Can Prescribed Fires Mitigate Health Harm?

A Review of Air Quality and Public Health Implications of Wildfire and Prescribed Fire

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Table of Contents

List of Figures

List of Tables

1.0 Introduction and Approach

Fire is critical to maintaining the health, resiliency, and diversity of habitats and ecosystems (U.S. DOI & USDA, 2014). Indigenous peoples of North America have used cultural fires for millennia to enhance biodiversity and other ecosystem benefits, as well as for ceremonial activities. Following Euro-American colonization, practices and policies shifted to promote fire exclusion, contributing to increased fuel loading and increased wildfire risk.

Over the last fifty years, the United States has experienced an increase in annual acreage burned from wildfire (U.S. EPA, 2021a). The increase in the frequency, severity, and intensity of wildfires in recent years is further exacerbated by climate change, which is increasing atmospheric aridity, fuel-drying, extended drought, extreme wind events, and pathogen-impacted forests (IPCC, 2021). Recent projections indicate that these conditions, along with overall wildfire risk, will continue to increase across many regions globally as climate change impacts intensify (IPCC, 2021).

As wildfires increase in frequency and intensity, so do public health risks associated with exposure to fire and smoke. In the western United States, recent wildfires have impacted a historic number of people through death, illness, injury, evacuations, and prolonged recovery efforts, particularly in populated areas at the wildland-urban interface. Recent data indicate that wildfire smoke is impacting air quality across the United States, extending the public health risks of wildfire to populations throughout the country (Burke et al., 2021) and adding to cumulative health burdens over a lifetime.

In response, policymakers, land managers, and impacted communities throughout the country are seeking to expand fire management treatments. One strategy that can be used to attenuate wildfire risk is prescribed fire, or fire conducted under specific conditions to reduce biomass fuel loads in targeted areas. However, similar to wildfire, prescribed fire also emits air pollutants that are hazardous to human health. Understanding the risks of wildfire and prescribed fire is therefore necessary to institute policies and practices that balance wildfire management and the protection of public health and safety.

In this report, we summarize existing research on the air quality and human health impacts of wildfire and prescribed fire. This report is intended to inform policy solutions that support safe and effective prescribed fire, and that reduce the scale of health impacts caused by smoke from catastrophic wildfires. Beyond the scope of this report are other fire management and mitigation strategies (e.g., forest thinning, pile burns, the use of thinned biomass for energy production), and other forms of prescribed fire used for purposes other than fire management (e.g., agricultural burning). Additionally, occupational wildfire-related exposures of firefighters and emergency responders are beyond the scope of this report.

This report is organized into the following sections:

- **1.0 Introduction and Approach:** Overview of wildfire risk in the United States and the need to evaluate and weigh the air quality and human health risks associated with prescribed fire smoke and wildfire smoke. Includes a report outline and approach for gathering and reviewing materials.
- **2.0 Summary:** Key findings related to the air quality and human health impacts of wildfire smoke and prescribed fire smoke, and a discussion of the comparative themes, existing research gaps, and policy recommendations.
- **3.0 Wildfire Smoke:** A review of the air quality and human health impacts of wildfire smoke, including a discussion of populations particularly vulnerable to wildfire smoke.
- **4.0 Prescribed Fire Smoke:** A review of the air quality and human health impacts of prescribed fire smoke and a summary of prescribed fire management practices aimed to reduce harmful smoke exposure.
- **5.0 Comparison of Air Quality and Health Impacts of Wildfire and Prescribed Fire Smoke:** A comparative discussion of the air quality and human health impacts of wildfire and prescribe fire smoke, including a summary of exposure reduction measures and research gaps.

1.1 Approach

Materials reviewed in this report include peer-reviewed journal publications, reports, and white papers on the air quality and human health impacts of wildfire and prescribed fire in the United States published from 2000 through November 15, 2021. Peer-reviewed journal articles were compiled via Web of Science using the search terms provided in the **Appendix**. Additional resources were compiled from PSE Healthy Energy's previous report, *Public Health Dimensions of California Wildfire and Wildfire Prevention, Mitigation and Suppression* (Hill et al., 2020), and the United States Environmental Protection Agency (U.S. EPA) *Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S.* (U.S. EPA, 2021a).

2.0 Summary

In this report, we summarize existing research on the air quality and human health impacts of wildfire and prescribed fire. Our goal is to inform policy solutions that support safe and effective prescribed fire, and that reduce the scale of health impacts caused by smoke from catastrophic wildfires. Below we summarize key findings related to the air quality and human health impacts of wildfire smoke and prescribed fire smoke.

2.1 Wildfire Smoke

Wildfire smoke is harmful to human health, though smoke composition is variable. Wildfire smoke contains numerous health-damaging air pollutants, the most widely studied of which is particulate matter (PM). Because wildfire smoke composition can be variable, each smoke event creates its own unique risk profile.

Wildfire pollutant emissions and wildfire smoke events are projected to increase in frequency and severity in the United States due to climate change. This increase will contribute to far-reaching health risks, as long-range transport of wildfire smoke has been observed across the continental U.S. and around the globe.

Wildfire smoke exposure is associated with numerous adverse health effects. It is well documented that exposure to wildfire smoke is associated with adverse respiratory, cardiovascular, and birth outcomes, and premature mortality. Recent studies also suggest that exposure to wildfire smoke is likely associated with increased risk of death from COVID-19.

2.2 Prescribed Fire Smoke

Prescribed fire can provide ecosystem benefits and mitigate catastrophic wildfire risk. In certain ecosystems, prescribed fires decrease hazardous fuel loadings; reduce the spread of pests and disease; remove invasive species that threaten native species; provide forage for game; improve habitat for threatened and endangered species; recycle nutrients back to the soil; and promote the growth of trees, wildflowers, and other plants. Cultural fires have been used by Indigenous peoples in North America for millennia.

Peer-reviewed literature focused on the air quality and health impacts of prescribed fire smoke is limited. While the benefits of prescribed fire are well documented, very few air monitoring or epidemiological studies have focused on the air quality and health impacts from prescribed fire smoke. The limited evidence that does exist suggests that smoke from prescribed fires can pose human health risks. These risks seem to be acute and more localized when compared to risks of wildfire smoke.

Prescribed fires are implemented under conditions to limit harmful smoke exposure. Prescribed fires are generally conducted when meteorological conditions are favorable, smoke production (fuel consumption) is less, atmospheric conditions support adequate smoke dispersion, and wind patterns allow smoke to move away from populated areas, hospitals, schools, and roadways. Some evidence suggests that higher PM concentrations coincide with heavier burning activities, indicating that air quality impacts can be reduced by limiting the size and intensity of a prescribed fire event.

2.3 Comparative Findings

Certain population subsets are more susceptible to wildfire smoke and prescribed fire smoke exposure. Smoke impacts vary based on an individual's susceptibility—which may be related to one's age, current health status, occupation, and socioeconomic vulnerabilities. Vulnerable individuals may be members of multiple at-risk life stages or subpopulations, which may compound vulnerabilities and further increase an individual's susceptibility to smoke. Subpopulations that may be particularly vulnerable and susceptible to wildfire and prescribed fire smoke include those with underlying respiratory and cardiovascular conditions, children and older adults, people who are pregnant, fetuses, outdoor workers, socioeconomically disadvantaged populations, and people without homes.

Peer-reviewed literature comparing specific health impacts of prescribed fire and wildfire is limited. Existing evidence suggests that wildfires have a greater potential for harmful smoke exposure when compared to prescribed fire. Wildfire and prescribed fire smoke are both associated with air quality and human health impacts, though these impacts may differ in magnitude and geographic scope. While limited, existing evidence suggests that there are differences in smoke composition, magnitude of emissions, and duration and frequency of exposure between wildfires and prescribed fire. While prescribed fire may also result in harmful smoke exposure, the overall air quality and health impacts are estimated to be lower than that of wildfire smoke. This is due to the low intensity, low burn rate, and relatively short duration typical of prescribed burns. Additionally, prescribed burn activities can be planned under specific, predictable conditions to avoid potential air quality standard exceedances and offer the opportunity to prepare and notify communities in advance to further reduce harmful smoke exposure.

Exposure reduction approaches for prescribed fire smoke can mirror exposure reduction approaches for wildfire smoke. There are many existing regulations, guidelines, and long-term land management practices in place that aim to minimize the smoke impacts from prescribed fire activities to protect nearby communities from potential adverse health impacts. Additional measures to reduce exposure to prescribed fire smoke can also help to reduce exposure to wildfire smoke. These include: **(1)** air quality surveillance coupled with public outreach; **(2)** access to indoor air filtration and clean air spaces; **(3)** the provision and use of respiratory protective equipment; and **(4)** additional emergency planning, response, and protections for vulnerable populations. Interventions that focus on reducing harmful smoke exposure among the most susceptible populations are likely to achieve the greatest health benefits.

Additionally, the U.S. EPA's "Smoke-Ready Toolbox," which is intended to help prepare fire-prone communities for wildfire smoke events by identifying measures the public can use to reduce their health risk before a wildfire, can be used to mitigate impacts of harmful smoke exposure year-round from both wildfire and prescribed fire. Measures identified within this toolbox have been implemented in Smoke-Ready Communities across the U.S., including in California, Oregon, and Washington.

2.4 Conclusions

Wildfire activity is predicted to increase in the decades ahead and expanded prescribed fire activity is needed to mitigate wildfire risk and associated impacts. While increasing prescribed fire activities may contribute to local air quality impacts, prescribed fire can be conducted in ways that minimize harmful smoke exposure potential.

Prescribed fire is a key fire management strategy that provides ecosystem benefits and can be used to mitigate the negative air quality, health, and safety impacts of large-scale wildfires. Existing research supports the notion that historical fire suppression policies are insufficient for longer-term fire management. Fire suppression has been shown to defer, rather than mitigate, air quality and health burdens associated with smoke. These strategies result in increased fire intensity and an increase in the number of people exposed in a single smoke event. Prescribed fire can simultaneously reduce fuels to reduce wildfire risk while supporting ecosystem health and resiliency.

Prescribed fires are implemented under planned, predictable circumstances where additional measures can be taken to minimize exposures. While there are existing regulations, guidelines and long-term land management practices in place that aim to minimize the smoke impacts from prescribed fire, expanded prescribed fire activities should be coupled with additional policies and best practices to mitigate potential harmful smoke exposure. Effective prescribed fire policies and best practices should include consideration of: fuel type and loadings; ambient air quality levels; potential for air quality standard exceedances; proximity to residential communities and vulnerable populations; the availability of advanced warning and notification systems; more comprehensive air monitoring efforts; and forecasting tools for use in fire management planning. Additionally, future policies should encourage strategies to further mitigate potentially harmful impacts from prescribed fire smoke, such as: **(1)** improved prescribed fire management planning by conducting more air quality monitoring during burn activities and expanding prescribed fire reporting and public notification; **(2)** utilization and/or further development of tools to forecast potential prescribed fire impacts; and **(3)** implementation of interventions and other mitigation efforts that reduce exposures, such as portable air cleaners and residential heating, ventilation, and air conditioning (HVAC) systems, among others.

Further research is needed to evaluate comparative risks of prescribed fire smoke and wildfire. Research focused on the comparative health risks of prescribed fire and wildfire is currently very limited. Future research on the air quality and health impacts of biomass smoke should include an assessment of the health impacts from prescribed fire smoke.

