezers, possibly contributing to increased gastrointestinal illnesses from consumption of spoiled food. One study detected a moderate but widespread citywide increase in diarrhea after the power outage, although the study did not have stool or food cultures available from which to draw a definitive causal inference (Marx et al., 2006). The *Times* reported that across the eight states and parts of Canada affected by the blackout, there were more than three times the normal calls to 911 (Barron, 2003). Adverse health impacts associated with the New York City blackout in 2003 represent the need for state and local agencies in California to anticipate and adequately prepare for the complexity of emergency situations resulting from PSPS events.

3.1.2 Addressing potential health and safety risks and impacts associated with public safety power shutoffs

The impact of PSPS events can be mitigated with two broad strategies: reducing the need for shutoffs in the first place, and creating a resilient power system that can meet critical power needs when such shutoffs do occur. The first approach is to reduce the fire risk from power lines themselves. The second is to create a distributed and flexible electric power system that provides resilience in the face of shutoffs and other emergencies and outages.

Strategies to reduce the ignition risk from power infrastructure includes vegetation management, wire burying, and grid hardening. PG&E has faced intense criticism and wildfire liability for insufficient investments in wildfire mitigation efforts (CPUC, 2020b). Unfortunately, years of inadequate grid investments and grid management may likewise take years to improve, but such improvements will reduce the need for power shutoffs. PG&E has detailed many key grid hardening steps in its wildfire mitigation plans, including the following (CPUC, 2019a):

- **Grid inspections and vegetation management:** Transmission and distribution power infrastructure require ongoing inspection and maintenance to remove tree branches and other vegetation growing too close to electric lines. Heavy rain years can contribute to a proliferation of new growth, but even ongoing vegetation management requires a significant investment in time and resources: PG&E alone operates more than 18,000 miles of transmission lines, more than 100,000 miles of distribution lines (PG&E, 2020), and nearly 700,000 distribution poles (CPUC, 2019a). Deployment of monitoring technology to assist in the inspection of poles and wires, such as using observational drones and video cameras, can help accelerate this task. In addition, inspections can help identify aging infrastructure, weather damage, and other grid components that may require repairs or replacement.

- **Burying wires:** Undergrounding electric wires significantly reduces risk of ignition, but can be prohibitively expensive and time-consuming and will likely only be applied in a limited number of locations. As Paradise (CA) rebuilds following the 2018 Camp Fire, PG&E committed to put all electric distribution power lines underground (PG&E, 2019).

- **Grid hardening:** Ignition risk can be further mitigated by hardening grid infrastructure, including covering exposed wires, and replacing poles and transformers with more fire-resistant alternatives. These efforts can be prioritized in high-wildfire risk areas.

The second broad strategy to reduce the impact of PSPS is to modernize the electric grid and replace the existing system, which is dominated by large power plants, with a system more reliant on distributed generation and energy storage to provide flexibility, resilience and backup power. This approach aligns with the state's objectives to reduce greenhouse gas emissions and adopt renewable energy, and can help facilitate the adoption of electric vehicles as well. Strategies to support this approach include:

- **Residential solar+storage:** Household-level solar+energy storage systems can provide resilience during PSPS events and other emergencies while supporting the transition to a clean, low-carbon electric grid. The size of the solar+storage system will determine the length of time that the system can provide electricity, and whether it will support all electricity demand or just critical electric loads. These systems may provide the greatest public health benefit if systems are prioritized for vulnerable populations, including those who depend on electricity to run medical equipment, refrigerate medicines, or pump water; the elderly; and those with underlying disease who may be vulnerable to heat waves or cold temperatures. The California Public Utilities Commission recently expanded its Self-Generation Incentive Program (SGIP), which provides incentives for solar+storage, to support equity and resilience projects for vulnerable populations in high-fire risk regions (CPUC, 2019b). To date, solar deployment in California's disadvantaged communities has lagged behind households in the rest of the state, suggesting that these and other incentives will be critical to ensure that solar+storage provides support to those communities which may be least resilient to the impacts of power outages and wildfires themselves (Lukanov and Krieger, 2019). The California Air Resources Board has developed a tool for users to compare solar+storage to other emergency backup power systems.[19] In certain circumstances, CARB is also currently exploring the use of battery power to support typical field deployment and rapid deployment of air quality monitors.[20]

- **Islandable solar:** Solar photovoltaic systems are typically set up such that they do not provide electricity when the grid at large goes down. This arrangement prevents solar systems from supplying electricity into a supposedly de-powered distribution system and potentially electrifying utility workers. However, the inclusion of a separate disconnect on solar systems can allow them to *island* from the grid and provide electricity while the sun is shining — either providing power directly to the house or through a separate outlet. Such an arrangement will provide less resilience than a solar+storage system, but at a significantly lower cost, and can provide a household with daily opportunities to plug in a refrigerator, charge cell phones, and otherwise meet critical electricity requirements.

- **Solar+storage for critical facilities and resources:** Solar+storage can provide back-up for critical facilities, including hospitals, clinics, police and fire stations, water treatment facilities, emergency responders and food distribution centers. In addition, solar+storage can help ensure that traffic lights, street lights, communications infrastructure and water distribution systems continue to function during grid outages. As an example, a proposed clean-energy microgrid for key community facilities in downtown Berkeley includes elements of solar+storage and islandable solar to support select public buildings, schools, and community centers (Van Dyke et al., 2019).

- **Diesel generators:** Like solar+storage, diesel generators can also supply critical power during outages. However, diesel combustion releases criteria pollutants such as particulate matter as well as greenhouse gases. Diesel generators are typically tested at regular intervals — weekly or monthly — releasing these pollutants all year. In

[19] CARB. Emergency Backup Power Options - Residential. ww2.arb.ca.gov/our-work/programs/public-safety-power-shutoff-psps-events/emergency-backup-power-options.

[20] Personal Communication with CARB Incident Air Monitoring Section. February 20, 2020.

addition, access to diesel fuel may be limited during extended outages; for example, during Hurricane Sandy, more than half of the gas stations did not work because their pumps required electricity and they lost power (Zernike, 2012).

- **Resilient community centers:** Resilient community centers, such as cooling centers, gyms, libraries, schools and other public buildings, can be equipped with solar+storage to provide a safe place for community members to receive critical support during grid outages. These centers can include air filtration systems to provide clean air during wildfires; heating and cooling; refrigeration for medicines or power for medical equipment; cell phone charging stations; and community meeting space.
- **Microgrids:** Solar, storage, and other generation resources can be integrated across larger regions — including city blocks or campuses — to island from the electric grid to provide resilience during blackouts. In addition, these microgrids can be used to help transition to clean advanced energy systems, including flexible demand resources, electric vehicle charging stations and building electrification. Microgrids can help defer distribution and transmission system upgrades and manage local distributed loads while simultaneously providing backup power as needed. The Blue Lake Rancheria tribe in Humboldt County created a microgrid of solar panels, storage batteries, and distribution lines, which equipped them to provide power to an estimated 8% of the county's population during the PSPS events in October 2019 (Wilson, 2020).
- **Advanced grid infrastructure:** Modernization of grid infrastructure, including smart meters, synchrophasors, flexible electric loads, and other forms of grid flexibility and demand management, can allow the utility to identify outages and other problems and shut off and restart portions of the grid remotely. San Diego Gas & Electric (SDG&E), for example, has integrated technologies to remotely turn off parts of the grid, while PG&E had to deploy operators to manually turn off parts of the grid during recent PSPS events (Penn, 2019). In the long term, additional resources such as electric vehicles may also be able to supply electricity in the case of emergencies.

The State has passed a number of initial laws to mitigate both electric grid wildfire risks and the impact of PSPS events. In October 2019, Governor Newsom signed into law bills requiring investor-owned utilities (IOUs) to address undergrounding electric lines in their wildfire mitigation plans (SB 70; Nielsen, 2019); provide backup power or otherwise mitigate impacts of power shutoffs on medical baseline customers, first responders, and health and communication infrastructure (SB 167; Dodd, 2019); and provide advanced notice to customers and rapid restoration of systems to mitigate potential loss of communication networks during outages (SB 670 and SB 560; McGuire, 2019a and 2019b). Additional pieces of wildfire-related legislation include the expansion of storage incentives to explicitly help vulnerable communities (AB 1144; Friedman, 2019).

These and other improved communication measures — both providing advanced notice of outages and backup for communication infrastructure during outages — will enable individual households as well as emergency workers to prepare (e.g. by fully charging electric batteries) and to operate effectively when power is shut off. In May 2019, the California Public Advocates Office urged the CPUC to use emergency powers to require that communications systems continue to operate in emergencies by immediately ordering cell carriers to provide backup battery or generators and network redundancy in areas with a high risk of wildfires or floods (Pogash and Chen, 2019). The CPUC has also proposed that utilities distribute multilingual communications before, during, and after a wildfire and required utilities to make communications available in any language spoken by at least 1,000 persons in an IOU's service territory (CPUC, 2020c).

In addition, the passage of AB 1054 (Holden, 2019) in July 2019 established a Wildfire Safety Division and Advisory Board at the CPUC, to be succeeded in 2021 by a new Office of Energy Infrastructure Safety at the Natural Resource Agency. This bill also expanded wildfire mitigation plan requirements for IOUs. The CPUC is taking numerous direct actions to improve future responses to wildfires, including the launch of an investigation into the 2019 PSPS events; a re-examination of how utilities use PSPS events; protection of consumers during PSPS events from being billed for services they did not receive; expansion of wildfire mitigation plans; and enlistment of new technology partnerships (CPUC, 2020d).

As the State increases its resilience efforts, it will be critical to incorporate health and equity measures into the deployment of resilient resources. Those living in low-income households or disadvantaged communities may be the most vulnerable to the impacts of both grid outages and wildfires. Social and economic inequities in California influence the capacity of communities to prepare and respond to PSPS events. For instance, the high initial cost of solar+storage installations may be prohibitive for low-income families (Kutz, 2019).

Coordination between numerous entities, including state and regional agencies, can be invaluable to provide resilience during wildfires and PSPS. For example, the City of Vallejo partnered with Touro University and Solano County to conduct wellness checks on residents with medical needs (Fusek, 2019).

3.1.3 Public safety power shutoffs and health: research gaps and limitations

With the well-meaning intention to prevent wildfires, public safety power shutoffs (PSPS) pose health and safety risks to affected populations. Notably, these risks extend to populations that may not reside in high wildfire risk areas, but rather rely on parts of the electrical infrastructure that resides within or crosses high wildfire risk areas. Although health and safety impacts associated with PSPS events during the 2019 wildfire season were documented on a case-by-case basis by journalists, they have yet to be formally evaluated on a wider scale. Research gaps regarding the health and safety risks and impacts associated with PSPS events include quantifying potential health and safety impacts and the severity of these impacts; and assessing disproportionate burden of PSPS events to further identify at-risk and vulnerable populations and mitigate risks. Electricity is critical to the health and well-being of specific vulnerable populations, such as those relying on refrigerated medicines, kidney dialysis machines, or electricity for hospice and life support. However, identifying these individuals is a challenge given privacy considerations and limited reporting, often at the local scale. Currently, the most comprehensive publicly available dataset includes only those individuals that rely on Medicaid (i.e. emPower Map 3.0; U.S. DHHS, 2020), which is not fully representative of all populations that may require electricity for medical needs.

Given that widespread PSPS impacted over two million people during the wildfire season in 2019, it would be valuable to study the potential adverse public health effects resulting from the shutoffs to help prioritize future resilience investments, such as deployment of distributed energy resources. While various measures to mitigate impacts associated with wildfires and PSPS have been proposed by California utilities and State agencies, regulatory oversight and evaluation of these measures can assure compliance and assess effectiveness of these interventions. Similar impact evaluations may be performed to assess the effectiveness of various distributed energy resources during natural disasters and other emergencies.

3.2 Forest management policies: wildland-urban interface, prescribed burns, and biomass waste to energy production

Forest management strategies primarily involve reducing available fuels to prevent wildfires and attenuate potential impacts. Several key factors related to forest management drive the increased frequency and severity of wildfires in California. Encroaching human development on natural lands has impaired ecosystems' historical fire regimes and contributed to fuel loading. Additionally, an estimated 129 million trees have died in California's national forests over the last decade due to conditions caused by climate change, intense drought, bark beetle infestation and high tree densities — contributing additional fuels for wildfires (US Forest Service, 2018). Compounded with an aging and vulnerable electricity transmission system, these stressors have led to a dramatic increase in the frequency, intensity and geographic reach of wildfires throughout California.

In 2018, California released the Forest Carbon Plan to outline the State's strategies and priorities for improving forest management (Forest Climate Action Team, 2018). The Plan proposes significantly increasing the rate of fuel treatment, including forest thinning and prescribed fire. The Plan also emphasizes the need to expand wood products manufacturing and harness existing bioenergy capacity to utilize materials removed during forest management. The environmental and health implications of forest management depend on proximity and density of nearby populations and on which combustion pathways dominate the landscape (i.e., large wildfires, controlled burns, pile burns, large-scale biomass power plants, or smaller distributed biomass power plants). The following sections describe the following California forest management policies used to mitigate wildfire risk, their associated implications for public health and research gaps and limitations. Broadly, forest management includes policies related to the wildland-urban interface (WUI) (Section 3.2.1, prescribed burning (Section 3.2.2), and biomass waste utilized for energy production (Section 3.2.3).

~~3.2.1 Forest~~ management: wildland-urban interface (WUI) policies

There is a direct connection between increased wildfire damages and increased development in the wildland-urban interface (WUI) (CalOES, 2018). Fires in the WUI often occur on lands that are representative of a natural ecosystem that historically experienced seasonal patterns of wildfire. Encroaching development has altered the fire regimes of these areas while also increasing the presence of humans, a major source of wildfire ignition, leading to greater risk of wildfires. The California Legislative Analyst’s Office reports that the number of households in fire-prone areas increased 11 percent between the years 2000 and 2012 (California Legislative Analyst’s Office, 2020). An estimated 4.46 million homes are located and 11.2 million people live within the WUI in California, more than any other state, representing the growing density and expansion of the WUI (Alvarez, 2020; Martinuzzi et al., 2015).

The State has developed numerous policies aimed at addressing the inherent wildfire risks associated with residential development at the WUI (CAL FIRE, 2018). Broadly, these policies include: risk identification, defensible space, vegetation management and home hardening. We focus more on evaluating risk identification policies, as these have the most direct implications for health.

Risk identification

Identifying high wildfire risk areas is critical to developing effective emergency response protocols and preventing catastrophic wildfires. In California, the distribution of wildland fire protection responsibility is designated in three jurisdictions: Federal Responsibility Areas (FRAs), State Responsibility Areas (SRAs), and Local Responsibility Areas (LRAs). Within SRAs, there are fire hazard severity zones, for which three levels exist: moderate, high and very high (CAL FIRE, 2007). Fire hazard severity zones are determined by factors such as vegetation density, weather, slope severity and fire department response time. Fire hazard severity zone designations are used to site irrigation and sprinklers, and determine necessary road widths, water supply and advisory signage. In SRAs, the State has primary fire protection responsibility, and CAL FIRE is responsible for fire suppression. In LRAs, only Very High Fire Hazard Severity Zones (VHFHSZ) are identified and recommended for cities and counties to accept as a designation; local firefighting agencies are responsible for suppressing fires in LRAs. Approximately a quarter of residential structures in California are within or in proximity of “high” or “very high” fire hazard severity zones (Wood, 2019). However, it is not mandatory for LRAs to accept a recommended VHFHSZ designation, for reasons that include perceived negative impacts on property values or potential loss of residential fire insurance (CalOES, 2018).

In addition to the purposes described above, fire hazard severity zones can guide land use decision-making by informing local general plan formulation and real estate transactions. While this and other policy tools disincentivize population growth within areas of high fire hazard, population growth in very high fire hazard severity zones persists in portions of the State. Figure 6 uses SRA and LRA Very High Fire Hazard Severity Zone (VHFHSZ) data and U.S. Census data to map population change in areas of high fire hazard between 2000 and 2010. This analysis demonstrates that population growth in VHFHSZs outpaced countywide growth in several parts of the State, with this phenomenon most visibly clustered along the North Coast and within the Los Angeles and San Diego metropolitan areas. Between 2000 and 2010, populations living in VHFHSZs increased by 1.67%; as of 2010, an estimated 3.5 million Californians — 9.4% of the state population — lived within VHFHSZs. For further reference, detailed information regarding county-level population change in Very High Hazard Severity Zones in Figure 6 is included in Appendix A (Table A-2).

Defensible space and vegetation management

Creating defensible space around structures through vegetation management is critical to preventing infrastructure from catching fire in the WUI. In California, homeowners in SRAs are required to remove flammable materials around their buildings to 100 feet, or the property line, in order to create a defensible buffer. Insurance companies insuring occupied structures or dwellings are permitted to require greater distances for defensible space where appropriate (PRC §4291, 2018). Defensible space is also recommended around electrical transmission or distribution lines, as well as public water systems. As a practice mandated through state policy that applies to homes located in Fire Hazard Severity Zones, defensible space around infrastructure comprises many forms of vegetation management: removing dead vegetation, creating horizontal and vertical spacing, mowing annual grass, and trimming trees around homes, buildings, electrical transmission lines, distribution lines and public water systems. Cities and other entities have also been known to use goats to graze on overgrown lands.

Following a series of destructive wildfires in 2018, California Governor Newsom established 35 projects targeting high-risk areas to manage vegetation and create fuel breaks. These projects treated 90,000 acres, protecting evacuation routes and priority infrastructure such as hospitals (Office of Governor Gavin Newsom, 2020).

Figure 6. Countywide population change in Very High Fire Hazard Severity Zones (VHFHSZ) in the State or Local Responsibility Areas, 2000-2010.

Home hardening

Home hardening requirements include building retrofits and performance-based, fire-resistant construction standards. These are designed to reduce structural ignitions from windblown embers and flame contact, and impede or halt the fire spread within a structure once ignited (CalOES, 2018). These strategies may help avoid urban conflagration, in which structures are the primary fuel and create a large, disastrous fire. Like defensible space and vegetation management requirements, building construction standards apply in State Fire Hazard Severity Zones. Retrofits can prevent embers from getting in homes and help withstand extreme heat. Retrofits include covering vents with wire mesh, enclosing eaves, and installing double pane windows and steel shutters. Regular inspections also benefit home hardening, and for maximum hardening, entire neighborhoods should be retrofitted. Notably, in the 2018 Camp Fire, approximately half of homes built after 2008, when stricter building codes were implemented into at-risk wildfire areas, were spared while only 20 percent of older homes were left largely undamaged (Kim, 2019).

Potential health implications of WUI policies

Populations living in the WUI are at greater risk of health and safety impacts associated with wildfires. Policies aimed at identifying wildfire risk areas and responsible fire response authorities (e.g., fire hazard severity zones) and policies to reduce wildfire risk in the WUI (e.g., defensible space, vegetation management, home hardening) are overwhelmingly beneficial from a public health perspective. Below are additional WUI-relevant policies that may further protect public health and safety.

- **Risk communication for all residing in the WUI**: While fire hazard severity zone designations help local and state agencies prepare for wildfires, increased awareness of these designations and associated risks may help those residing in these areas better prepare for wildfire. Transparency about potential wildfire risk is essential for those considering to move to or build within WUI areas with heightened wildfire risks. Recently adopted AB 38 will require that, as of January 1, 2021, anyone selling a home located in a "high" or "very high" fire hazard severity zone and constructed prior to WUI building codes to disclose these details (Wood, 2019). This level of disclosure could help increase future homeowners' awareness of wildfire risk and improve residents' preparedness to evacuate in the event of wildfire. Another potential implication of this disclosure is that residents may recognize the elevated likelihood of experiencing a power shutoff during wildfire season, allowing them to prepare for these circumstances. Additionally, seasonal or temporary residents or workers in WUI areas should be informed of the risk of wildfire.
- **Utilize safe fire-resistant building materials:** This includes the further development, evaluation, and implementation of safe fire-resistant building materials. These materials may include wood treated with flame retardants, or foams used in combination with concrete (Graff, 2019). Materials containing high levels of fire

retardants are a concern for human exposure since there are unknowns about the chemicals applied, which may include toxic per- and polyfluoroalkyl substances (PFAS) that are associated with known human health impacts at low concentrations. (More information about fire suppressants is provided below in Section 3.3). Fire-resistant building materials should be well-characterized and evaluated to ensure that they pose little to no risk to human health and the environment under normal conditions and in the event of conflagration.

- **Re-evaluate local zoning and land-use policies in the WUI:** Future zoning policies could aim to limit construction of new structures in very high fire hazard severity zones. Current construction standards exist for fire-resistant homes, but there are regions of the state where development still occurs in high fire hazard regions. While new development is required to meet certain standards, modifications and retrofitting should also be considered for existing development.
- **Promote development of dense urban infill:** The cost and scarcity of housing in urban areas is driving the increased development in the WUI. A partial solution to reducing the number of residents living in the WUI is to construct more housing in urban areas. Urban infill policies can promote healthy, active lifestyles and provide access to healthy food, affordable housing, and quality jobs by directing development in underutilized urban areas (PHLP, 2009).

Research gaps and limitations related to WUI policies

Populations that reside within the WUI are presented with increased health and safety risks associated with wildfires. However, WUI policies are overwhelmingly health-protective and can promote safety in communities that reside in the WUI. Coordination and communication between local, state and federal agencies is necessary to enforce WUI policies and strengthen WUI policies to further reduce risk.

Anticipating the potential health impacts of managing wildfire risks at the WUI can be difficult given the unpredictable spread of wildfire and structural ignition patterns. Future research of the WUI should also address specific risk mitigation measures that have been encouraged or required, including topics such as effective design for home hardening and potential health implications of chemicals in fire-resistant construction materials. Additionally, local and regional planning could evaluate the capacity for promoting urban infill to reduce wildfire risk for populations in proximal WUI regions in California.

3.2.2 Forest management: prescribed burns

Prescribed burns are used to attenuate wildfire risk by reducing fuel loads in targeted areas. As a result of complete and incomplete combustion, prescribed burns emit air pollutants that may be hazardous to human health, much like wildfires. Over the last century in California, fire exclusion — the approach of eliminating fires by relying on fire suppression — was the primary approach to wildfire prevention (Agee, 1993). However, continuous fire exclusion contributes to fuel loading and heightens wildfire risk. Recently, the occurrence of large, life-threatening wildfires has steered conversations and policies towards promoting the use of prescribed burns and forest management treatments that return ecological areas to their traditional fire regimes. Figure 7 illustrates long-term trends in annual prescribed burn acreages in California. Although the acres burned fluctuate from year-to-year, there is a long-term, positive trend over the last several decades.