3.0 Wildfire Smoke

Fire is a natural process that drives ecological processes and promotes ecosystem health and resilience. However, historical fire exclusion policies, climate drivers (e.g., atmospheric aridity and prolonged drought), and present-day human activities and infrastructure (e.g., power lines), have led to recent catastrophic wildfires, most notably across the western U.S. (**Figure 1; Figure 2**). Over the last three decades, the acreage burned annually by wildfire across the United States has doubled. This trend is driven by western states such as California, which experienced a fivefold increase in annual acreage burned from wildfire over the last half-century (Williams et al., 2019). While wildfires can impact the environment and human health through various pathways (e.g., impaired drinking water, soils, and crops), in this section we focus specifically on the air quality impacts of wildfire smoke and the adverse health effects associated with wildfire smoke exposure.

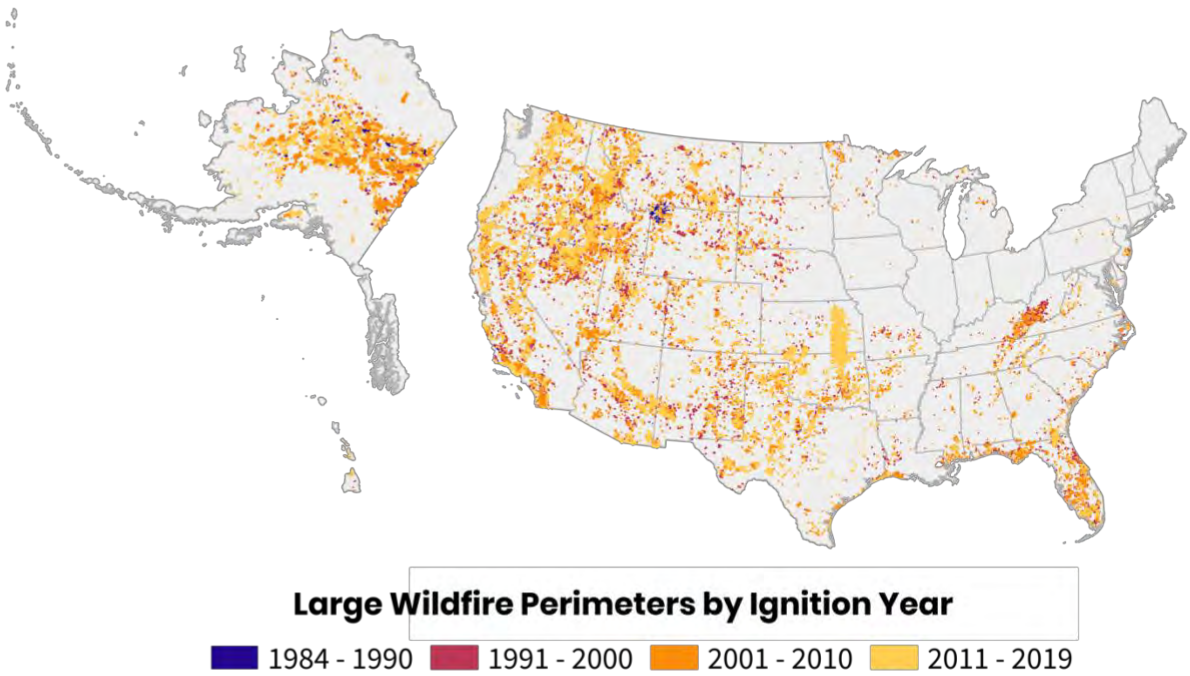

Figure 1. U.S. Wildfire Perimeters: 1984-2019. Wildfires tend to be more pervasive in the western U.S. Data source: MTBS 1984-2019.

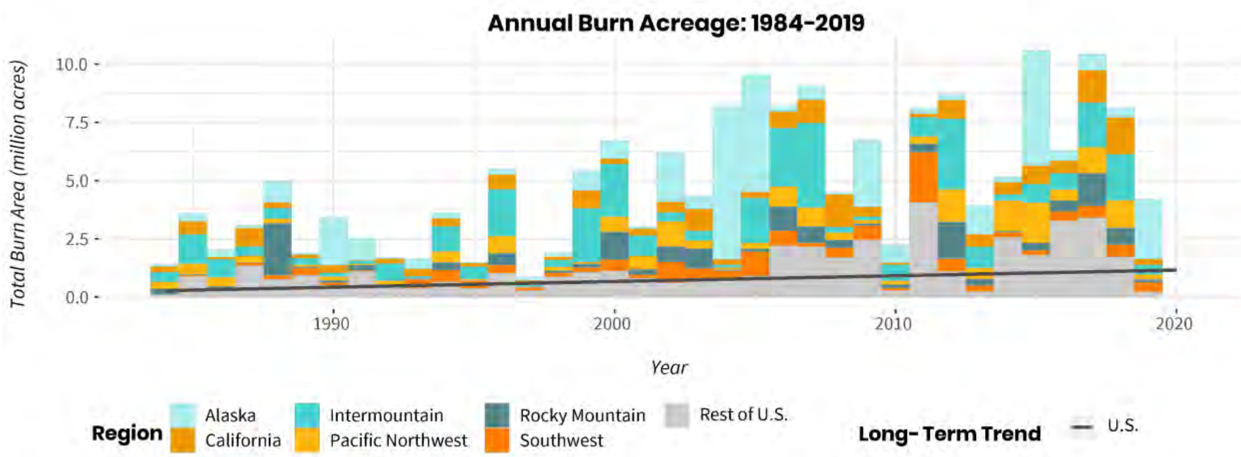

Figure 2. Annual Wildfire Burn Acreage by Sub-Region. The West consistently comprises the majority of wildfire burn acreage in the United States each year. The West also outpaces the nation at large for upward trend in burn acreage. Data Source: MTBS 1984-2019.

3.1 Air Quality Impacts of Wildfire

3.1.1 Wildfire Smoke Composition

Wildfire smoke composition can vary between fires and even within a single fire event. Types and quantities of air pollutants 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 a wildfire (e.g., flaming, smoldering, and glowing) are distinct from one another, which also contributes to the range of combustion products.

KEY MESSAGES

Wildfire Smoke & Air Quality

- Wildfire smoke composition can vary between fires and within a single fire event.
- Wildfire smoke contains numerous health-damaging air pollutants, the most widely studied of which is particulate matter (PM).
- Long-range transport of wildfire smoke has been observed across the continental U.S. and around the globe.
- Wildfire pollutant emissions and wildfire smoke events are projected to increase in frequency and severity in the United States due to climate change.

Wildfire smoke is composed of various compounds known to be hazardous to human health, including federally-designated criteria air pollutants. Criteria air pollutants include fine ($PM_{2.5}$) and inhalable (PM_{10}) particulate matter (PM), carbon monoxide, nitrogen dioxide, sulfur dioxide, lead, and ground-level ozone—all of which may be directly emitted from a wildfire from the combustion and incomplete combustion of biomass and synthetic materials (U.S.

EPA, 2021b). PM and ozone can also form secondarily from precursor emissions during a wildfire that undergo chemical interactions in the atmosphere. PM is the most widely studied criteria air pollutant found in wildfire smoke for its impacts on air quality and public health. Broadly, exposure to criteria air pollutants is associated with various adverse respiratory and cardiovascular outcomes, among other health and environmental impacts (U.S. EPA, 2021b).

The remaining components in wildfire smoke are a complex mixture of hundreds of gases and particles. Wood smoke contains many of the same toxic and carcinogenic substances as cigarette smoke, including benzene, a known human carcinogen (Balmes, 2018). 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). Structure fires include various household products, building materials, vehicles, and other built environment infrastructure which, when combusted, can release an array of hazardous compounds (CITRIS Policy Lab, 2019; Fabian et al., 2010). Examples of structural materials burned in fires including polystyrene plastics, vinyl compounds, treatment wood products, roofing materials, and vehicles, which can emit hazardous air pollutants—air pollutants regulated under the Clean Air Act that are known to cause cancer and other serious health impacts (U.S. EPA, 2015a). The compounds emitted from burned structural materials have been shown to affect health as human carcinogens, asphyxiants, respiratory irritants, and reproductive and developmental toxicants (Adetona et al., 2016; Fabian et al., 2011; OEHHA, 2020; Purser, 2010).

3.1.2 Recent Wildfire Smoke Events: Dispersion and Transport

Understanding the atmospheric dispersion of wildfire smoke and its health-damaging constituents is essential to assessing wildfire smoke exposure and associated health impacts. Numerous studies have demonstrated long-range transport of wildfire smoke using methods such as satellite imagery, back trajectory analysis, and direct reading instruments (Sapkota et al., 2005; Xue et al., 2021; Zu et al., 2016).

During the 2018 Camp Fire—the deadliest and most destructive wildfire in California's history—nearly 19,000 structures in Paradise, California and the surrounding area burned (CAL FIRE, 2021a, 2021b). Air monitoring during the Camp Fire revealed elevated concentrations of lead, zinc, calcium, iron, and manganese, with smoke containing these metals traveling more than 150 miles (CARB, 2021). Long-range transport of smoke from recent wildfires has been documented across North America and around the world. For example, in July 2021, smoke originating from wildfires in the western U.S. and Canada traveled across the continental U.S. (NASA, 2021) (**Figure 3**).

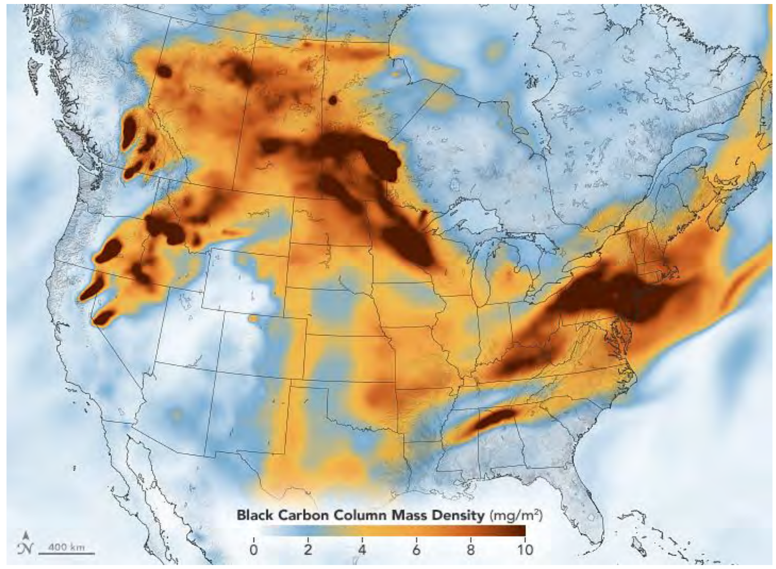

Figure 3. 2021 Wildfire Smoke Transport. Plumes of wildfire smoke from fires in western North America passing across the continental U.S. and Canada, July 2021 (Source: NASA, 2021).

Secondary formation of ozone following the transport of ozone precursors (e.g., nitrogen oxides) presents additional concerns about wildfire smoke distribution. 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 (Black, Tesfaigzi, et al., 2017; Chalbot et al., 2013; Pfister et al., 2008).

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 in the United States will be subject to a 57% and 31% increase in the frequency and intensity of smoke waves, respectively (Liu et al., 2016a).

3.2 Health Impacts of Wildfire Smoke

Numerous adverse health impacts are associated with wildfire smoke exposure. In this section, we summarize the literature evaluating the health risks and impacts associated with exposure to wildfire smoke and describe populations that may be particularly vulnerable to wildfire smoke exposure.