In discussing prescribed burning, it is critical to acknowledge that it has been a technique practiced by native populations in California for millennia. In present day California, an estimated few thousand acres are burned annually by traditional cultural techniques by the Miwok, Yurok, Hupa, Karuk, and other Native American nations (Fuller, 2020; Yüyan, 2019).

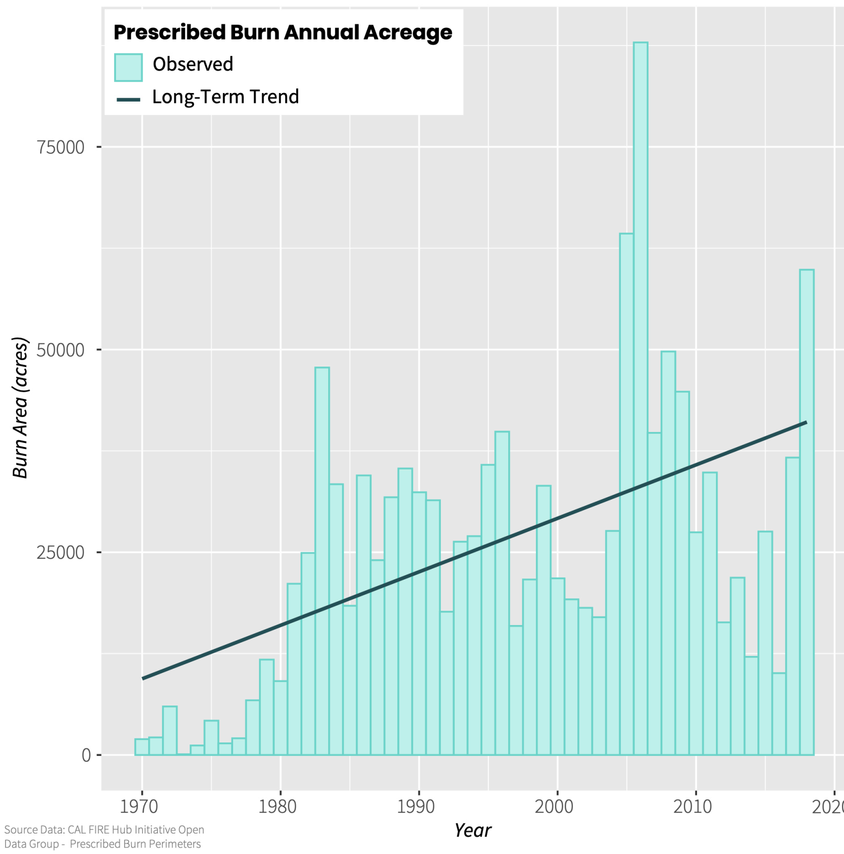


Figure 7. Prescribed burn acreage over time. (Source Data: Prescribed Burns, CAL FIRE Open Data Group, 2019).

There are several challenges to conducting prescribed burns. One challenge is ensuring burns take place during safe air quality and meteorological conditions, as prescribed fires should not be initiated during dry or windy weather, or on days when the air pollution levels are already elevated. To account for these potential risks, regional air districts rely on a daily burn authorization system that considers air quality and meteorological conditions, among other factors (CARB, 2001). Other challenges include the risk of fire extending beyond the intended borders and the real and perceived risks of burning near communities (Forest Climate Action

Team, 2018). Furthermore, there has been limited funding and crew availability to meet the demand for prescribed burns in the State (Miller et al., 2020).

In California, the Prescribed Fire Information Reporting System (PFIRS) collects burn permit records from 22 of the state's 35 air districts. Recent analysis of the system found that 16 of the 22 reporting air districts have consistently reported burns since 2013 (Miller et al., 2020). The PFIRS records include information about the planned and burned acres for registered burns. Of the 16 local air districts that report consistently, the analysis found that between 2013 and 2018 an estimated 38% to 51% of acres planned to burn have actually been burned (Miller et al., 2020). Significantly, about 93% of the acres planned but not burned during this six-year period were in the jurisdiction of a federal government agency, with the majority planned by the US Forest Service (Miller et al., 2020).

In response to the challenges of conducting prescribed burns and in recognition of their value as a tool for wildfire mitigation, SB 1260 mandated the California Air Resources Board (CARB) to coordinate a prescribed burn public awareness campaign and smoke monitoring program (Jackson, 2018). Consistent with present guidelines, CARB partners with local air pollution control and air quality management districts to develop this air quality monitoring program. CARB has recently invested in new technologies to increase monitoring and provide local information for prescribed burning near WUI communities.[21]

Potential health implications of prescribed burns

There are trade-offs to consider when evaluating the potential health impacts of prescribed burns. Implementing prescribed burns reduces overall fuel load, which mitigates the health and safety risks associated with large-scale wildfires. Wildfire and prescribed fire produce air quality impacts at different scales. Prescribed fires are low intensity, short-term and produce smoke plumes with impacts constrained primarily to local communities, whereas a high intensity wildfire can have longer-term and far-reaching air quality population health impacts (Williamson et al., 2016).

Additionally, fires may emit different compositions of air pollutants due to differences in intensity and materials burned. Emissions from structures burned during a wildfire may differ from the emissions of biomass from a prescribed burn. For example, during flaming combustion, synthetic materials have been found to produce more particles per mass consumed and a greater proportion of ultrafine particulate matter as compared to wood-based materials (Fabian et al., 2010). The presence and amount of ultrafine particulate matter emitted from synthetic materials holds significant implications for health, as ultrafine particulate matter can deposit deep into the respiratory system and vascular system, and cause toxic effects on internal tissues (Fabian et al., 2010). Additionally, emission factors ($g\ kg^{-1}$) for submicron particulate matter from wildfires are estimated as two to six times greater than that of prescribed fires, a range dependent on the material and quantity of fuel burned (Liu et

[4] Personal Communication with CARB Incident Air Monitoring Section. February 25, 2020.

al., 2017). Data from the EPA's 2014 National Emissions Inventory suggest wildfires emit nearly three times more particulate matter per acre burned than prescribed fires. For wildland fires, an estimated 271,220 tons of $PM_{2.5}$ were emitted and 635,494 acres were burned, representing 0.43 tons of $PM_{2.5}$ for every acre burned. For prescribed fires, 24,218 tons of $PM_{2.5}$ were emitted and 152,649 acres were burned, representing 0.16 tons of $PM_{2.5}$ for every acre burned (U.S. EPA, 2014).

Investigations into health risks and impacts associated with prescribed fire smoke are fairly limited. A recent study compared air pollutant concentrations emitted during a prescribed fire and a wildfire, and examined differences in asthma and markers of immune function among exposed school-aged children in Fresno, California (Prunicki et al., 2019). Concentrations of all measured pollutants (PAHs, PM, elemental carbon, O_3, CO, NO_2, NO_x) were higher during wildfire as compared to prescribed burns. Additionally, the wildfire smoke exposed group reported greater evidence of worsened health outcomes (wheezing and asthma exacerbation) as compared to the group exposed to prescribed fire smoke (Prunicki et al., 2019). Another recent study observed associations between prescribed burn activity in Georgia and increased local and regional asthma hospitalizations (Huang et al., 2019). However, this study is limited because it relies on concentration-response functions derived from epidemiological research focused on wildfire impacts, a limitation which is due to the lack of prescribed burning-specific epidemiological studies (Huang et al., 2019).

State and local air boards use established Smoke Management Guidelines to regulate prescribed burns for days when air quality is not expected to exceed standards for ozone, carbon monoxide or PM_{10}, or result in impacts to smoke-sensitive areas. The guidelines define smoke-sensitive areas as sites where air pollutants may negatively impact public health, including populated areas such as towns, campgrounds, trails, recreational spaces, hospitals, nursing homes, schools, roads, airports, public events and shopping centers. These categories are similar to the populations described in Table 1. Policies that aim to prevent large high-intensity fires will need to balance prescribed burn frequency with air quality effects, weighing potential impacts on vulnerable populations. Overall, policies that re-introduce natural fire to landscapes are prioritizing long-term air quality and public health by preventing large high intensity fires (Schweizer and Cisneros, 2016).

Strategies to address potential health implications of prescribed burns

Policies promoting the use of prescribed burns for wildfire management are designed to ensure fuel is burned in safe conditions that account for weather and public health. However, research shows that policies can also act as barriers to burning sufficient fuel for proper wildfire management (Miller et al., 2020).

All prescribed burns are registered with the local air district, and must meet certain conditions and reporting requirements depending on the expected size and emissions of the burn. The air district, in consultation with CARB, considers factors such as air quality, meteorological conditions during burning (including wind speeds, wind directions, and atmospheric stability), the types and amount of materials to be burned, the location and timing of the burn, the location of smoke sensitive areas, and smoke from nearby burning activities that may cumulatively impact surrounding regions.

The smoke management guidelines for prescribed burning currently in place and managed by CARB prioritize public health in its consideration of smoke sensitive areas. Smoke-sensitive areas are designated spaces where smoke and air pollutants may negatively impact public health, including towns, campgrounds and other populated recreational areas, hospitals, nursing homes, schools, roads, airports, public events and shopping centers.

Recent analysis of PFIRS shows that 22 of the State's 35 air districts report to PFIRS, with only 16 districts reporting consistently (Miller et al., 2020). Prescribed burn management that prioritizes public health could be improved through more consistent and expanded reporting. For instance, the following strategies could be employed:

- **Air quality monitoring:** Current smoke management guidelines require districts to evaluate air quality when determining a permissive burn day. SB 1260 (Jackson, 2018) tasked CARB with preparing for wildfire and prescribed fire by monitoring air quality during fire events. Future air quality monitoring during prescribed burns could produce useful data for studying potential associated health impacts in surrounding populations.
- **Expanding prescribed burn reporting:** The Smoke Management Guidelines could be expanded to require increased geographic information details, such as coordinates of the burn area perimeters and estimated or measured emissions.
- **Expanded notification system:** Current public notification procedures are required in smoke management plans for burns greater than 100 acres or emitting more than ten tons of PM. Notification procedures should be evaluated to determine if they are effective for alerting residents surrounding a prescribed burn. Ideally, an automated notification system would be used to ensure that all populations potentially exposed to smoke from a prescribed burn were made aware.

Research gaps and limitations relevant to prescribed burns

While prescribed burns are a key strategy to managing wildfire risk, their emissions are potentially of concern and have yet to be fully investigated. There is currently very limited public reporting of emissions associated with prescribed burn events. At this time, there is insufficient epidemiological research on prescribed burns. It has yet to be determined whether chronic exposure to low levels of smoke from small prescribed burns may influence the health of exposed populations.

Future research should explore the differences between smoke from prescribed burns and smoke from wildfires, focusing on the implications for public health. This type of research would ideally be supported by air quality surveillance and exposure assessment during prescribed burn events. Results from queries into these comparisons would assist policymakers in more accurately determining the public health trade-offs of prescribed burns and wildfires.

3.2.3 Forest management: biomass waste for energy production

As part of a broad suite of efforts to reduce the number, intensity and impact of future wildfires and address the ample acreage requiring fuels treatment, the State is promoting increased utilization of wood biomass (herein referred to as biomass) (Forest Climate Action Team, 2018). Current State legislation incentivizes converting biomass, both from dead trees and thinned forests, into steam, heat or combustible gases for heating and energy production. Biomass waste from timber harvesting and forest thinning can also be used to create wood products such as biochar, landscaping materials, compost and wood stove pellets (Forest Climate Action Team, 2018). However, there are concerns and challenges facing the prospect of increased bioenergy and biofuel production. For instance, the majority of the wood fueling biomass combustion facilities is the byproduct of commercial logging operations, rather than the result of forest management strategies (Barad, 2019; Beck Group, 2019). Additionally, logging operations are seen as counter to the aim of preserving trees as carbon sinks.

Biomass is currently used to generate electricity in California using two technologies: gasification and direct combustion. In 2019, California had twenty-six biomass power plants that utilized wood waste solids, and nineteen of these plants were operational and providing electricity to the grid (CEC, 2020). Together, these facilities account for roughly 1.6% of the electricity generated within California, with fuel sources specific to wood waste solids, which includes dead trees, wood scrap and paper mill residues (U.S. EIA, 2020). Figure 8 shows a map of tree mortality zones and operational biomass facilities in California, inclusive of plants that generate electricity or heat but do not supply power directly to the electric grid.

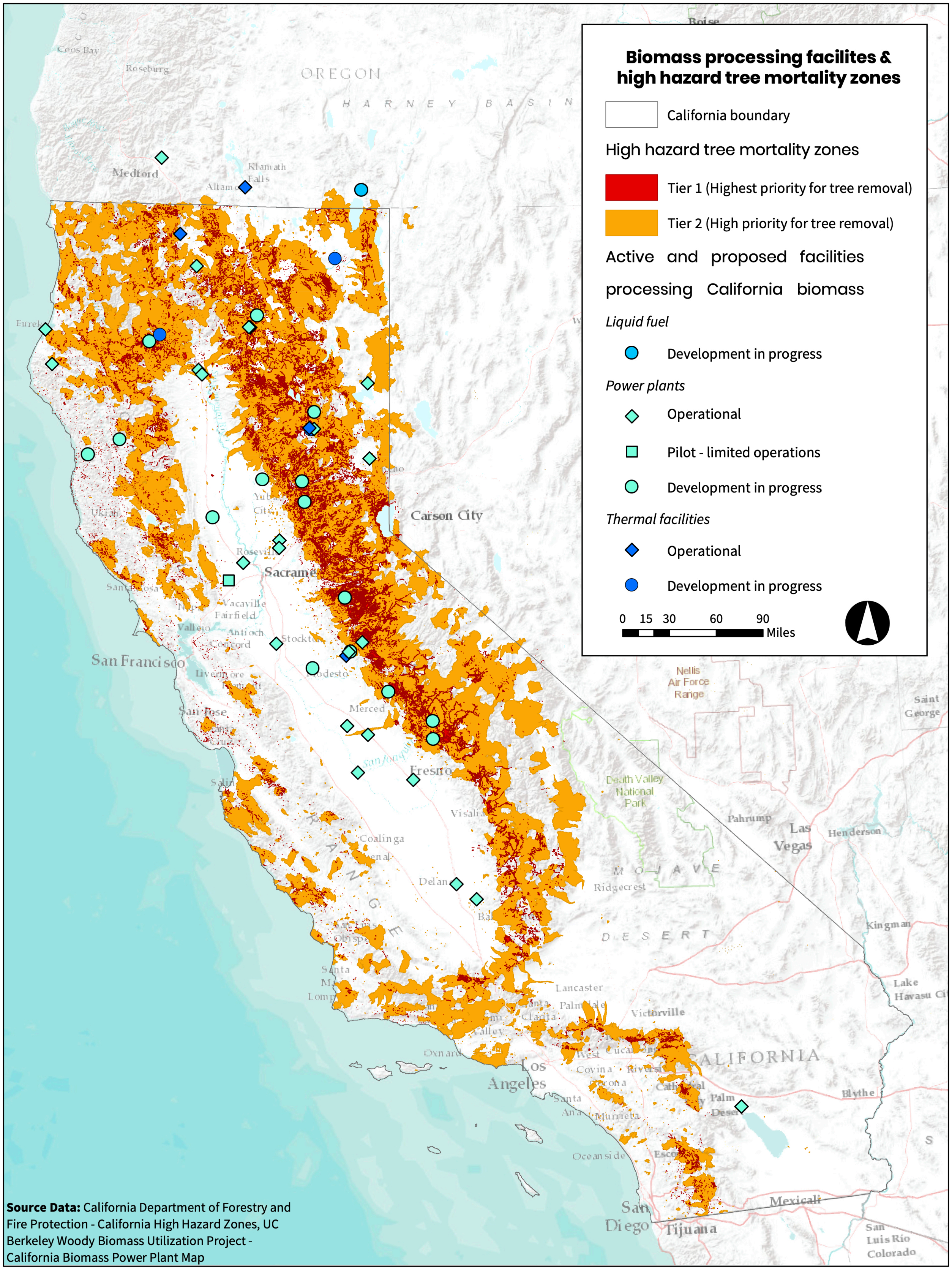


Figure 8. Biomass facilities and tree mortality zones.

Potential health implications of biomass power plants

The potential health implications of using biomass for electricity production depend on the quantity of fuel used, the technology used to generate electricity or heat, the location of these facilities, the timing of use with respect to air quality and atmospheric conditions, and the proximity, density and characteristics of nearby populations (Krieger et al., 2016). The process used to produce electricity from biomass, such as direct combustion or two-step process or gasification, significantly impacts the resulting emissions. While emissions of certain criteria air pollutants (PM_{10}, CO), volatile organic compounds and greenhouse gases from centralized biomass power generation facilities are estimated to be less than that of open pile burning, larger, traditional direct combustion biomass facilities in California are among the highest sources of PM and NO_x on the California electric grid (Krieger, 2020; Springsteen et al., 2011, 2015; TSS Consultants and Placer County Air Pollution Control District, 2011).

However, small-scale *gasification* technologies, such as those used to manufacture biochar, restrict airflow and produce a synthesis gas (syngas) that is combusted for energy, resulting in significantly lower NO_x emissions due to the supply of excess air during the combustion of syngas, a step which minimizes NO_x formation by diluting the combustion zone (TSS Consultants and Placer County Air Pollution Control District, 2011). NO_x can also be controlled by selective catalytic or non-catalytic reduction through the introduction of ammonia. However, gasification technology is less mature and more expensive in the United States, and therefore less common, and transporting fuel to these facilities could prove cost-prohibitive. Emission control technologies can be used to mitigate air pollution in any combustion process (including direct combustion and syngas combustion), but these use technologies may vary by facility and depend on regulatory requirements. Selection of emission controls technologies and continued operations of biomass facilities should consider emission impacts on air quality, health and climate.

Strategies to address potential health implications of biomass facilities

Site-specific assessments of the potential health impacts associated with biomass facility emissions would account for factors such as operation duration, meteorological conditions and proximity, density and characteristics of nearby populations. Using intake fraction — an estimate of exposure based on mass of pollutant emitted and mass of pollutant inhaled by nearby populations— exposure would likely be greater in and upwind of regions with higher population density. Biomass power plants are typically located in more rural areas as compared to other combustion-based power plants. The median population density living within one mile of all operational biomass facilities in California is about 1,400 people, and the most urban plant has 7,600 people living within one mile (Krieger, 2020).

Strategic placement of future biomass facilities and ongoing operation of existing facilities should consider both potential health impacts for nearby populations as well as locations of key tree mortality zones identified and mapped by CAL FIRE (Figure 8). The identified regions are classified as high hazard zones which represent areas of greatest tree-mortality associated with wildfire risk for people, property, and ecosystem health, and are of the highest priority for dead tree removal (CAL FIRE, 2019a; 2019b). Additionally, to minimize the cost of transporting fuels, biomass-to-energy facilities should be located in close proximity to tree mortality zones. Smaller, distributed biomass processing facilities can be sited in proximity to tree mortality zones, and have lower air pollutant emission rates than larger biomass plants; however, an increased number of small facilities may require the construction of additional transmission infrastructure to deliver electricity to population centers. Undergrounding of electrical lines is key given these facilities and transmission lines would be located within or directly adjacent to areas with high wildfire risk. Of note, in contrast to biomass facilities that rely on direct combustion, production of syngas does not require on-site combustion and syngas could be transported to locations other than where it is produced.

Research gaps and limitations relevant to biomass facilities

As an alternative to increasing prescribed burns, biomass facilities present a promising solution to managing excess fuel in forests. However, additional research about the frequency of biomass facility operations and emissions is critical to understanding the potential associated public health effects, particularly if new facilities will be constructed in the future. Previous research has compared emissions from open pile burns to emissions from biomass facilities, yet future investigations should evaluate and compare individual facility operations and emissions. A beneficial initiative regarding biomass facilities would be tracking pre-fire fuel treatments, such as forest thinning, metrics which could aid researchers and policy-makers in understanding the success of management strategies. These metrics could include data about biomass utilization, such as how much fuel is diverted to waste to energy facilities. Additional research and investment into cost reduction for emerging, distributed and lower-emission biomass gasification systems could also be explored.

3.3 Chemical fire suppression

In this section, we discuss the use of chemical fire suppressants to suppress wildfires once they have ignited, and the implications for public health (Section 3.3.1). Policies and approaches to address health hazards and risks (Section 3.3.2) and research gaps and limitations are also discussed (Section 3.3.3).

3.3.1 Chemical fire suppression: implications for public health

Chemical fire suppressants (fire retardants and foams) are used to help contain fires to protect infrastructure and human life. Fire retardants, generally salt-based and soluble in water, are used to coat fuels, depriving them of oxygen necessary to burn. Retardants are primarily released aerially in direct support of firefighting efforts on the ground and can also be used to preventatively treat high wildfire risk areas. Retardants are persistent in the environment. Foams, typically detergent-based and insoluble in water, are primarily used for short-term applications during wildfires along the WUI and when human lives are at risk (Carratt et al., 2017).

While no publicly available annual data are available about firefighting foam usage, Figure 9 shows annual reporting of fire retardant applied aerially on National Forest System lands throughout the United States and in California. Between 2012 and 2018, aerial fire retardant applied in California accounted for 38 - 66% of the annual aerial fire retardant applied throughout National Forest System lands in the United States (US Forest Service, 2020).