KEY MESSAGES

Wildfire Smoke & Human Health

- Studies show that wildfire smoke exposure is associated with various adverse health outcomes, including adverse respiratory, cardiovascular, birth outcomes, and premature mortality.
- Recent studies show wildfire smoke exposure is also associated with increased risk of death from COVID-19.
- Subpopulations that may be particularly vulnerable and susceptible to wildfire smoke impacts include those with underlying respiratory and cardiovascular conditions, children and older adults, people who are pregnant, fetuses, outdoor workers, socioeconomically disadvantaged populations, and people without homes.

3.2.1 Adverse Health Outcomes Associated with Wildfire Smoke Exposure

In the most serious cases, close proximity to fire and subsequent smoke exposure can be fatal. Fatalities from fire are caused in part by asphyxiant gases, specifically carbon monoxide 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 carbon monoxide and the susceptibility of the person exposed (NRC, 2010). Additionally, emitted carbon dioxide 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 loss of consciousness (Langford, 2005). Intense heat from direct exposure to smoke can also cause physical damage along the respiratory pathway (Rehberg et al., 2009).

Peer-reviewed studies provide evidence of associations between wildfire smoke and the following adverse health outcomes: eye irritation; respiratory outcomes including asthma exacerbation, bronchitis, dyspnea, and exacerbation of chronic obstructive pulmonary disease (COPD); increased hospital admissions for respiratory illness; adverse birth outcomes; out-of-hospital cardiac arrests, and premature mortality (**Table 1**). A recent review of the literature reports mixed evidence regarding an association between wildfire smoke exposure and cardiovascular outcomes (Chen et al., 2021). However, cardiovascular outcomes are complex to study. While wildfire smoke exposure results in more immediate respiratory health effects, cardiovascular events have been observed to lag for days after high wildfire smoke periods.

Some posit that those who receive immediate care or are hospitalized for respiratory outcomes reduce the overall risk pool to experience a cardiovascular event (DeFlorio-Barker et al., 2019). Very few studies evaluated wildfire smoke exposure and metabolic health outcomes. One study reported an association between wildfire-specific $PM_{2.5}$ and diabetes-related emergency department visits and hospital admissions (Malig et al., 2021). Another study found an association between increased PM during wildfire season and diabetes-related ambulance dispatch and paramedic assessments (Yao et al., 2020).

Additionally, recent studies have examined the influence of air pollution and wildfire smoke on public health during the COVID-19 pandemic. An initial study reported a positive association between long-term exposure to ambient $PM_{2.5}$ and increased risks of COVID-19 death across the U.S. (Wu et al., 2020). Another recent study found that high levels of $PM_{2.5}$ during the 2020 wildfire season also exacerbated the COVID-19 health burden in many western U.S. counties as evidenced by increased COVID-19 cases and deaths (Zhou et al., 2021).

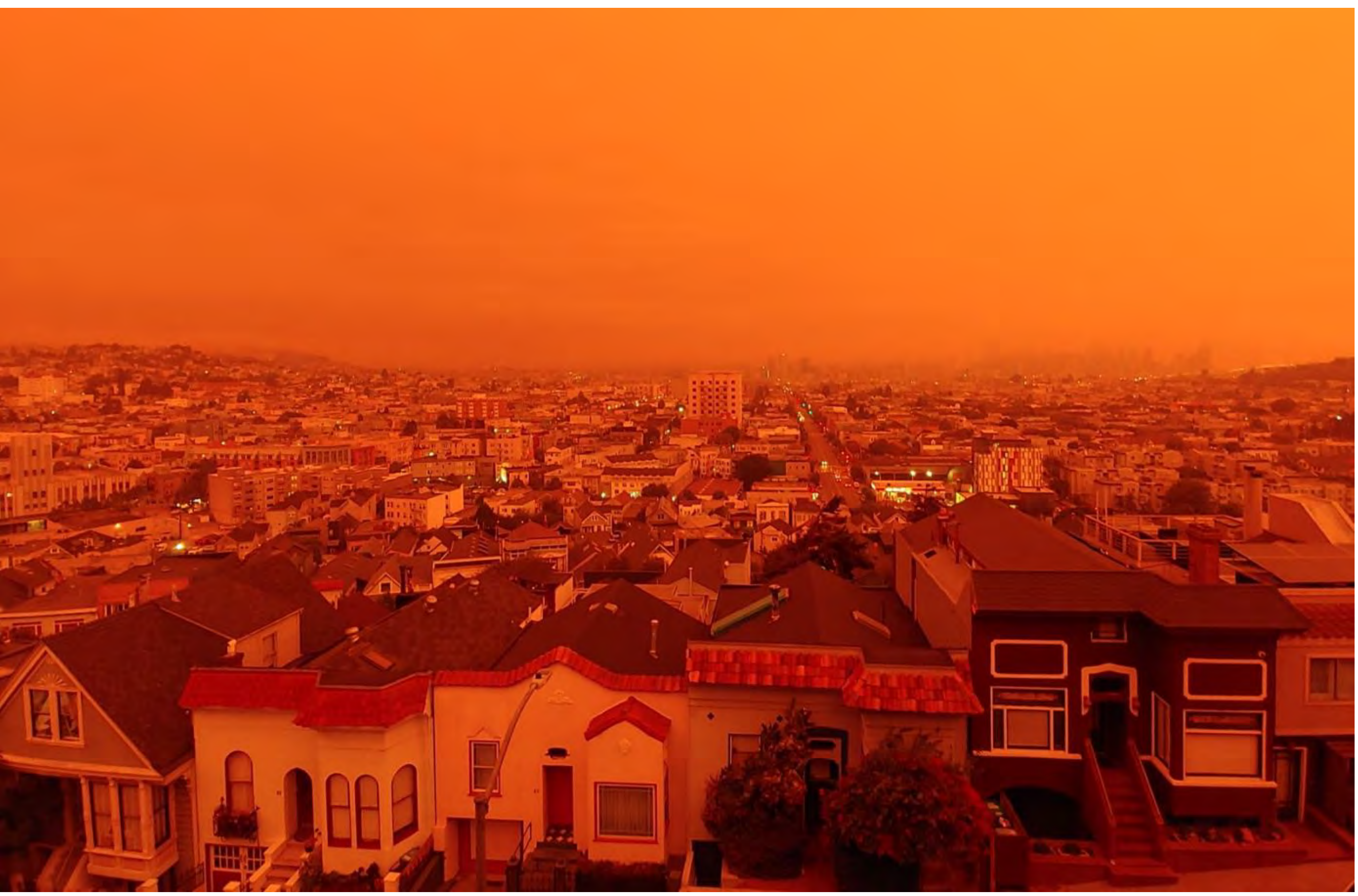

Table 1. Health effects associated with wildfire smoke exposure commonly examined in the peer-reviewed literature. Studies included provide examples and listed studies are not intended to be exhaustive of all peer-reviewed literature examining each health effect.

Health Effect Category	Health Effect(s) Associated with Wildfire Smoke Exposure
Eye Effects	● Eye irritation (Duclos et al., 1990) ● Corneal abrasions (Shusterman et al., 1993)
Respiratory Effects	● Exacerbation of asthma and chronic obstructive pulmonary disease (COPD) (Adetona et al., 2016; Finlay et al., 2012; Morrison et al., 2014) ● Emergency department visits for asthma, bronchitis, dyspnea and COPD (Black, Gerriets, et al., 2017; Reid et al., 2019) ● Emergency department visits for respiratory disease, asthma, chronic lower respiratory disease (Malig et al., 2021) ● Respiratory hospitalizations (Aguilera et al., 2021a) ● Pediatric respiratory emergency and urgent care visits (Aguilera et al., 2021b) ● Asthma rescue inhaler medication refills (Gan et al., 2020) ● Asthma diagnosis in emergency departments, office visits, and outpatient visits (Gan et al., 2020) ● Self-reported respiratory symptoms, health services usage and medication uptake for respiratory-related problems among young adults born extremely premature or low birthweight (Haikerwal et al., 2021)
Birth & Maternal Health Outcomes	● Low birth weight (Holstius et al., 2012) ● Preterm birth (Abdo et al., 2019) ● Gestational diabetes and gestational hypertension (Abdo et al., 2019)
Cardiovascular Effects	● Out-of-hospital cardiac arrests (Dennekamp et al., 2015; Haikerwal et al., 2016; Jones et al., 2020) ● Emergency department visits for ischemic heart disease, dysrhythmia, heart failure and pulmonary embolism (Wettstein et al., 2018) ● Emergency department visits for acute myocardial infarction (Malig et al., 2021)
Premature Mortality	● All-cause mortality (Hoek et al., 2013; Krewski et al., 2009; Tamura-Wicks et al., 2018; Xi et al., 2019, 2020) ● Multiple-cause mortality (Zou et al., 2019) ● Respiratory mortality (Doubleday et al., 2020)

3.2.2 Populations Particularly Vulnerable to Wildfire Smoke Exposure

Wildfire smoke impacts vary based on an individual's susceptibility—which may be related to one's age, current health status, occupation, and socioeconomic vulnerabilities. Vulnerable individuals may be members of multiple at-risk life stages or subpopulations, which can compound vulnerabilities and further increase an individual's susceptibility to wildfire smoke. Below we describe why certain population subsets may be more vulnerable to wildfire smoke exposure and the potential health effects these subpopulations may experience (adapted from U.S. EPA, 2019a):

- **People with Asthma, COPD and Other Respiratory Diseases:** Respiratory diseases result in compromised health status that can trigger severe respiratory responses from wildfire smoke exposure. These can lead to breathing difficulties and exacerbations of chronic lung diseases that result in increased medication usage, emergency department visits, and hospital admissions.

- **People with Cardiovascular Disease:** Circulatory diseases result in compromised health status that can trigger severe cardiovascular events from wildfire smoke exposure. Adverse cardiovascular effects include triggering angina pectoris, heart attacks, and stroke; worsening heart failure; or abnormal heart rhythms that can lead to emergency department visits, hospital admissions, and even death.

- **Children:** 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. Children may experience coughing, wheezing, difficulty breathing, chest tightness, and decreased lung function; children with asthma may experience worsening of asthma symptoms or heightened risk of asthma attacks.

- **Pregnant People and Fetuses:** Pregnancy-related physiologic changes such as increased breathing rates may increase vulnerability to wildfire smoke exposure. During critical development periods, the fetus may experience increased vulnerability to wildfire smoke exposure. Some evidence suggests air pollution-related effects on pregnant people and the developing fetus, including low birth weight and preterm birth.

- **Older Adults:** Older adults have higher prevalence of pre-existing lung and heart disease and decline of physiologic processes, such as defense mechanisms. Wildfire smoke exposure may exacerbate underlying heart and lung diseases leading to emergency department visits, hospital admissions, and even death.

- **Socioeconomically Disadvantaged Populations:** Less access to health care can 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 filtration, ability to evacuate to a safer area) could lead to higher levels of exposure to wildfire smoke. Greater exposure to wildfire smoke, along with higher likelihood of untreated or insufficiently treated health conditions and lack of access to healthcare, could lead to increased risks of experiencing the health effects described above.

- **Outdoor Workers:** Outdoor workers, including but not limited to those who work in agriculture, forestry, construction, and recreation, may experience extended periods of time exposed to high concentrations of wildfire smoke. Greater exposure to wildfire smoke can lead to increased risks of experiencing the range of health effects described above.