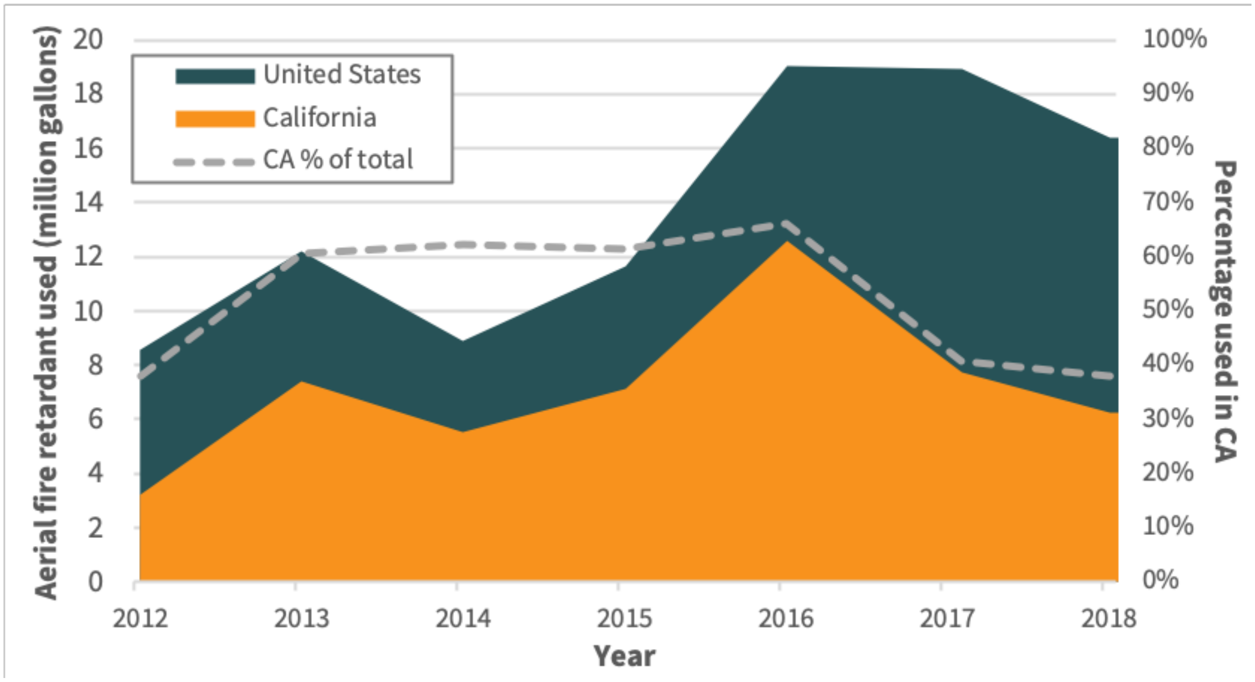


Figure 9. Gallons of aerial fire retardant used annually on National Forest System lands in California (**orange**) and in the United States (**green**), 2012 - 2018. **Grey** line shows the percentage of aerial fire retardant nationally used in California annually (Data source: US Forest Service, 2020).

Many chemicals used in fire retardant and foam formulations are considered proprietary and therefore are not publicly disclosed (Weiser, 2017), highlighting uncertainties about the toxicological properties of these compounds and their potential impacts on human health and the environment. While many unknowns remain about the composition of chemical fire suppressants, per- and polyfluoroalkyl substances (PFAS) have commonly been used in *firefighting foams*, used in close application fire suppression settings and in contrast to *fire retardants* which are typically used in aerial applications during wildfire. PFAS are also used in a wide array of consumer products, are very persistent in the environment and can bioaccumulate in the human body. PFAS have been widely detected in soils, surface water and groundwater throughout the United States, primarily at fire training facilities, military sites, airports, and industrial sites (ATSDR, 2018a). Most Americans tested have one or more PFAS in their blood (ATSDR, 2018b). Exposure to certain PFAS may impact endocrine and immune function and fertility, and has been associated with low birth weight, preeclampsia in pregnant women, and increases in cholesterol levels and cancer risk (ATSDR, 2019).

3.3.2 Addressing potential health and safety risks and impacts associated with chemical fire suppression

Numerous policies can be implemented to address potential health and safety risks and impacts associated with chemical fire suppression, including public disclosure and toxicological evaluation of constituents that comprise chemical fire suppressants, replacement of harmful fire suppression substances with safer alternatives, identification of water and soil contamination associated with fire suppressant application; and the establishment and enforcement of health-based response and notification levels and drinking water standards.

To address potential health and safety risks and impacts associated with chemical fire suppression, public disclosure of chemicals used in fire suppressants and fire-fighting foams is necessary. While disclosure of toxic flame retardants used in household products, such as household furniture, is required in the State of California (SB 1019; Leno, 2014), the same public disclosures are not required regarding chemical fire suppressants used for wildfire suppression. Chemical constituents that make up chemical fire suppressants should have well elucidated toxicological profiles that demonstrate little to no risk to human health and the environment. Given the persistence of fluorinated fire-fighting compounds, biodegradability should be prioritized in alternatives assessments for fire-fighting compounds.

Upon identification of fire suppressant constituents that pose risks to human health or the environment or have unknown toxicological profiles, compounds may be replaced by substances with known toxicological profiles that pose little to no toxicity to human health and the environment. While PFAS have been used for fire suppression across the globe, the European Union has phased out the production and use of fluorinated compounds (e.g., PFAS) for fire suppression under the chemical regulatory framework Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (ECHA, 2020). Numerous fluorine-free alternative fire suppressants have been developed, but third-party validation of performance standards and fluorine-free status needs to be evaluated; furthermore, toxicity of these chemical formulations also require further characterization and evaluation (NYS Pollution Prevention Institute, 2019). Under the Federal Aviation Administration (FAA) Reauthorization Act of 2018, airports will no longer be required to use fluorinated compounds for firefighting substances to meet performance standards (FAA Reauthorization Act, H.R. 302, 2018). In California, proposed SB 1044 (Allen, 2020) would mandate a ban on PFAS chemicals in firefighting foam. While not applicable to aerial application of fire *retardants* during wildfire suppression, this bill may be relevant for on-the-ground firefighting efforts by fire departments during active wildfire using firefighting foams.

To mitigate concerns about surface water contamination, fire suppressants can be applied away from surface water sources. In the United States, aerial application of fire retardants and foams is prohibited within 300 feet of waterways (US Forest Service, 2008), as these chemical formulations have been found to be toxic to aquatic life (Fagan, 2019). Additionally, application of fire retardants should be avoided in designated avoidance areas, which may include endangered, threatened or sensitive species. However, application is allowed if public safety and human life is threatened, and application of fire retardant is expected to alleviate the threat (US Forest Service, 2011b).

Regarding potential groundwater contamination, the State Water Resources Control Board (SWRCB) is currently conducting a phased investigation into PFAS contamination in California groundwater by targeting suspected sources of PFAS. The second phase of the PFAS investigation conducted from June through August 2019 focused on a source investigation and nearby drinking water well sampling in non-airport fire training areas and 2017-2018 urban wildfire areas (Newton et al., 2019). Results from this investigation are pending.

Recent changes in PFAS health-based advisory and regulatory drinking water standards

Drinking water standards for PFAS, compounds commonly used in firefighting foams, are becoming lower and more health protective. Notably, California reference levels for perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) recommended by the California Environmental Protection Agency Office of Environmental Health Hazard Assessment (OEHHA) and informed by recent toxicological reviews (ATSDR, 2018a) are significantly than federal standards (Table 3). However, these reference levels are currently lower than concentrations that can be reliably detected in drinking water using available technologies. Therefore, OEHHA recommended that SWRCB set notification levels at the lowest concentrations at which PFOA and PFOS can be reliably detected. Recently, the SWRCB updated treated water notification levels and response levels for PFOA and PFOS. Notification levels and response levels are both nonregulatory health-based measures that can be used when regulatory drinking water standards, such as maximum contaminant levels (MCL) have not been established. Notification levels warrant water suppliers to notify governing boards and conduct further monitoring or further monitoring and assessment, whereas response levels recommend water systems consider taking a water source out of service or provide additional treatment, if available. SWRCB also tasked OEHHA with developing a public health goal for PFOA and PFOS as a next step toward establishing MCLs (SWRCB, 2020).

Table 3. Federal and state health-based advisory levels and California notification and response levels for PFOA and PFOS.

Compound	U.S. EPA health-based advisory level[1]	OEHHA reference level for cancer[2]	OEHHA reference level for noncancer	SWRCB notification level (NL)	SWRCB response level (RL)
PFOA	70 ppt[3]	0.1 ppt	2 ppt	5.1 ppt	10 ppt
PFOS	70 ppt	0.4 ppt	7 ppt	6.5 ppt	40 ppt

[1] Based on lifetime exposure; levels set for individual and combined concentration of PFOA and PFOS in drinking water (U.S. EPA, 2016b).
[2] Would not pose more than a one in a one million cancer risk based on lifetime exposure.
[3] Parts per trillion.

3.3.3 Chemical fire suppression and health: research gaps and limitations

As discussed above, the chemicals used in chemical fire suppressants are often proprietary and are not disclosed publicly. Without knowing specifics about chemical formulations, it is impossible to assess the toxicity of compounds in fire suppressants. Further, constituents that comprise past and current chemical fire suppressants may not have developed toxicological profiles, raising questions about their toxic potential on human health and the environment.

Furthermore, as different chemical formulations have been adopted for fire suppression, further research is needed to identify safe and effective substitutions. Fluorine-free alternatives require composition to be well-characterized and verified that they are fluorine-free and meet performance standards. Additionally, these alternative fire suppressants should also be evaluated for ecotoxicity and toxic potential in humans.

Given that PFAS have been used in firefighting foams historically throughout the United States and in California, and are highly persistent in the environment, the extent of PFAS contamination in the broader environment is an area of continuous research. The extent of PFAS groundwater contamination attributable to fire suppression activities in California, including firefighting foam usage related to wildfire suppression, is largely unknown, although current, ongoing investigations by the SWRCB will provide additional information.

Further research is needed to determine the extent of population exposure to PFAS compounds and other compounds in chemical fire suppressants associated with wildfire suppression activities. Additionally, while there are many sources of PFAS in the environment, the extent of PFAS exposure in human populations, specifically from firefighting foams, is also currently unknown. Additional research is needed regarding the potential health impacts associated with PFAS exposure, specifically low dose and long-term exposure over time in human populations.

4.0 Addressing California wildfires in a public health context: discussion and next steps

4.1 Summary

In this report, we reviewed public health dimensions of wildfire, including the health hazards indirectly introduced via environmental exposure pathways (air, water, and soil), and impacts on mental health. Additionally, we also discuss the public health dimensions of various approaches to wildfire prevention, mitigation and suppression including public safety power shutoffs (PSPS), forest management strategies (e.g., prescribed burns), and chemical fire suppression. Detailed report findings, including specific examples and policy models aimed to mitigate potential health risks and identified research gaps and limitations, are summarized in the Executive Summary, Table ES-1.

4.2 Emerging and compounding health risks related to wildfire response and preparedness

Compounding health and safety risks associated with climate change

Forests are important carbon sinks where carbon is sequestered from the atmosphere. Wildfires in forests and the intentional burning of biomass (e.g., prescribed burns, biomass-to-energy facilities, etc.) indirectly impact human health through the emission of carbon dioxide, leading to the exacerbation of climate change. Simultaneously, wildfires are expected to increase in the decades to come alongside other climate-induced risks to health, such as increased frequency and intensity of heatwaves. Ensuring continuous access to electricity, water and other utilities is critical to reduce health risks and limit mortality and morbidity during heat events and natural disasters, including wildfires and hurricanes (Phillips et al., 2020). Additionally, costs related to these compounding risks are significant; while not addressed in this report, costs and losses associated with California wildfire will be addressed in a forthcoming report by the California Council on Science and Technology (CCST).[22]

Coronavirus Disease 2019 (COVID-19)

COVID-19, an infectious disease caused by an emergent coronavirus (SARS-CoV-2), is now a global pandemic affecting populations across the world. The disease is primarily transmitted through small droplets expelled from the nose or mouth of an infected person that enter the air and land on nearby surfaces. An individual may become infected if they breathe in respiratory droplets from an infected individual or by touching surfaces with these respiratory droplets and then touching their eyes, nose, or mouth (WHO, 2020). Many individuals

[22] CCST. Cost and Losses of Wildfires in California. https://ccst.us/reports/costs-and-losses-of-wildfires-in-california/.

that contract COVID-19 may remain asymptomatic, while others may develop moderate or severe symptoms, including death. As there is no treatment or vaccine currently available at the time of this writing, frequent handwashing, wearing masks in public spaces, and physical distancing from others are recommended practices aimed at stopping the spread of the virus (CDC, 2020a). The recent emergence of COVID-19 presents many challenges to addressing wildfire risks in California, with respect to efforts to prevent and prepare for the frequency and intensity of wildfire and efforts to mitigate risks and impacts to public health and safety during active wildfire events.