- **People Without Homes:** Individuals who may not have access to clean air spaces, including those who spend extended periods of time in informal settlements and live 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). Greater exposure to wildfire smoke, along with higher likelihood of untreated or insufficiently treated health conditions and lack of access to healthcare could lead to increased risks of experiencing the health effects described above.

4.0 Prescribed Fire Smoke

Prescribed fire is defined as the planned ignition of an area in accordance with applicable regulations and laws as a means of reducing fuel loadings and wildfire risk of vulnerable regions, as well as to improve ecosystem health (Jaffe et al., 2020). Prescribed fire, in this context, does not refer to agricultural burning, which involves the intentional burning of croplands and is conducted for reasons other than wildfire management purposes. According to the United States Department of Agriculture's (USDA) Forest Service, prescribed fires have the potential to reduce catastrophic wildfires while improving ecosystem health, as they: (1) reduce hazardous fuels, protecting human communities from extreme fires; (2) minimize the spread of pest insects and disease; (3) remove unwanted species that threaten species native to an ecosystem; (4) provide forage for game; (5) improve habitat for threatened and endangered species; (6) recycle nutrients back to the soil; and (7) promote the growth of trees, wildflowers, and other plants (USDA Forest Service, 2016). The benefits of prescribed fire activity are supported in the peer reviewed literature as well, especially for those landscapes most prone to wildfire such as the Sierra Nevada forest region in California (Moreira et al., 2020; North et al., 2012).

Prescribed Fire and Cultural Fire

Cultural fires have been utilized by native populations in North America for millennia as a cultural practice and means of controlling wildfire and restoring fire-adapted ecosystems (Clark et al., 2021). While cultural fire is seen as a subset of prescribed fire, cultural fire and prescribed fire are two distinct concepts. Prescribed fire is generally conducted using models to determine conditions for burning, whereas cultural fire relies upon holistic knowledge of the area to determine timing and implementation of fire activities (Clark et al., 2021). In present-day California, an estimated few thousand acres are burned annually with traditional cultural techniques by the Miwok, Yurok, Hupa, Karuk, and other Native American nations (Fuller, 2020; Yüyan, 2019).

The Indigenous Peoples Burning Network was created in 2015 to support revitalizing of traditional indigenous fire practices within tribes across North America, such as the Yurok, Hoopa, and Karuk in California; pueblos in New Mexico; Klamath tribes in the Pacific Northwest; the Leech Lake Band of Ojibwe near the Great Lakes in Minnesota; and the Alabama-Coushatta Tribe of Texas (The Nature Conservancy, 2021). However, as these practices increase, cultural fire practitioners have run into regulatory barriers that make it difficult to continue and expand these traditional burns. For example, a 2021 report assessing Good Fire practices of the Karuk Tribe in California found California's regulation of intentional fires, including air quality and burn permitting and environmental review requirements, to conflict with Tribal sovereignty over the cultural practice (Clark et al., 2021). This report concluded that both state and federal agencies lack an adequate understanding of cultural fire practitioners' authority, expertise, and land tenure, as well as the requirements of cultural burns (Clark et al., 2021).

Prescribed Fire Activity in the United States

In the United States, the interagency Monitoring Trends in Burn Severity (MTBS) program tracks fire perimeters since 1984 for fires 1,000 acres or greater in the western U.S. and 500 acres or greater in the eastern U.S.[1] Based on these data, annual prescribed fire acreage associated with fire management has increased in the United States over time. In 1984, when the database's records began, 136,000 acres of land were subjected to prescribed fire. In 2019, this number increased to 816,000 acres. It should be noted, however, that this database in not comprehensive, as there is no national repository of prescribed fire data that provides spatial information (perimeters for all fires regardless of magnitude of acreage burned) and temporal information (date each fire occurred). Although MTBS is useful for monitoring trends in burn size and severity over time, it likely underestimates total burn acreage because it only includes large fires. In contrast with MTBS' 816,000 acre total for 2019, the Coalition of Prescribed Fire Councils estimates that based on state permitting data, 10,000,000 acres were subjected to prescribed burn in the same year (Coalition of Prescribed Fire Councils Inc., 2020). A centralized database detailing prescribed burn location, size, and perimeter is accordingly needed to discern the exact extent of prescribed fire intended for fire management in the United States.

Considering nationally available data, prescribed fire activity is not uniform across fire-prone regions (**Figure 4**). An assessment of lands treated with prescribed fire found that from 1998 to 2018, 70% of all prescribed fire in the United States was conducted in the Southeast (Kolden, 2019).[2] The Southeast accounted for 98% of the increase in prescribed fire acreage observed

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[1] Prescribed fires are defined in MTBS as "any fire intentionally ignited by management actions in accordance with applicable laws, policies, and regulations to meet specific objectives" (MTBS, 2022). Prescribed fire data is compiled from the Integrated Reporting of Wildland-Fire Information (IRWIN) or the Department of the Interior and USDA National Fire Plan Operations and Reporting System (NFPORS), and therefore these data are unlikely to include other forms of prescribed fire beyond fire management, such as agricultural burning (Personal communication with U.S. Forest Service MTBS, 2022).
[2] Kolden (2019) relies on data from the National Interagency Fire Center (NIFC) Situation Reports and Historical Wildland Fire Summaries, which are interpreted here as prescribed fire acreage associated with fire management activities.

from 1998 to 2018 and more than twice the amount of land was treated with prescribed fire as the rest of the United States combined. Conversely, western states experienced a decrease in prescribed fire activity during this period. Overall, prescribed fires completed by federal land management agencies have declined by roughly 60% over the past two decades; from 90% of all prescribed fires down to 30% annually (Kolden, 2019). This is likely due in part to limited funding and crew availability to meet demand for prescribed burns (Miller et al., 2020). Of the federal land management agencies evaluated, only the Bureau of Indian Affairs (BIA) was found to have significantly increased the use of prescribed fire over this period (1998-2018), with an average of 7.5% of tribal lands burned annually (Kolden, 2019). This prioritization of prescribed fire use is reflected in the BIA budget; 50%-80% of the agency's fire suppression budget is reserved for prescribed fire.

In California, between 2013 and 2018 an estimated 38% to 51% of acres planned to burn were actually burned (Miller et al., 2020). About 93% of the acres planned but not burned during this six-year period were in federal jurisdiction, with the majority planned by the U.S. Forest Service (Miller et al., 2020). However, a new federal initiative by the U.S. Department of Agriculture was announced in January 2022 that includes increased use of prescribed burn practices on federal lands (Newburger, 2022).

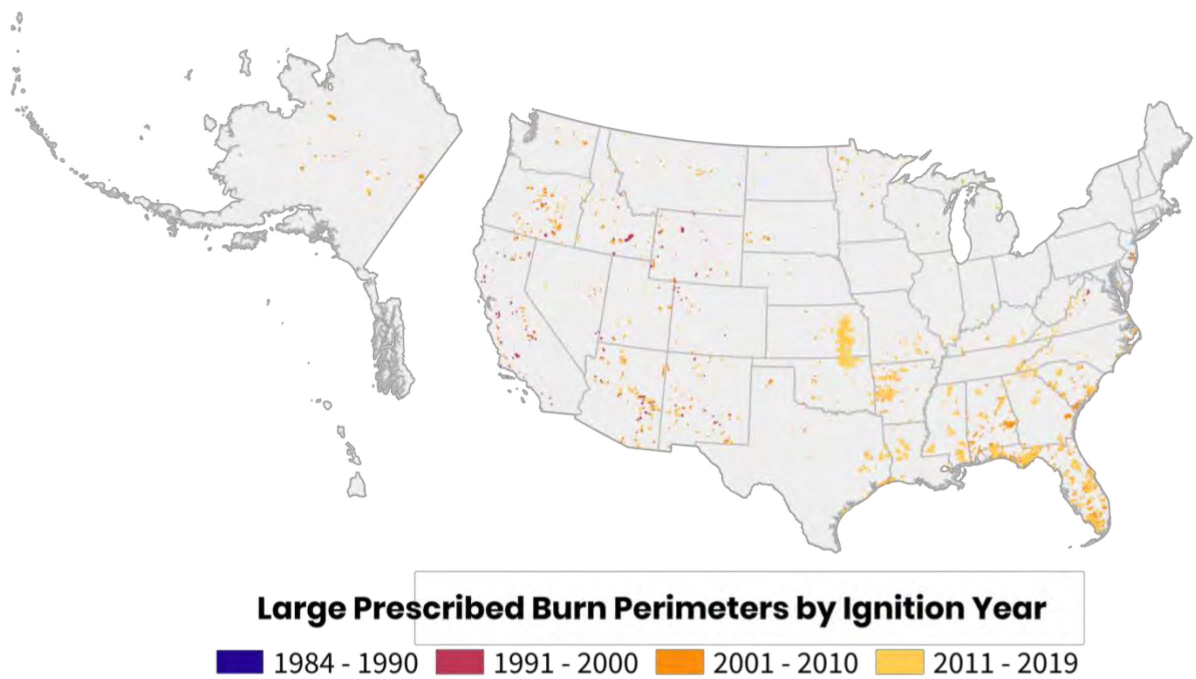

Figure 4. U.S. Prescribed Burn Perimeters: 1984-2019. Much of the U.S.'s prescribed burn activity occurs in the Southeast. A large portion of land that has undergone prescribed burning has done so in the last decade. Data source: MTBS 1984-2019.

The United States has many forest and rangeland types, many of which are fire dependent. The Southeast recognized this dependence and has developed a large, prescribed fire program on all ownership types (Cohesive Fire Strategy Group, 2022; Southern Group of State Foresters, 2014). There is also variability in the fire impacts of different fuel types and treatments in reducing wildfire risk. The Southeast typically has much lighter fuels available in forest areas where prescribed fire is routinely applied; this allows for rapid wildfire suppression. Multiple studies highlight the effectiveness of prescribed fire in the Southeast in keeping the massive growth of fuels from becoming a potential wildfire conflagration (Afrin & Garcia-Menendez, 2020; Hu et al., 2019; Kolden, 2019).

Prescribed Fire Planning and Implementation

To avoid adverse impacts, prescribed fires are generally conducted when meteorological conditions are favorable, smoke production (fuel consumption) is less, atmospheric conditions support adequate smoke dispersion, and wind patterns allow smoke to move away from sensitive areas, including populated areas, hospitals, schools, and roadways. Prescribed fires are typically implemented during non-summer months and permitted so that smoke levels do not exceed established air quality standards and result in harmful exposures (Jaffe et al., 2020).[3]

There are many existing regulations, guidelines, and long-term land management practices in place that aim to limit the smoke impacts from prescribed fire activities to protect nearby communities from potential adverse health impacts. Federal land management agencies by policy use Basic Smoke Management Practices and are also trained in smoke management when conducting prescribed fires (U.S. Forest Service & NRCS, 2011). As recognized by the U.S. EPA, a properly managed prescribed fire is less likely than a wildfire to cause or contribute to an exceedance or a violation of the National Ambient Air Quality Standards (NAAQS) (U.S. EPA, 2019b). Many state forestry agencies share these requirements, and train their private land managers to use smoke management best practices as well as regulate prescribed fire activity to minimize smoke impacts to protect both public health and safety (National Wildfire Coordinating Group, 2020). Updates on smoke management are also included as a part of the U.S. Forest Service's annual burn boss refresher course (National Wildfire Coordinating Group, 2021).

[3] Under the U.S. EPA's exceptional events rule (U.S. EPA, 2019b), air quality exceedances of $PM_{2.5}$ and ozone NAAQS that occur as a result of prescribed fire smoke can be excluded from regulatory non-attainment considerations (Jaffe et al., 2020). However, this process is resource intensive, requiring states to submit detailed supporting documentation.

4.1 Air Quality Impacts of Prescribed Fire

Smoke from prescribed fire is, in general, localized to a small region and has a less widespread impact on air quality (Hu et al., 2019). However, in regions with heavy prescribed fire use, such as in the Southeast, chronic exposure to smoke can be just as impactful on health as acute exposure to wildfires. The majority of prescribed burning (70%) in the United States occurs in the Southeast, where it accounts for approximately 25% of primary $PM_{2.5}$ (i.e., particulates that are directly emitted) emissions (Afrin & Garcia-Menendez, 2020).[4] Similarly, forest prescribed burn activities in Ohio from 2008 to 2017 were estimated to have emitted ~420,000 tons of $PM_{2.5}$ to the air, accounting for ~21% of total $PM_{2.5}$ emissions in the state (Wu et al., 2021a).

KEY MESSAGES

Prescribed Fire & Air Quality

- Prescribed and cultural fire are an important tool to mitigate the risk of large-scale, high severity wildfire, particularly in the Western U.S.
- Prescribed fire smoke can result in air quality impacts. In general, smoke from prescribed fire is localized to a small region and is less likely to impact air quality outside of the fire region when compared to wildfire smoke.
- Higher $PM_{2.5}$ concentrations coincide with heavier burning activities, suggesting that air quality impacts can be reduced by limiting the size and intensity of a prescribed fire event.

Very few studies quantify the air quality impacts from prescribed fire events. A five year study evaluated the air quality impacts from prescribed fire in forestland regions in the Southeastern U.S., in which they characterized emission factors for approximately 100 trace gases and particulate matter found in smoke (Weise et al., 2015). The measurements and associated emission factors derived in this study highlight the differences in emissions among fuel types (e.g., semi-arid shrublands, pine understory) and loadings, as well as among different burn intensities (e.g., flaming, smoldering, residual smoldering). One study evaluated the contribution of prescribed fire smoke to 24-hour National Ambient Air Quality Standards (NAAQS) $PM_{2.5}$exceedances in Georgia (Johnson Gaither et al., 2019). The authors found that prescribed fire contributed during 34% (41 of 120 days) of the days where $PM_{2.5}$ concentrations exceeded standards. $PM_{2.5}$ exceedances were more likely to occur during prescribed fire events on non-industrial private landowner, government, and commercial lands (Johnson Gaither et

[4] This study focused on a broad definition of prescribed fire activity, but silvicultural (forest management) burns were dominant burn type in both Georgia and Florida. In Georgia, prescribed fire acreage was characterized as 83% silvicultural, 11% agricultural, and 6% land clearing. In Florida, prescribed fire acreage was characterized as 63% silvicultural, 36% agricultural, and 1% land clearing. (Afrin & Garcia-Menendez, 2020).

al., 2019). Another study reported that prescribed fire smoke in Georgia contributed more than 30% of daily $PM_{2.5}$ for nearly 13% of measurements in 2018 (Huang et al., 2019).[5]

A study focused in the Pacific Northwest found prescribed fire activity in parts of the region substantially impacted regional air quality and visibility (Ravi et al., 2019). Ground-level measurements of $PM_{2.5}$ in the Washington-Baltimore metropolitan area demonstrated that air quality deteriorations coincided with progression of prescribed fire smoke (Huff et al., 2021). An assessment of prescribed fire smoke in the southeastern U.S. found elevated $PM_{2.5}$ concentrations within fire-intensive areas and higher $PM_{2.5}$ concentrations coinciding with heavier burning (Afrin & Garcia-Menendez, 2020). For example, during the 2013-2016 prescribed fire seasons, the average 24-hour $PM_{2.5}$ concentration in Albany, Georgia was 50% greater than the state average. More than 80% of 24-hour $PM_{2.5}$ concentrations 25-35 $\mu g/m^3$ occurred when burn areas greater than 1,000 acres were permitted nearby. Additionally, almost half of all $PM_{2.5}$ concentrations greater than 15 $\mu g/m^3$ in Georgia and Florida during prescribed fire season occurred when a prescribed fire area greater than 1,000 acres was permitted within 60 kilometers (roughly 37 miles) of an air monitoring location (Afrin & Garcia-Menendez, 2020).[6]

[5] Prescribed fire contributed more than 30% of $PM_{2.5}$ measured by air monitors located throughout Georgia during days with prescribed fire activity in 2018.

[6] See footnote #4.

4.2 Health Impacts of Prescribed Fire Smoke

Investigations into health risks and impacts associated with prescribed fire smoke are limited. Below we summarize the available peer-reviewed literature evaluating prescribed fire smoke and adverse health outcomes and secondary health impacts.

KEY MESSAGES

Prescribed Fire Smoke & Human Health

- There are very few studies focused on the health impacts from prescribed fire smoke. The limited evidence suggests that smoke from prescribed fires can pose health risks, although these risks seem to be acute and more localized when compared to wildfire smoke.
- To reduce harmful exposure from smoke, prescribed fires should be conducted when meteorological conditions are favorable, smoke production (fuel consumption) is less, atmospheric conditions support adequate smoke dispersion, and wind patterns allow smoke to move away from sensitive areas (e.g., populated areas, hospitals, schools, roadways).

4.2.1 Epidemiological Studies

Three studies (Prunicki et al., 2019; Wu et al., 2021a; Wu et al., 2021b) examined prescribed fire smoke and health using primary data collection. Two studies evaluated the health effects of prescribed fire exposure among firefighters implementing prescribed fires in the Midwest and found prescribed fire smoke exposure was associated with elevated urinary mutagenicity (an indicator of exposure to substances toxic to genes) and systemic oxidative changes (i.e., an indicator of bodily stress) to be associated with exposure (Wu et al., 2021a, 2021b). The evidence suggests that wildland firefighters responsible for conducting prescribed fires are directly exposed to elevated levels of smoke during off-wildfire seasons compared to the general public (Wu et al., 2021a). However, no occupational exposure limits (OELs) were exceeded by the exposure concentrations observed in the firefighters (Wu et al., 2021a).[7]

A two-year study in Fresno, California evaluated respiratory outcomes and markers of immune function among school-aged children exposed to wildfire and prescribed burn smoke (Prunicki et al., 2019). Children in the wildfire group exhibited greater evidence of adverse respiratory health outcomes (wheezing and asthma exacerbation), as compared to the prescribed fire group (Prunicki et al., 2019). Furthermore, monitoring before, during, and after the fire event demonstrated that prescribed burns likely did not contribute substantially to $PM_{2.5}$ levels, with concentrations actually decreasing from pre- to post fire (Prunicki et al., 2019).

[7] by 8-h time-weighted average (TWA).

4.2.2 Other Studies Estimating Health Risks and Impacts

Four studies estimate health risks and impacts associated with prescribed fire activities, three of which focus in Georgia. One study reported that prescribed fire smoke in certain areas of southern Georgia was associated with an estimated ~40% increase in rates of emergency department visits and hospitalizations (Hu et al., 2019). Another prescribed fire in Georgia during the 2015 burn season was associated with 145 asthma-related emergency department visits; by 2018, this number increased by 18% (Huang et al., 2019). This study is limited, however, as it relies on concentration-response functions derived from research focused on wildfire impacts due to the lack of prescribed burning-specific epidemiological studies (Huang et al., 2019). A third study estimating the health impacts of $PM_{2.5}$ emissions from prescribed fires in Georgia reported that cumulative exposure considering average smoke event days during pregnancy was associated with a 1.02% increase in instances of low birth weight and premature birth (Jones & Berrens, 2021). However, the numbers presented in this study are an indication of potential public health impacts and are not representative of epidemiologic studies examining associations between prescribed fire smoke and health.[8]

Another study estimated the health impacts from prescribed fire-related $PM_{2.5}$ exposure in the Pacific Northwest under three scenarios in 2011: (1) 100% prescribed fire; (2) no prescribed fire; (3) 30% prescribed fire (Ravi et al., 2019). Under the 30% fire scenario, prescribed burn activities were reduced by 70% and supplemented with manual biomass clearing for conversion to biofuels. Under the 100% prescribed fire scenario, smoke exposure was associated with 280-710 excess mortalities. When prescribed fire is reduced by 70% and supplemented by manual clearing activities, excess mortalities were found to be approximately 200-500 deaths, representing a 28% to 30% decrease. Additionally, the authors found $PM_{2.5}$ exposure under the 100% prescribed fire scenario to be associated with approximately 100,000 asthma cases, 400 acute bronchitis cases, 100-200 chronic bronchitis cases, 65-70 emergency-room visits, and 20-40 hospital admissions. These findings would suggest that alternatives to prescribed fires, such as biomass clearing for use as biofuel, could be used in tandem with burn activities to effectively manage forest fuel loads and reduce the impacts to air quality and health. However, these estimates do not factor in the air quality and health impacts of burning biofuel created from cleared biomass. A previous study assessing the full supply chain impacts of biomass-to-biofuel found biorefinery emissions to be a substantial local source of $PM_{2.5}$, nitrogen oxides and carbon monoxide, contributing to the secondary formation of ozone (Ravi et al., 2018). Furthermore, mechanical treatments, are less feasible than prescribed fire in vast expanses of steep terrain and do not provide comparable ecosystem benefits to prescribed fire.

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[8] Authors relied on results from previous studies and estimate health impacts due to smoke using modeling tools such as BenMAP (i.e., secondary analysis).

5.0 Comparison of Air Quality and Health Impacts of Wildfire and Prescribed Fire Smoke

Below we discuss similarities and differences of wildfire and prescribed fire in the United States in the context of air quality, smoke exposure, and human health. We identify peer-reviewed studies and government reports that include explicit comparisons of wildfire and prescribed fire and include information from studies focused solely on impacts from each type of fire. In this section, we discuss **(1)** the number and magnitude of wildfires and prescribed fires in recent years in the United States; **(2)** smoke composition, magnitude of smoke emissions, and duration of exposure; **(3)** health risks and impacts documented in the literature; **(4)** vulnerability and equity dimensions; and **(5)** smoke exposure reduction measures. We also summarize research gaps and provide future research recommendations.

5.1 Number and Magnitude of Fires in Recent Years

The Monitoring Trends in Burn Severity (MTBS) dataset, described above in **Section 4.0**, is a collaborative effort between federal science and land management agencies to accurately map long-term trends in fire magnitude and severity (Nelson, 2021). The database uses geographic information systems to map prescribed burn and wildfire perimeters going back several decades. Though this dataset has limitations noted above in **Section 4.0**, the available data show that, since at least the 1980s, wildfire has burned substantially higher acreage annually than prescribed fire. However, this varies on a regional basis. For example, the Southeast sees substantial prescribed fire acreage for fire management relative to other regions; meanwhile, the West has minimal prescribed fire acreage but comprises the majority of wildfire acreage nationally. For both types of fire, there is a long-term upward trend in annual acreage burned.