COVID-19 risks have complicated preparations for wildfire season, including efforts to recruit and train firefighters, conduct controlled burns, create fuel breaks, and perform maintenance on aboveground electrical poles and wires. In late March 2020, the U.S. Forest Service suspended controlled burn activities due the risk of COVID-19 spread among firefighters (Groom, 2020). The pandemic has also slowed PG&E's fire-prevention efforts and will continue to result in disruptions in personnel availability and deployment (Bay Area News Group Editorial Board, 2020). California state prisons, which typically supply a significant portion of the state's firefighting force, have experienced COVID-19 outbreaks, causing the release of thousands of incarcerated persons since March (CDCR, 2020). Additionally, COVID-19 risks in Conservation Camps housing firefighting inmates have forced numerous inmate crews under lockdown to comply with public health guidance (Fimrite, Koseff and Dizikes, 2020). In response the COVID-19 pandemic and its economic implications, state budget adjustments have resulted in reduced funding for home retrofitting measures and increased funding for the California Office of Emergency Services and for CAL FIRE to hire additional fire personnel and provide resources for fire response (CBS SF, 2020).

Wildfire emergency response efforts may also face complications due to the COVID-19 pandemic. Evacuation efforts involve transporting and sheltering displaced populations in indoor environments where individuals may come into contact with people who they may not otherwise interact with, potentially introducing new opportunities for transmission of the virus. Similarly, on days with heavy wildfire smoke, indoor public spaces with filtered air and air conditioning have been promoted as clean air spaces where individuals can reduce their exposure to wildfire smoke. These enclosed, indoor physical conditions are risk factors for the spread of COVID-19. In response to sheltering concerns in relation to the COVID-19 pandemic, the California Department of Social Services and the California Office of Emergency Services have updated their care and sheltering measures by requiring evacuees to receive a health screen when entering a shelter facility. Evacuees will also have access to medical and mental healthcare, and Gov. Newsom has announced plans to procure other housing for individuals to shelter in non-congregated places (Martichoux, 2020). Nevertheless, these conditions may increase the spread of COVID-19 in affected communities, especially if additional precautionary measures are not taken and if the number of displaced individuals exceeds the capacity of the available resources.

Furthermore, recent studies suggest that long-term exposure to $PM_{2.5}$ — a primary component of wildfire smoke — is associated with an increased risk of death from COVID-19 in the United States (1 $\mu g/m^3$ increase in $PM_{2.5}$ associated with an 8% increase in death rate) (Wu et al., 2020). As respiratory symptoms (e.g., shortness of breath and difficulty breathing) are primary symptoms in moderate to severe COVID-19 cases, additional exposure to air pollution, such as wildfire smoke, may exacerbate the condition (CDC, 2020b). These findings are bolstered by results of a recent meta-analysis that found that active smoking is a risk factor for progression of COVID-19, with smokers having higher odds of COVID-19 progression than never smokers (Patanavanich and Glantz, 2020).

In sum, addressing wildfire risks amid the COVID-19 pandemic is a complex challenge. The steps taken by California decisionmakers and communities to meet this challenge will hold implications for not only Californians, but for the global community. Therefore, it is critical – perhaps now more than ever – to incorporate the best available public health science into wildfire decision making and policy conversations.

4.3 Key findings, conclusions and recommendations

Below, we provide the key findings, conclusions and recommendations (FCRs) from our review of the literature, organized under overarching principles. The aim of these FCRs is to inform efforts to integrate public health into decision-making regarding wildfire emergency response and recovery and wildfire prevention, mitigation and suppression efforts in California.

Principle #1. Integrated, dense, resilient, and rapidly deployable air quality surveillance is beneficial to assess smoke exposure during wildfires and prescribed burns.

Increase resolution of air quality monitoring

Finding 1.1. Existing stationary air monitoring networks are distributed across California with low spatial density, in particular in high wildfire risk areas. As such, real-time air quality data during wildfire and prescribed burn events are often not readily available.

Conclusion 1.1. While current stationary air monitoring networks support assessments of regional air quality, these networks may not reflect local air quality, introducing uncertainty to the information necessary to estimate wildland smoke exposure and engage in enhanced risk communication and management efforts. Rapid deployment of air quality monitors may be necessary to capture air quality data during wildland fire smoke events in areas that lack air quality monitors. Efforts underway pursuant to Assembly Bill 617 (AB 617) are forming a model of how spatial intensity of this coverage could expand.

Recommendation 1.1. Agencies with jurisdiction should integrate or support the integration of air quality data from disparate air quality networks throughout the State of California and support additional air quality surveillance in high wildfire risk areas and in areas of high population density. These efforts could build upon the AB 617 community air quality monitoring program as a model to expand geo-spatial intensity of air quality data.

Researchers, as well as local and state air quality agencies should be prepared to capture air quality data in real-time as wildfires occur and build these data into publicly accessible and real time reporting tools. Emerging efforts by the California Air Resources Board may help to address some of these air quality monitoring needs.

Ensure zero-emission backup energy sources for air quality monitors

Finding 1.2. Air quality monitoring networks largely rely on power provided by utility-scale electricity transmission infrastructure to collect and transmit air quality data and this infrastructure is vulnerable to failure and de-energization during wildfires and public safety power shutoffs (PSPS), respectively.

Conclusion 1.2. In the event of PSPS and other unexpected power outages, air quality monitoring networks may fail to collect air quality data to inform decision-making, risk communication and risk management.

Recommendation: 1.2. Air monitoring networks should be supported by zero-emission back-up energy sources (e.g., solar arrays, battery power, or other distributed energy resources) to provide power in the event of unexpected or utility-initiated loss of access to electricity.

Characterize the chemical composition of wildfire and prescribed fire smoke

Finding 1.3. The chemical composition of wildfire smoke is highly variable and is dependent on multiple factors, including but not limited to the materials that burn and the temperature of combustion. Wildfires directly and indirectly, through atmospheric transformation, emit criteria air pollutants and various toxic air contaminants. Existing characterizations of wildfire smoke composition and associated exposures often focus on criteria air pollutants, primarily particulate matter and ozone. Air pollutant emissions from prescribed burns may differ from air pollutant emissions from wildfires, particularly wildfires that result in the combustion of structural materials (e.g., homes, cars, businesses, etc.). Relatedly, few studies evaluate the differences in smoke composition between prescribed burns and wildfires.

Conclusion 1.3. While studies have investigated the patterns and concentrations of particulate matter and tropospheric ozone associated with wildfire smoke, these studies are limited by the exclusion of a wider range of health-damaging air pollutants that may also be present (e.g., toxic air contaminants). Expanded information regarding the concentration and distribution of chemicals in wildfire smoke and prescribed fire smoke will help inform risk communication and management efforts aimed to protect populations from the impacts of both wildfire and prescribed burn activities.

Recommendation 1.3. Agencies with jurisdiction should support air quality and exposure surveillance that includes a broader array of health-damaging air pollutants beyond criteria pollutants including, but not limited to VOCs and ultrafine particles. This information should be integrated into risk communication and management efforts. Further, agencies with jurisdiction could support air quality monitoring and research that identifies and characterizes the drivers of wildfire smoke composition. Future exposure and risk assessments should consider multiple pollutant exposures associated with smoke from wildfire and further research is also needed to assess chronic (repeated) exposure to prescribed fire smoke and potential health risks.

Principle #2. Detailed and integrated health outcome surveillance during and following wildfire is necessary to support epidemiological investigations, identify disproportionate health risks and impacts, and implement effective public health interventions.

Evaluate additional health outcomes and chronic (repeated) exposures and outcomes

Finding 2.1. The existing peer-reviewed literature indicates a positive association between wildfire smoke exposure and various adverse health outcomes, including eye irritation, respiratory outcomes (asthma exacerbation, bronchitis, dyspnea and chronic obstructive pulmonary disease, and increased hospital admissions for respiratory illness); adverse birth outcomes; out-of-hospital cardiac arrests, and premature mortality. Commonly used public health metrics (deaths, hospitalizations, emergency department visits) do not comprehensively measure the total public health impact of wildfire smoke exposure, as these measures exclude subclinical or asymptomatic effects and impacts that take time to manifest.

Conclusion 2.1. The literature focused on associations between wildfire smoke exposure and various health outcomes is expansive for some health outcomes, and limited for others. For instance, health studies in populations repeatedly exposed to wildfire fire smoke have not been undertaken. A comprehensive health surveillance system would help to quantify the magnitude of health effects that result from wildfires and could result in more effective public health interventions.

Recommendation 2.1. Future research on health impacts associated with wildfire smoke exposure should assess understudied health outcomes including, metabolic disorders, pediatric cognitive development, cognitive decline among older adults, maternal health, as well as mental health outcomes and health outcomes with long latency (e.g., cancer). Long-term surveillance of populations repeatedly exposed to wildland fire smoke can help to evaluate the effects of repeated exposures. Additionally, stress should be examined for its role in the relationship between wildfire smoke exposure and various health outcomes.

Support mental health surveillance and mental health services

Finding 2.2. Events associated with wildfires (e.g., destruction of home and community, the process or threat of evacuation, and perception of risk) may contribute to mental health burdens or exacerbate existing mental health conditions in affected communities.

Conclusion 2.2. Mental health impacts can be mitigated by ensuring sufficient services are available to meet the needs of populations undergoing traumatic events. Mental health research may be informed by recent wildfire events and other natural disasters.

Recommendation 2.2. Additional studies are needed to evaluate wildfire smoke exposure and mental health outcomes, as wildfire smoke events may increase in frequency and intensity for certain populations due to climate change and other drivers. Mental health outcomes should be included in health surveillance during and after wildfire events, as well as an exploration of other factors tied to wildfires that influence mental health (e.g., the potential increase in experiences of homelessness in communities where properties have been damaged by fire). Studies can additionally evaluate more widespread mental health impacts associated with wildfires on broader populations via vicarious traumatization.

Principle #3. Strategic deployment of distributed clean energy resources can provide backup power to support critical services during wildfires, public safety power shutoffs (PSPS) and other natural disasters and grid outages.

Finding 3.1. PSPS – or the de-energization of electricity transmission infrastructure – is a critical tool to prevent wildfires. However, the continuity of electricity in communities is also fundamental to support critical public health services during wildfires and other natural disasters. During the 2019 wildfire season, public safety power shutoffs (PSPS) for wildfire prevention resulted in numerous documented impacts to public health and safety. These health and safety implications of PSPS are noted at various settings, including residential (e.g., the inability to refrigerate medications and food, breast milk, pump water, filter indoor air, and regulate indoor temperature, power medical devices, and access emergency information via the internet); community (e.g., inability to pump and deliver water through distribution systems, traffic accidents due to traffic light outages; lack of cellular network for communication); and healthcare settings (e.g., rescheduling of medical procedures). Distributed clean energy resources (e.g., solar+storage systems) provide electricity and can serve as backup power options that, unlike diesel-powered generators, do not contribute to the cumulative burden of climate-forcing and health-damaging air pollutants.