KEY MESSAGES

Recent Fire Trends

- Since the 1980s, wildfire has burned substantially higher acreage annually than prescribed fire, although differences in acreage burned varies regionally.
- Prescribed fire acreage burned for fire management in the Southeast is higher relative to other regions; meanwhile, the West has minimal prescribed burn acreage in recent years but comprises the majority of acreage burned by wildfire nationally.

Though this report does not focus on prescribed fire in contexts beyond fire management, a portion of prescribed fire activities conducted in the U.S. includes extensive agricultural burning (e.g., sugar cane burning, rice burning, grass burning), which is not intended for preventative fire management purposes (Tullis, 2020). Considering a broader definition of prescribed fire activities, acreage burned is greater in southeastern U.S. compared to other U.S. regions. Annual acreage burned from prescribed fire activities in the Southeast is estimated to be approximately 6.5 million acres for forest management and 3.8 million acres for agriculture (Cohesive Fire Strategy Group, 2022). California is looking to expand prescribed fire activity to help control the occurrence of catastrophic wildfires and has plans to eliminate agricultural burning in the San Joaquin Valley by January 1, 2025, in favor of less harmful agricultural practices (e.g., tilling, composting) (CARB, 2021a).

5.2 Smoke Composition, Magnitude of Emissions, and Duration of Exposure

The evidence suggests that there are indeed differences in smoke composition, magnitude, and duration of exposure to wildfires compared to prescribed fire. While outside the geographic scope of this review, similar trends have also been observed in Australia, with prescribed fire smoke found to be less impactful to air quality and health than wildfire smoke (Bell & Adams, 2009; Borchers Arriagada et al., 2021; Price et al., 2018). While less impactful, it should be made clear that prescribed fire can still results in air quality impacts and pose public health risks.

KEY MESSAGES

Smoke Impacts on Air Quality

- Wildfire and prescribed fire produce air quality impacts at different scales and magnitudes.
- Impacts of prescribed fires are typically constrained to local communities and persist for a short duration, whereas the impacts of high-intensity wildfires are often long-term (weeks to months) and far-reaching.

The composition and magnitude of smoke emissions from fires is complex, and is largely dependent on fuel type and density, the type of management practices implemented in the forest system and burning conditions. Other factors, such as the total area burned, are less important (Jaffe et al., 2020; U.S. EPA, 2021a; Williamson et al., 2016). The relative proportion of fire-related $PM_{2.5}$ emissions varies regionally throughout the United States; estimates indicate prescribed fire drives fire-related $PM_{2.5}$ emissions in the Midwest and Southeast, while wildfires are responsible for the vast majority of fire-related $PM_{2.5}$ emissions in the West in recent years (**Figure 5**).

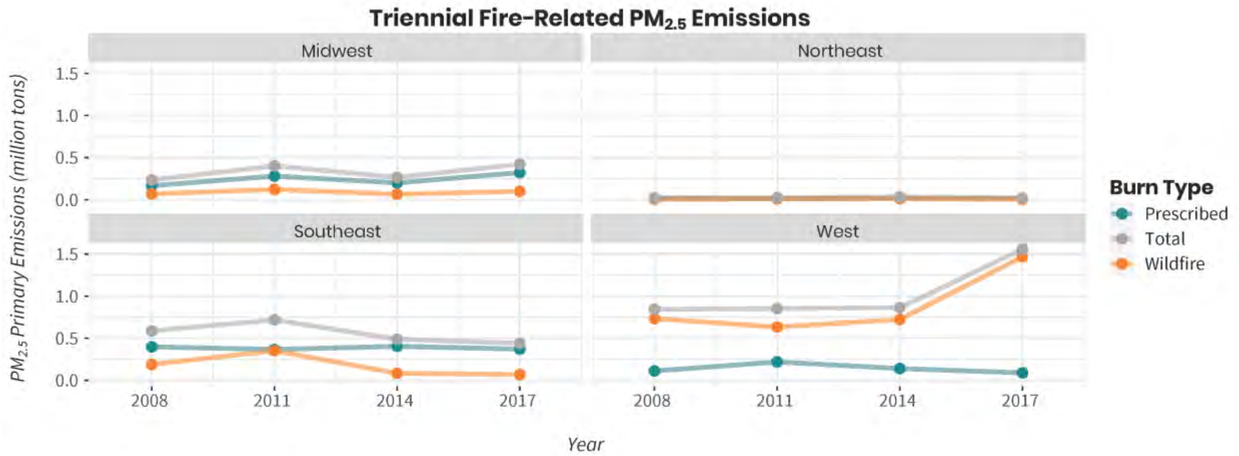

Figure 5. Fire Particulate Matter Emissions by Region. Prescribed fires are the primary drivers of fire-related $PM_{2.5}$ emissions in the Southeast and Midwest most years. The West tends to experience the highest aggregate fire-related emissions, largely due to the high magnitude of emissions from wildfires in the region. Data source: U.S. EPA National Emissions Inventory (NEI) 2008, 2011, 2014, 2017.

Fires may also emit different types of air pollutants due to differences in intensity and materials burned. In general, the majority of emissions (80-90%) from biomass fires (i.e., cropland, wildland fire, prescribed fires) are comprised of CO_2, followed by CO, VOCs, $PM_{2.5}$ (primary particulates)[9], methane and other inorganic compounds (e.g., NO_x, hydrogen cyanide, ammonia, nitrous acid) (Jaffe et al., 2020). Emissions from structures burned during a wildfire may differ from the emissions of biomass from a prescribed burn (see **Section 3.1.1**). 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 firefighter and nearby community health, as ultrafine particulate matter can deposit deep into the respiratory and vascular systems and cause toxic effects on internal tissues (Fabian et al., 2010).

Additional studies have indicated that wildfires emit more particulate matter per fuel burned or area burned than prescribed fires. Emission factors for wildfire-specific submicron PM ($PM_{1.0}$) are estimated to be two to six times greater than that of prescribed fires, a range dependent on the material and quantity of fuel burned (Liu et al., 2017). $PM_{1.0}$ emission rates were reported to be nearly four times higher in wildfires than spring and fall prescribed fires (Friedman, 2021; Liu et al., 2017). When PM emissions are considered in combination with differences in fuel

[9] $PM_{2.5}$ can be directly emitted (i.e., primary particulates) or formed in the atmosphere via chemical reactions involving primary gaseous emissions (i.e., secondary particulates).

consumption, it is estimated that wildfires emit approximately 18 times more PM per area burned compared to prescribed fires (Friedman, 2021).

The air quality impacts of wildfires also occur on a much larger scale as compared to prescribed fire. In 2021, the U.S. EPA released a *Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S.*, that modeled $PM_{2.5}$ emissions levels and the economic value of damages from death and illness due to smoke exposure (U.S. EPA, 2021a). The assessment focused on two case study wildfires, with each case study representing a different type of fire setting and size: **(1)** the Timber Crater 6 (TC6) Fire (Oregon), which represents a smaller fire (~3,000 acres burned) in a location removed from large populations, and; **(2)** the Rough Fire (California), which represents a larger fire (~150,000 acres burned) near large, populated areas (U.S. EPA, 2021a). In the case of the TC6 fire scenario, prescribed fire emissions were derived from real-world data, presented as the sum of all prescribed fires in the location and modeled for a period when the authors knew prescribed fires occurred (exact dates unavailable). For the Rough Fire scenario, the prescribed fire modeled was hypothetical because there were no available prescribed fire data for the Rough Fire. Under both scenarios, $PM_{2.5}$ emissions from wildfires were found to be substantially greater than from prescribed fires. $PM_{2.5}$ emissions from wildfires were estimated to be ~1,800-86,000 tons whereas emissions from prescribed burns were estimated to be ~120-500 tons per fire, with the sum of the TC6 prescribed fires emitting 1,071 tons of $PM_{2.5}$ (**Table 2**) (U.S. EPA, 2021a).

Table 2. Case-study assessment of comparative wildfire and prescribed fire impacts. Impacts shown include estimated $PM_{2.5}$ emissions and damages attributable to illness and death from two fires in California and Oregon (Source: U.S. EPA, 2021a). (95% CI = 95 percent confidence interval).

	$PM_{2.5}$ Emissions		Damages Attributable to Illness/Death	
	Wildfire	**Prescribed Fire**	**Wildfire**	**Prescribed Fire**
TC6 Fire *Oregon*	1,869 tons	1,071 tons (sum) (117-565 tons per fire)	$18M (95% CI $2-47M)	$4M (95% CI $0-$9M)
Rough Fire *California*	85,638 tons	499 tons per fire	$3,000M ($3B) (95% CI $260-7,900M)	$60M (95% CI $5-160M)

M = million; B = billion; 95% CI = 95% confidence interval.

Additional studies further demonstrate the larger scale air quality impacts of wildfire as compared to prescribed fire. One study estimated that, in recent years, wildfires accounted for up to 25% of total ambient $PM_{2.5}$ in the United States, and up to half of total ambient $PM_{2.5}$ in some western states (Burke et al., 2021). Another study in the Sierra Nevada region of California compared the air quality impacts of smoke exposure from prescribed fires, managed fires, and wildfires (Schweizer et al., 2019). The smoke extent (i.e., the total area under a given smoke density during a fire) was found to be the highest for the Rough Fire, a 2015 wildfire, for all smoke densities assessed. When comparing the rate and intensity of burn, the smoke extent and community exposure potential were highest for wildfires with high intensity and high burn rates (83 person-days per hectare) (Schweizer et al., 2019). Lower rates of burn and low-intensity fires, such as prescribed fires, appear to reduce smoke transport, thus resulting in reduced exposure (5.5 person-days per hectare) (Schweizer et al., 2019).

Another study evaluated the effects of fire smoke on children living in Fresno, California who were exposed to either a prescribed fire or wildfire approximately 70 miles away in 2015 (Prunicki et al., 2019). The authors found all measured ambient pollutant levels to be higher during wildfire as compared to prescribed fire, with concentrations of nitrogen dioxide (NO_2), nitrogen oxides (NO_x), polycyclic aromatic hydrocarbon (PAHs), elemental carbon (EC), and carbon monoxide (CO) from wildfires more than twice that of prescribed fires (**Table 3**; Prunicki et al., 2019). Additionally, wildfire smoke associated with this particular wildfire event contributed to elevated ambient $PM_{2.5}$ levels as compared to pre- and post-fire ambient concentrations, while prescribed fire smoke did not substantially contribute to measured ambient $PM_{2.5}$ in this study (Prunicki et al., 2019).

Table 3. Average ambient concentrations of pollutants during wildfire and prescribed fire. Pollutants were statistically significantly higher during wildfire as compared to prescribed fire ($p<0.0001$ for each pollutant shown) (Adapted from Figure 1, Prunicki et al., 2019).

Pollutant *(95% CI)*	**Wildfire**		**Prescribed Fire**	
NO_2 (ppb)	10.7	± *0.3*	4.0	± *0.2*
NO_x (ppb)	25.6	± *1*	9.9	± *0.5*
PAHs (ng/m^3)	11.4	± *0.4*	5.3	± *0.2*
EC (µg/m^3)	1.0	± *0.02*	0.48	± *0.01*
CO (ppm)	0.56	± *0.02*	0.25	± *0.01*
PM_{10}(µg/m^3)	41.5	± *1.1*	28.0	± *0.3*
$PM_{2.5}$ (µg/m^3)	15.9	± *0.4*	10.0	± *0.2*

NO_2 = nitrogen dioxide; NO_x = nitrogen oxides; PAHs = polycyclic aromatic hydrocarbons; EC = elemental carbon; CO = carbon monoxide; PM_{10} = coarse particulate matter; $PM_{2.5}$ = fine particulate matter; ppb = parts per billion; ppm = parts per million; µg/m^3 = micrograms per cubic meter; ng/m^3 = nanograms per cubic meter; 95% CI = 95% confidence interval.