Conclusion 3.1. PSPS should remain a tool available to reduce risk of wildfires. However, creating resilient and reliable electric power systems and preparing communities for power outages are critical to address decrease public health impacts of PSPS. PSPS also present health hazards, risks and impacts for populations both within and outside of wildfire risks areas. Distributed clean energy resources (e.g., solar and battery storage) can provide essential electricity to residences, critical facilities, and communities at large during wildfires, PSPS and other emergencies and natural disasters.

Recommendation 3.1. Agencies with jurisdiction should support advanced grid solutions to monitor for wildfire risk and implement targeted, rather than widespread, PSPS, when possible. Agencies with jurisdiction should support the development and siting of distributed clean energy resources to provide backup power and support critical services during wildfires, PSPS and other natural disasters and grid outages. Approaches to support the proliferation of these energy resources could be in the form of market-based incentives (e.g., rebates and financial incentives), power procurement requirements, or energy requirements during post-disaster community rebuilds.

Principle #4. Small-scale biomass-to-energy facilities should be evaluated further in the context of energy reliability, wildfire risk mitigation, and impacts to air quality compared to other vegetation management practices.

Finding 4.1. Vegetation management is an important pillar of wildfire risk management. Wood biomass in wildfire prone areas of the state may either be burned by wildfire, combusted via prescribed or pile burns or burned to generate electricity, all of which contribute to degraded air quality. Traditional direct combustion biomass facilities in California are among the highest sources of particulate matter (PM) and nitrogen oxides (NO_X) on the California electric grid. Small-scale gasification technologies (e.g., biochar) result in lower NO_X emissions, but in the United States these technologies are less mature and more expensive, and therefore less common. The health implications of wood biomass utilization for electricity generation are largely dependent on the quantity of fuels used, technology used to generate electricity or heat, the location of these facilities, the timing of use with respect to air quality and atmospheric conditions and the proximity, density and demographic characteristics of nearby populations.

Conclusion 4.1. Approaches to vegetation management should take air quality and public health factors into consideration. Strategic siting of future small-scale, distributed biomass facilities and ongoing operation of existing facilities should consider potential air quality and health impacts and key tree mortality and vegetation management zones.

Recommendation 4.1. Additional research should be undertaken to evaluate human health, energy reliability, air quality, ecological, and other implications associated with approaches to vegetation management. Research should evaluate the differential impacts to air quality between vegetation management techniques including but not limited to wildfire, prescribed and pile burns, and the siting of small (e.g., 5 MW), distributed biomass-to-energy facilities in key vegetation management zones to provide simultaneous benefits of fuel reduction and more resilient access to power in places that may also be likely to experience wildfire and PSPS. Detailed tracking of biomass from fuel reduction efforts can be used to verify that biomass is combusted in settings that prioritize reducing air quality impacts (e.g., biomass-to-energy facilities vs. open pile burns). Additional research and investment into cost reduction for emerging, distributed and lower-emission biomass gasification systems could also be explored.

Principle #5. While chemical fire suppressants are critical to protect human life and infrastructure from wildfire, numerous uncertainties remain regarding potential health risks associated with the use of these compounds.

Finding 5.1. While some ingredients in chemical fire suppressants are well-characterized, complete chemical formulations of fire retardants and foams are considered trade secrets and are not publicly disclosed.

Conclusion 5.1. Public disclosure of chemical formulations in chemical fire suppressants is essential to assess potential risks to human health and the environment.

Recommendation 5.1. Chemical formulations of fire suppressants should be publicly disclosed. Compounds in chemical fire suppressants that pose risks to human health or the environment or have unknown toxicological profiles should be replaced by substances with known toxicological profiles that pose little to no toxicity to human health and the environment. Alternatives assessments should require that alternatives have well-characterized chemical compositions, are evaluated for ecotoxicity and toxic potential in humans, and are tested to ensure performance standards are met.

Principle #6. Wildfire response and wildfire-related public health interventions need to be re-evaluated and adapted amid the COVID-19 global pandemic.

Finding 6.1. COVID-19, an infectious disease caused by an emergent coronavirus (SARS-CoV-2), is now a global pandemic affecting the global human population with no known treatment or vaccine. Key wildfire mitigation strategies including evacuations (e.g., transport and indoor sheltering of displaced populations) and clean air spaces (e.g., indoor public spaces that provide filtered air to reduce wildfire smoke exposure) present physical conditions that are clear risk factors for transmission of COVID-19, particularly if additional precautionary measures are not undertaken.

Conclusion 6.1. Strategies to mitigate health and safety risks associated with wildfire through existing wildfire emergency response efforts (e.g., evacuations and indoor shelters) and proposed public health interventions (e.g., clean air spaces) may increase risk of COVID-19 transmission among wildfire-impacted populations.

Recommendation 6.1. Multiple agencies have already begun efforts to re-evaluate typical wildfire emergency response activities in the context of COVID-19, and these efforts should continue to adapt to evolving circumstances. Agencies with jurisdiction should follow current and future CDC, WHO, and state and local health department guidance to reduce the spread of COVID-19 during wildfire emergency response activities and wildfire smoke exposure interventions, such as wearing face coverings, in particular when adequate physical distancing may not be possible.

5.0 Abbreviated terms

AB	Assembly Bill
CAL FIRE	California Department of Forestry and Fire Protection
Cal OES	California Governor's Office of Emergency Services
Cal/OSHA	California Division of Occupational Safety and Health
CARB	California Air Resources Board
CCLHO	California Conference of Local Health Officers
CDPH	California Department of Public Health
CEC	California Energy Commission
COPD	chronic obstructive pulmonary disease
CPUC	California Public Utilities Commission
DBP	disinfection byproduct
DTSC	California Department of Toxic Substances Control
FEMA	Federal Emergency Management Agency (FEMA)
NAAQS	National Ambient Air Quality Standard
O_3	ozone
OEHHA	California Office of Environmental Health Hazard Assessment
OHCA	out-of-hospital cardiac arrests
OSHPD	California's Office of Statewide Health Planning and Development
PAH	polycyclic aromatic hydrocarbon
PFAS	per- and poly-fluoroalkyl substances
PFIRS	Prescribed Fire Information Reporting System
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PG&E	Pacific Gas and Electric
PM	particulate matter
PSPS	public safety power shutoff
SB	Senate Bill
SF DPH	San Francisco Department of Public Health
SGIP	Self-Generation Incentive Program
WUI	wildland-urban interface
VOC	volatile organic compound
U.S. EPA	United States Environmental Protection Agency

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7.0 Appendix

Table A-1. Selection of health-relevant compounds potentially emitted from wildfire smoke upon combustion of biomass or structural materials.

	Materials burned	
Health relevance	**Biomass**	**Structural**
Known human carcinogens (OEHHA Proposition 65)	Benzene[1] Formaldehyde[1] Styrene[1] Benzo[a]pyrene[3] Dibenz[a,h]anthracene[3] Particulate matter (PM)[2]	Benzene[1] Formaldehyde[1] Styrene[1] Benzo[a]pyrene[3] Arsenic[4] Chromium[4] Asbestos[5] Particulate matter (PM)[2]
Asphyxiants (Fabian et al., 2011; Purser, 2010)	Carbon monoxide (CO)[2] Hydrogen sulfide (H_2S)[5]	Carbon monoxide (CO)[2] Hydrogen sulfide (H_2S)[5] Hydrogen cyanide (HCN)[5]
Reproductive or developmental toxicants (OEHHA Proposition 65)	Benzene[1]	Benzene[1] Lead[3] Hydrogen cyanide (HCN)[5]
Respiratory irritants (Adetona et al., 2016; Fabian et al., 2011)	Acrolein[1] Fluorene[3] Particulate matter (PM)[2] Nitrogen oxides (NOx)[2]	Hydrogen chloride (HCl)[5] Phenols[5] Particulate matter (PM)[2] Nitrogen oxides (NOx)[2]

[1] Volatile organic compounds (VOC)
[2] Criteria air pollutants
[3] Polycyclic aromatic hydrocarbons (PAHs)*
[4] Heavy metals*
[5] Other health-relevant air pollutants
*Class of compounds includes specific chemicals that may or may not be associated with reported health effect or combustion material.

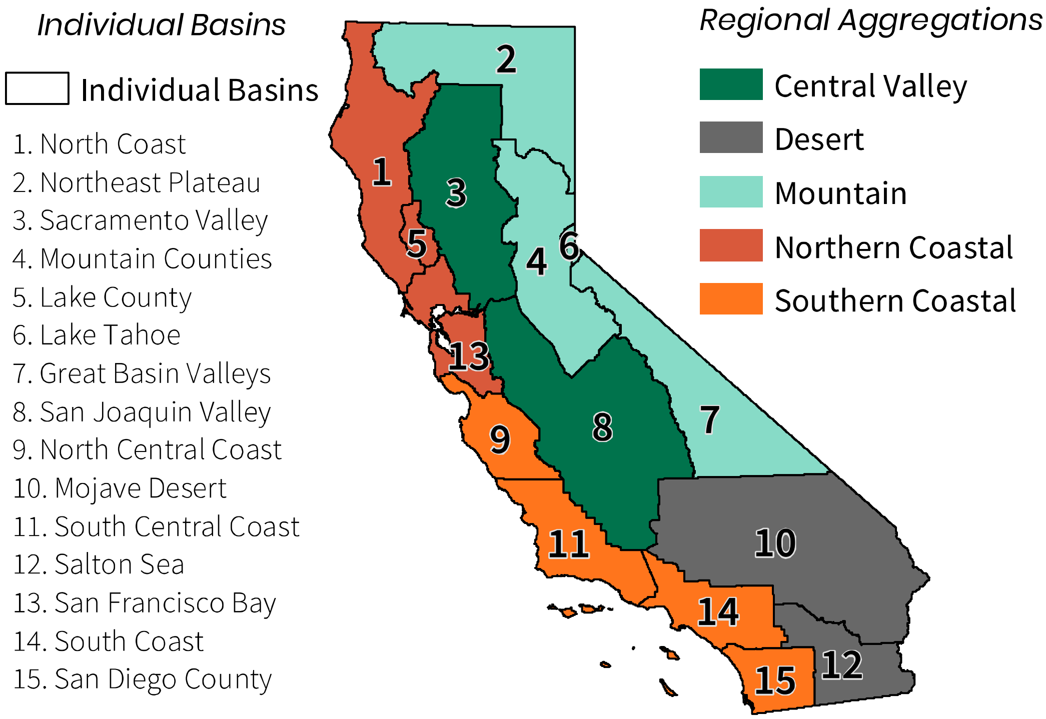

Figure A-1. Map of California air basins aggregated by region.

Table A-2. Changes in county-level population in Very High Fire Hazard Severity Zones (VHFHSZ) between 2000 and 2010.