One review study found measured $PM_{2.5}$ concentrations during wildfire to be lower than concentrations from prescribed fire; however, the resulting concentrations cannot be directly compared. Wildfire-related $PM_{2.5}$ concentrations included in this assessment represent levels in both communities near fire as well as urban centers far away. Meanwhile, prescribed fire related $PM_{2.5}$ concentrations represent levels directly near prescribed fires (Navarro et al., 2018). This may explain why this trend was observed, as factors such as monitor location, distance from the fire perimeter, and concentration averaging time impact reported ambient $PM_{2.5}$ concentrations (Navarro et al., 2018).

5.3 Health Risks and Impacts

Air quality impacts of both wildfire and prescribed fire activities can pose health risks. Exposure duration is critical to the development, progression, and exacerbation of adverse health outcomes. Less is known regarding the health impacts from longer exposure durations, such as peak exposures over multiple days, exposures over many months, and exposures due to repeated fire events over multiple fire seasons. Wildfires and associated smoke impacts may occur over weeks and months, whereas prescribed fires occur over a few days (Navarro et al., 2018). However, wildfire smoke exposures may be also be episodic and occur over short to moderate durations, with increased frequency over a lifetime. Thus, wildfire smoke exposures may be considered chronic or long-term.

KEY MESSAGES

Smoke and Human Health

- Peer-reviewed literature comparing the specific health impacts of prescribed fire and wildfire is very limited.
- Children exposed to wildfire smoke had markers of immune dysregulation and exhibited more severe respiratory health symptoms (wheezing, asthma exacerbations) compared to children exposed to prescribed fire smoke.
- A recent comparative assessment relying on estimated morbidity and mortality indicate that wildfires result in greater illness, deaths, and damages than prescribed fire.

Epidemiologic studies examining whether the health effects and corresponding risks vary between prescribed fire and wildfire smoke are limited. Even so, available evidence suggests there are differences in the public health risks and impacts from wildfire and prescribed fire smoke. A two-year epidemiologic study in Fresno, California evaluated respiratory outcomes and markers of immune function among three groups: one group of unexposed school-aged children; one group of children exposed to prescribed fire smoke; and one group exposed to wildfire smoke (Prunicki et al., 2019). Wildfire smoke exposure was associated with lower blood levels of cells involved in immune response. Wildfire smoke exposure was also associated with indicators of reduced allergic and other immune responses. Additionally, children in the wildfire group exhibited greater evidence of adverse respiratory health outcomes (wheezing and asthma exacerbation), as compared to the prescribed fire group (Prunicki et al., 2019).

A comparative assessment by the U.S. EPA estimated health impacts and corresponding economic values of damages from death and illness due to smoke exposure, comparing wildfire to prescribed fire (U.S. EPA, 2021a). While not an epidemiologic study, this secondary analysis still provides useful insights. Damages attributable to illness or death were substantially greater from wildfires than from prescribed fires. Damages from wildfires were ~$18 million-$3 billion whereas damages from prescribed burns were estimated to be ~$4-$60 million (**Table 3**) (U.S. EPA, 2021a). Well-designed prescribed fires targeted for specific locations may be able to reduce air quality and health impacts of subsequent wildfires (U.S. EPA, 2021a).

Results from the 2015 Rough Fire case study indicate a ~40% reduction in excess cardiovascular- and respiratory-related emergency room visits, hospitalizations, and premature deaths could have been achieved if a prescribed fire had occurred as a land management tool prior to the occurrence of the Rough Fire (U.S. EPA, 2021a).

5.4 Vulnerability and Equity Dimensions

Health impacts associated with wildfire and prescribed fire smoke exposure can vary based on an individual's susceptibility, which may be related to one's age, current health status, occupation, and socioeconomic vulnerabilities. This is described in detail in the context of wildfire smoke in **Section 3.2.2**. Housing conditions contribute to disparities in smoke exposure, as older, smaller homes and homes occupied by low-income households are known to have greater infiltration of outdoor pollutants (Burke et al., 2021). Wildfire smoke exposure also has complex environmental justice implications including issues related to access to exposure reduction

KEY MESSAGES

Fire Smoke, Vulnerability and Equity

- People with underlying respiratory or cardiovascular diseases, children, older adults, people who are pregnant, fetuses, socioeconomically disadvantaged populations, outdoor workers and people without homes are at a greater risk of adverse health impacts from smoke exposure.
- Interventions that focus on lowering smoke exposure among the most susceptible populations are likely to achieve the greatest health benefits.
- Indigenous people have been using cultural and prescribed fire (“good fire”) to manage their home landscapes for millennia; and, in many places, are not currently allowed to do so due to federal fire suppression policies and agency culture, among others.

measures. Several studies found low socioeconomic status and older individuals to be at greater risk of adverse health impacts (Cascio, 2018; Liu et al., 2015; Reid et al., 2016). While one study found that U.S. counties with a larger percentage of the non-Hispanic white population are less exposed to *total* $PM_{2.5}$, the study reported non-Hispanic whites are actually more exposed to *wildfire-related* $PM_{2.5}$. How this translates to individual exposures, however, is difficult to determine, as it depends on a number of factors, such as housing, work conditions, and time spent outside (Burke et al., 2021).

Disparate exposure to prescribed fire smoke has also been observed across populations. In Georgia, $PM_{2.5}$ emissions from prescribed fire were found to be greater in communities with a higher percentage Black population (Johnson Gaither et al., 2019). Approximately 25% of prescribed fire activity hot spots in Georgia occurred in areas with concentrated social vulnerability, with average social vulnerability index (SVI) scores for these communities 25% more than the Georgia state average (Afrin & Garcia-Menendez, 2021).[10] In contrast, areas without prescribed fire (i.e., "cold spots") had an SVI 15% less than the state average, indicating that communities farther from burn activity are less likely to exhibit socioeconomic factors that could worsen the human health impacts from fire smoke exposure. These findings suggest prescribed fire smoke in wildland urban interfaces (WUI) (i.e., fires that occur within or adjacent to an "at-risk community") may disproportionately impact communities with lower socioeconomic status, a higher proportion of older people and people with disabilities, and those with limited access to transportation and housing in Georgia (Afrin & Garcia-Menendez, 2021).

Interventions that focus on lowering smoke exposure among the most susceptible populations are likely to achieve the greatest health benefits. As wildfires and the potential for harmful smoke exposure are anticipated to increase in United States, the number of smoke-vulnerable Americans is also projected to rise. Between 2018 and 2060, the total share of the United States population over 65 is expected to increase by 7%, nearly doubling the size of this at-risk population (Mather et al., 2015). In California, a recent analysis found that areas more heavily impacted by wildfire were home to a greater proportion of older adults and low-income residents and had lower median household incomes and home values as compared to the rest of the state (Masri et al., 2021). Furthermore, the most recent Housing and Urban Development (HUD) survey indicated that 18 of every 10,000 people in the United States were unhoused in January 2020, up 2.2% from the year prior (HUD, 2021); these individuals are at particular risk

[10] This study focused on a broad definition of prescribed fire activity, but silvicultural (forest management) burns were dominant burn type in both Georgia; prescribed fire acreage was characterized as 83% silvicultural, 11% agricultural, and 6% land clearing (Afrin & Garcia-Menendez, 2021).

due to limited access to clean air spaces and other factors including socioeconomic vulnerabilities.

Indigenous people have been using cultural and prescribed fire ("good fire") to manage their home landscapes for millennia, and, in many places, are not currently allowed to do so due to federal fire suppression policies and agency culture (Clark et al., 2021). Excessive restrictions and limitations around the use of fire by Indigenous peoples ultimately contributes to greater frequency and severity of wildfires. This was evidenced by the Slater Fire of 2020, which occurred on an overgrown and undermanaged landscape that was once managed by the Karuk Tribe (Venton, 2021).

5.5 Exposure Reduction Measures for Wildfire & Prescribed Fire Smoke

There are trade-offs to consider when evaluating the potential air quality and health impacts of prescribed burns. Implementing prescribed fires reduces overall fuel loads, which can mitigate the health and safety risks associated with large-scale wildfires. While prescribed fires are implemented in ways that minimize harmful smoke exposure potential, these activities do result in local air quality impacts and can pose health risks. Therefore, additional strategies and policies intended to reduce impacts from prescribed fire smoke exposure should be considered.

5.5.1 Methods to Reduce Wildfire Smoke Exposure and Adverse Health Impacts

Air quality surveillance and public outreach. Spatially distributed air monitoring networks can provide real-time and time-averaged air quality data to decision makers and the public. Access to air quality data can inform public notification systems and community efforts to reduce exposure during periods of poor air quality related to fire 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 vulnerable populations. The AQI is designed to indicate the potential for

KEY MESSAGES

Reducing Wildfire Smoke Exposure

Numerous strategies can be implemented to reduce public health impacts associated with wildfire smoke exposure, many of which also mitigate smoke exposure from prescribed burn activities. Briefly, these strategies include

(1) air quality surveillance coupled with public outreach and public notification systems;

(2) indoor air filtration and clean air spaces;

(3) provision and use of respiratory protective equipment; and

(4) additional emergency planning and response, including protections for vulnerable populations.

acute health effects among exposed populations within a few hours or days of 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, 2019). The 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. For example, 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 & Chen, 2019). Another tool used to assess air quality and fire smoke is the Fire and Smoke Map provided by the U.S. EPA and U.S. Forest Service, which utilizes data from both regulatory monitors and Purple Air sensors to give a broader representation of smoke and PM exposure (U.S. EPA, 2022). Even so, the Fire and Smoke Map has similar limitations to the AQI, as it is limited in the pollutants monitored and reported from wildfire smoke. Despite limitations, the AQI and the Fire and Smoke Map both provide useful context of wildfire smoke impact on air quality.

Indoor air filtration. 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 (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 at 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 et al., 2002).

Clean air spaces. Public facilities equipped with centralized air filtration systems can provide clean air access to a greater number of individuals in areas with wildfire smoke. Clean air shelters can include public libraries, community centers, gymnasiums, senior centers, movie theaters, malls, and museums. Considerations that should be made when determining policy about clean air shelters include the duration of shelter availability for public use, the effectiveness of the heating, ventilation, and air conditioning (HVAC) system, the ability of buildings to accommodate high efficiency filters, and the availability of reliable backup power during power outages. 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 within the home will provide greater health benefits than relying on clean air shelters alone.

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 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 public. For instance, N95 masks may not be able to be properly fitted for children or individuals with facial hair (FDA, 2020; Hodenfield, 2018). Additionally, if the respirator limits breathing or causes discomfort for people with lung disease, they should consult with their healthcare provide about wearing N95 masks or any respirator. Generally, other ways to reduce exposure (e.g., limiting time outdoors and reducing activity) may be appropriate.

Outdoor workers may also be at greater risk of exposure to wildfire smoke and require additional protections in the workplace. In July 2019, after agricultural workers worked through numerous intense smoke events in California, the California Division of Occupational Safety and Health (Cal/OSHA) issued an emergency regulation (§5141.1) to outline specific worker protections from wildfire smoke. 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). Recent, expanded wildfire smoke protections for workers have also been implemented in Washington and Oregon (Oregon OSHA, 2022; WA Department of Labor and Industry, 2021).