County	Fire Hazard Class	County Area (%)	Population 2000	Pop. in VHFHSZ 2000 (%)	Population 2010	Pop. in VHFHSZ 2010 (%)	10-Year Change	10-Year Change (%)	ΔFHSZ (%) / ΔCounty (%)
Alameda	VHFHSZ	7.4%	67,115	4.6%	71,499	4.7%	4,384	6.5%	1.42
	Countywide	100.0%	1,443,741		1,510,271		66,530	4.6%	
Alpine	VHFHSZ	2.9%	18	1.5%	17	1.4%	-1	-5.6%	2.03
	Countywide	100.0%	1,208		1,175		-33	-2.7%	
Amador	VHFHSZ	21.3%	9,831	28.0%	9,933	26.1%	102	1.0%	0.12
	Countywide	100.0%	35,100		38,091		2,991	8.5%	
Butte	VHFHSZ	28.6%	39,222	19.3%	39,871	18.1%	649	1.7%	0.20
	Countywide	100.0%	203,171		220,000		16,829	8.3%	
Calaveras	VHFHSZ	46.7%	17,502	43.2%	18,751	41.1%	1,249	7.1%	0.58
	Countywide	100.0%	40,554		45,578		5,024	12.4%	
Colusa	VHFHSZ	6.0%	405	2.2%	239	1.1%	-166	-41.0%	-2.95
	Countywide	100.0%	18,804		21,419		2,615	13.9%	
Contra Costa	VHFHSZ	8.2%	45,289	4.8%	44,741	4.3%	-548	-1.2%	-0.11
	Countywide	100.0%	948,816		1,049,025		100,209	10.6%	
Del Norte	VHFHSZ	16.3%	1,574	5.7%	1,520	5.3%	-54	-3.4%	-0.86
	Countywide	100.0%	27,507		28,610		1,103	4.0%	
El Dorado	VHFHSZ	28.0%	60,871	38.9%	61,655	34.1%	784	1.3%	0.08
	Countywide	100.0%	156,299		181,058		24,759	15.8%	
Fresno	VHFHSZ	2.0%	953	0.1%	968	0.1%	15	1.6%	0.10
	Countywide	100.0%	799,407		930,450		131,043	16.4%	
Glenn	VHFHSZ	8.3%	158	0.6%	157	0.6%	-1	-0.6%	-0.10
	Countywide	100.0%	26,453		28,122		1,669	6.3%	
Humboldt	VHFHSZ	25.7%	4,588	3.6%	4,805	3.6%	217	4.7%	0.74
	Countywide	100.0%	126,518		134,623		8,105	6.4%	
Imperial	VHFHSZ	0.2%	39	0.0%	41	0.0%	2	5.1%	0.23
	Countywide	100.0%	142,361		174,528		32,167	22.6%	
Inyo	VHFHSZ	0.0%	0	0.0%	0	0.0%	0	0.0%	0.00
	Countywide	100.0%	17,945		18,546		601	3.3%	
Kern	VHFHSZ	5.7%	9,344	1.4%	11,967	1.4%	2,623	28.1%	1.04
	Countywide	100.0%	661,645		839,631		177,986	26.9%	
Kings	VHFHSZ	0.3%	0	0.0%	1	0.0%	1	0.0%	0.00
	Countywide	100.0%	129,461		152,982		23,521	18.2%	
Lake	VHFHSZ	28.6%	16,281	27.9%	16,970	26.2%	689	4.2%	0.39
	Countywide	100.0%	58,309		64,665		6,356	10.9%	
Lassen	VHFHSZ	11.5%	7,371	21.8%	7,487	21.5%	116	1.6%	0.50
	Countywide	100.0%	33,828		34,895		1,067	3.2%	
Los Angeles	VHFHSZ	24.8%	795,793	8.4%	841,919	8.6%	46,126	5.8%	1.84
	Countywide	100.0%	9,519,338		9,818,605		299,267	3.1%	
Madera	VHFHSZ	1.8%	1,671	1.4%	1,520	1.0%	-151	-9.0%	-0.40
	Countywide	100.0%	123,109		150,865		27,756	22.5%	
Marin	VHFHSZ	2.9%	14,293	5.8%	14,949	5.9%	656	4.6%	2.22
	Countywide	100.0%	247,289		252,409		5,120	2.1%	

County	Fire Hazard Class	County Area (%)	Population 2000	Pop. in VHFHSZ 2000 (%)	Population 2010	Pop. in VHFHSZ 2010 (%)	10-Year Change	10-Year Change (%)	ΔFHSZ (%) / ΔCounty (%)
Mariposa	VHFHSZ	6.5%	1,219	7.1%	1,409	7.7%	190	15.6%	2.38
	Countywide	100.0%	17,130		18,251		1,121	6.5%	
Mendocino	VHFHSZ	29.1%	11,352	13.2%	11,682	13.3%	330	2.9%	1.59
	Countywide	100.0%	86,265		87,841		1,576	1.8%	
Merced	VHFHSZ	0.0%	0	0.0%	0	0.0%	0	0.0%	0.00
	Countywide	100.0%	210,554		255,793		45,239	21.5%	
Modoc	VHFHSZ	7.2%	483	5.1%	503	5.2%	20	4.1%	1.65
	Countywide	100.0%	9,449		9,686		237	2.5%	
Mono	VHFHSZ	0.4%	206	1.6%	165	1.2%	-41	-19.9%	-1.90
	Countywide	100.0%	12,853		14,202		1,349	10.5%	
Monterey	VHFHSZ	18.4%	32,559	8.1%	29,903	7.2%	-2,656	-8.2%	-2.47
	Countywide	100.0%	401,762		415,057		13,295	3.3%	
Napa	VHFHSZ	30.1%	9,186	7.4%	7,807	5.7%	-1,379	-15.0%	-1.53
	Countywide	100.0%	124,279		136,484		12,205	9.8%	
Nevada	VHFHSZ	41.6%	42,747	46.4%	45,359	45.9%	2,612	6.1%	0.84
	Countywide	100.0%	92,033		98,764		6,731	7.3%	
Orange	VHFHSZ	30.8%	191,253	6.7%	216,445	7.2%	25,192	13.2%	2.29
	Countywide	100.0%	2,846,289		3,010,232		163,943	5.8%	
Placer	VHFHSZ	25.7%	23,615	9.5%	23,072	6.6%	-543	-2.3%	-0.06
	Countywide	100.0%	248,399		348,432		100,033	40.3%	
Plumas	VHFHSZ	20.5%	7,206	34.6%	6,983	34.9%	-223	-3.1%	0.79
	Countywide	100.0%	20,824		20,007		-817	-3.9%	
Riverside	VHFHSZ	25.9%	363,720	23.5%	543,013	24.8%	179,293	49.3%	1.18
	Countywide	100.0%	1,545,387		2,189,641		644,254	41.7%	
Sacramento	VHFHSZ	0.2%	78	0.0%	124	0.0%	46	59.0%	3.69
	Countywide	100.0%	1,223,499		1,418,788		195,289	16.0%	
San Benito	VHFHSZ	17.3%	1,434	2.7%	2,222	4.0%	788	55.0%	14.37
	Countywide	100.0%	53,234		55,269		2,035	3.8%	
San Bernardino	VHFHSZ	5.5%	458,902	26.8%	574,165	28.2%	115,263	25.1%	1.32
	Countywide	100.0%	1,709,434		2,035,210		325,776	19.1%	
San Diego	VHFHSZ	64.4%	454,049	16.1%	566,673	18.3%	112,624	24.8%	2.48
	Countywide	100.0%	2,813,833		3,095,313		281,480	10.0%	
San Francisco	VHFHSZ	0.0%	0	0.0%	0	0.0%	0	0.0%	0.00
	Countywide	100.0%	776,733		805,235		28,502	3.7%	
San Joaquin	VHFHSZ	0.0%	1	0.0%	1	0.0%	0	0.0%	0.00
	Countywide	100.0%	563,598		685,306		121,708	21.6%	
San Luis Obispo	VHFHSZ	25.1%	23,268	9.4%	22,555	8.4%	-713	-3.1%	-0.33
	Countywide	100.0%	246,681		269,637		22,956	9.3%	
San Mateo	VHFHSZ	13.7%	39,607	5.6%	40,515	5.6%	908	2.3%	1.44
	Countywide	100.0%	707,161		718,451		11,290	1.6%	
Santa Barbara	VHFHSZ	16.9%	32,347	8.1%	31,182	7.4%	-1,165	-3.6%	-0.59
	Countywide	100.0%	399,347		423,895		24,548	6.1%	
Santa Clara	VHFHSZ	19.3%	26,302	1.6%	27,823	1.6%	1,521	5.8%	0.98
	Countywide	100.0%	1,682,585		1,781,642		99,057	5.9%	
Santa Cruz	VHFHSZ	2.0%	846	0.3%	815	0.3%	-31	-3.7%	-1.38
	Countywide	100.0%	255,602		262,382		6,780	2.7%	

County	Fire Hazard Class	County Area (%)	Population 2000	Pop. in VHFHSZ 2000 (%)	Population 2010	Pop. in VHFHSZ 2010 (%)	10-Year Change	10-Year Change (%)	ΔFHSZ (%) / ΔCounty (%)
Shasta	VHFHSZ	52.1%	68,672	42.1%	72,461	40.9%	3,789	5.5%	0.64
	Countywide	100.0%	163,256		177,223		13,967	8.6%	
Sierra	VHFHSZ	19.0%	568	16.0%	691	21.3%	123	21.7%	-2.44
	Countywide	100.0%	3,555		3,240		-315	-8.9%	
Siskiyou	VHFHSZ	24.8%	15,902	35.9%	15,854	35.3%	-48	-0.3%	-0.22
	Countywide	100.0%	44,301		44,900		599	1.4%	
Solano	VHFHSZ	2.2%	333	0.1%	404	0.1%	71	21.3%	4.47
	Countywide	100.0%	394,542		413,344		18,802	4.8%	
Sonoma	VHFHSZ	15.2%	8,515	1.9%	10,205	2.1%	1,690	19.8%	3.60
	Countywide	100.0%	458,614		483,878		25,264	5.5%	
Stanislaus	VHFHSZ	6.6%	363	0.1%	413	0.1%	50	13.8%	0.91
	Countywide	100.0%	446,997		514,453		67,456	15.1%	
Sutter	VHFHSZ	0.0%	0	0.0%	0	0.0%	0	0.0%	0.00
	Countywide	100.0%	78,930		94,737		15,807	20.0%	
Tehama	VHFHSZ	44.2%	10,261	18.3%	12,781	20.1%	2,520	24.6%	1.85
	Countywide	100.0%	56,039		63,463		7,424	13.2%	
Trinity	VHFHSZ	20.5%	4,288	32.9%	4,787	34.7%	499	11.6%	1.98
	Countywide	100.0%	13,022		13,786		764	5.9%	
Tulare	VHFHSZ	1.5%	765	0.2%	711	0.2%	-54	-7.1%	-0.35
	Countywide	100.0%	368,021		442,179		74,158	20.2%	
Tuolumne	VHFHSZ	16.0%	34,049	62.5%	36,404	65.8%	2,355	6.9%	4.36
	Countywide	100.0%	54,501		55,365		864	1.6%	
Ventura	VHFHSZ	22.3%	47,337	6.3%	49,414	6.0%	2,077	4.4%	0.47
	Countywide	100.0%	753,197		823,318		70,121	9.3%	
Yolo	VHFHSZ	4.0%	203	0.1%	241	0.1%	38	18.7%	0.98
	Countywide	100.0%	168,660		200,849		32,189	19.1%	
Yuba	VHFHSZ	35.6%	6,462	10.7%	7,615	10.6%	1,153	17.8%	0.90
	Countywide	100.0%	60,219		72,155		11,936	19.8%	
State of California	**VHFHSZ**	15.4%	3,010,416	8.9%	3,513,407	9.4%	502,991	16.7%	1.67
	Statewide	100.0%	33,871,648		37,253,956		3,382,308	10.0%	