Emergency planning and response. Emergency planning and response must also consider vulnerable populations during wildfire smoke events. Specific populations are more susceptible to the adverse health impacts associated with wildfire smoke exposure than others based on factors such as life stage and socioeconomic vulnerabilities. Ad hoc initiatives, such as pop-up clean air centers and the provision of respirators, can help reduce smoke exposure. However, coordinated emergency planning and response efforts can ensure that information reaches a wider expanse of the impacted population and exposure reductions occur more equitably. For example, following the 2018 record-breaking wildfire season, numerous Bay Area stakeholders developed the Bay Area Regional Air Quality Messaging Toolkit (Bay Area UASI, 2018). 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, people without homes, and people with limited English proficiency.

The "Smoke-Ready Community" framework also provides a comprehensive approach to prepare communities for wildfire and ultimately reduce harms to public health and safety. As defined by the U.S. EPA, a Smoke-Ready Community is a community: **(1)** with public buildings equipped with filtration for fire smoke; **(2)** whose residents understand the health risks associated with smoke exposure and can readily access tools to protect their health; and **(3)** with available resources aimed to help those most vulnerable to smoke exposures (McGown, 2020; U.S. EPA, 2018).

Additionally, the U.S. EPA provides a "Smoke-Ready Toolbox" to prepare fire-prone communities for wildfire smoke events (U.S. EPA, 2018). This toolbox provides information, trainings and measures the public can use to understand and reduce potential health risks and reduce health impacts before, during, and after a wildfire event occurs (U.S. EPA, 2018). These include resources such as: online training for health care providers to better understand how wildfire smoke can impact their patients' health; health and wildfire preparedness fact sheets, which provide information on how to reduce your smoke exposure, how to protect your children, pets, and/or large animals from smoke and ash exposure, and indoor air filtration options, among others; information related to public notification systems and the best ways to stay informed during a wildfire event; and recommended supplies to take with you in the event of an evacuation (among others) (U.S. EPA, 2018). Measures identified within this toolbox can also be applied to help mitigate the impacts from prescribed fire events as well, and have been implemented in communities across the U.S., including in California, Oregon, and Washington (McGown, 2020; Troisi, 2021).

5.5.2 Methods to Reduce Prescribed Fire Smoke Exposure and Adverse Health Impacts

Expanded prescribed fire activity can help mitigate wildfire risks in the United States. The literature supports the view that historical fire suppression policies are ineffective long-term fire management tools. Fire suppression strategies appear to push the health burden associated with smoke exposure to a later date and result in increased fire intensity and a higher number of people exposed in a single smoke event. While prescribed burns also have the potential for harmful smoke exposure, these overall impacts are significantly reduced, due to the low intensity, low burn rate, and relatively short duration typical of prescribed fires, as well as the fact that they are typically scheduled for days with specific meteorologic conditions to reduce smoke impacts. The increased use of prescribed fire should be considered and can be further improved upon by burning during good dispersal conditions and mitigating poor conditions when the smoke extent is largely over wilderness areas (Schweizer et al., 2019).

KEY MESSAGES

Reducing Prescribed Fire Smoke Exposure

In addition to existing prescribed fire management strategies, exposure to prescribed fire smoke can be further mitigated through the following strategies:

(1) improved prescribed fire management planning by conducting more air quality monitoring during burn activities and expanding prescribed fire reporting and public notification systems;

(2) utilization and/or further development of tools to forecast potential prescribed fire impacts; and

(3) implementation of interventions and other mitigation efforts that reduce exposures, such as portable air cleaners and residential heating, ventilation, and air conditioning (HVAC) systems, among others.

As prescribed fire activity continues to increase in the United States, especially in the Southeast and Pacific Northwest, states have implemented policies and guidelines for smoke management, as well as developed tools to forecast potential prescribed fire impacts. For example, the Georgia Department of Natural Resources (GaDNR) uses a prescribed fire impact forecasting system, referred to as HiRes2, to provide daily forecasts (one day in advance) of potential air quality impacts from prescribed fire in Georgia (Odman et al., 2018). HiRes2 forecasts are based on several factors, including meteorological and wildland conditions like wind, precipitation, and fuel humidity and quantity, and are used by GaDNR and other agencies to provide official air quality forecasts to protect public health.

Another web-based tool, referred to as the Southern Integrated Prescribed Fire Information System (SIPFIS), was developed to provide daily forecasts of potential air quality impacts from prescribed fires for the southeastern U.S. (Hu et al., 2019). SIPFIS provides access to air quality and fire-related products as well as visualizations of exposure to prescribed fire smoke and has been shown to help users accomplish activities related to fire management, especially for those involved in the assessment of environmental and health impacts from prescribed fire smoke. Such activities include looking up community-level smoke exposures, screening for fire-related circumstances that could lead to air quality exceedances, supporting evaluations for air quality forecasts, and assessing prescribed burn activities (Hu et al., 2019).

States and local municipalities should consider using tools similar to HiRes2 or SIPFIS to forecast potential prescribed fire impacts. Forecasting systems that integrate methods to apportion air quality impacts from individual fires should also be considered, such as the Dispersive Apportionment of Source Impacts (DASI) method implemented by Huang et al. (2020). Information on individual fire impacts could aid wildland and air quality managers in determining which burns should be allowed or restricted based on their individual impacts to air quality and health.

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. 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:** Future air quality monitoring during prescribed burns could produce useful data for modeling potential associated health risks and impacts from smoke exposure in surrounding populations.
- **Expanding prescribed burn reporting:** Smoke management guidelines could be expanded to require increased geographic details, such as coordinates of the burn area perimeters and estimated or measured emissions.
- **Expanded notification system:** Current public notification procedures in California, for example, 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 were made aware.

The comparative assessment conducted by the U.S. EPA also highlights the potential public health benefits of implementing interventions and other mitigation efforts that reduce prescribed fire and wildfire smoke exposure risks (e.g., air filtration, usage of residential HVAC systems) (U.S. EPA, 2021a). Preliminary results suggest a 14-31% reduction in population $PM_{2.5}$ exposure could be achieved depending on the mitigation measures implemented. It is important to note that this estimate is based on individual mitigation options and the assumption that every individual has access to and is using that measure.

5.6 Key Research Gaps and Limitations

5.6.1 Research Gaps and Limitations Relevant to Wildfire

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, and implementing and evaluating the effectiveness of public health interventions. Below we offer research recommendations from a review of available literature.

Air quality monitoring, when feasible, should include chemical speciation of wildfire smoke emissions to address the unknowns regarding chemical constituents in wildfire smoke beyond $PM_{2.5}$. Additionally, future epidemiological studies should (1) include evaluations of cumulative or multiple-pollutant exposures, rather than individual compounds ($PM_{2.5}$) to better evaluate risk and impact; and (2) evaluate health effects over longer durations and multiple fire seasons, as impacts under these exposure scenarios are not known.

Challenges in exposure assessment make it difficult 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. The current monitoring network in the United States was not designed to measure wildfire smoke, so air monitors are lacking in many key areas. 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 $PM_{2.5}$. 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.

Denser air quality monitoring networks, with higher spatial and temporal resolution, should be implemented to allow better estimation of exposure to $PM_{2.5}$ and other pollutants during wildfire smoke events, especially in regions that have limited air monitoring and are prone to wildfires.

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 et al., 2016). To address this challenge, air quality surveillance should be increased in areas with limited monitors and that are prone to wildfires. 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).

Future research on the health impacts of wildfire smoke should (1) evaluate the associations of wildfire smoke exposure to understudied health endpoints not present in the existing peer-reviewed literature (e.g., metabolic disorders, pediatric cognitive and motor development, cognitive decline, mental health, and maternal health); (2) include further investigation of cardiovascular outcomes to better elucidate the potential exposure-response relationship with wildfire smoke; and (3) consider the long-term health impacts of repeated exposures to wildfires.

The peer-reviewed literature suggests that adverse health outcomes associated with exposure to wildfire smoke primarily include respiratory outcomes, birth outcomes, and premature mortality. However, there are numerous understudied health endpoints related to wildfire smoke exposure in the peer-reviewed literature and results differ across studies regarding the impact of wildfire smoke on cardiovascular disease. Data on deaths, hospitalizations, and visits to emergency departments, urgent care, and physicians may be the most 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 (Cascio, 2018). 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 single or multiple exposure events. One challenge in determining evidence of chronic health outcomes is that endpoints, such as cancer, have longer latency periods. Other constraints are the extensive financial and time requirements to conduct long-term surveillance of populations exposed to wildfire smoke.

5.6.2 Research Gaps and Limitations Relevant to Prescribed Burns

Future research should (1) evaluate the potential health impacts from chronic exposure to low levels of smoke from small prescribed burns; (2) explore the differences in health impacts between smoke from prescribed burns and smoke from wildfires; (3) incorporate emission estimates using a dense air monitoring network with high spatial and temporal resolution, to allow for better estimation of exposure to $PM_{2.5}$ and other pollutants during prescribed fire smoke events, especially in regions that have limited air monitoring and are frequently exposed to seasonal prescribed fire activity; and (4) evaluate the efficacy of prescribed burns in reducing wildfire activity, size, and smoke production.

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. Furthermore, there are numerous understudied health endpoints that need to be explored before any judgment can be made as to whether prescribed fire smoke is associated with specific adverse effects.

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 policy makers in more accurately determining the public health trade-offs of prescribed burns and wildfires.

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7.0 Appendix

Materials reviewed in this report include peer-reviewed journal publications, reports, and white papers on the air quality and human health impacts of wildfire and prescribed fire in the United States published between 2000 and present. Peer-reviewed journal articles published through November 15, 2021 were compiled via Web of Science using the search terms provided below:

TS=(wildfire OR “wildland fire” OR “prescribed burn” OR “fire smoke” OR “wildfire smoke” OR “wildland smoke” OR “controlled burn” OR “prescribed fire”) NOT TS=(“tobacco” OR “industrial”) AND TS=(“Health” OR “epidemiological” OR “occupational” OR “symptom” OR “health risk*” OR “occupational health” OR “firefighter” OR “physiological” OR “hospitalization” OR “asthma” OR “mortality” OR “cancer” OR “morbidity” OR “adverse pregnancy outcomes” OR “birth” OR “congenital” OR “birth defects” OR “birth weight” OR “low birth weight” OR “preterm birth” OR “premature birth” OR “preterm delivery” OR “small for gestational age” OR “LBW” OR “PTB” OR “PTD” OR “SGA” OR “fetal death” OR “mental health” OR “cardiovascular” OR “exposure” OR “respiratory”) NOT TS=(Europe OR Australia OR China OR India OR “Middle East” OR Africa) AND TS=(“U.S.” OR “United States” OR USA OR Canada OR “North* America” OR Alabama OR Alaska OR Arizona OR Arkansas OR California OR Colorado OR Connecticut OR Delaware OR Florida OR Georgia OR Idaho OR Hawaii OR Illinois OR Indiana OR Iowa OR Kansas OR Kentucky OR Louisiana OR Maine OR Maryland OR Massachusetts OR Michigan OR Minnesota OR Mississippi OR Missouri OR Montana OR Nebraska OR Nevada OR “New Hampshire” OR “New Jersey” OR “New Mexico” OR “New York” OR “North Carolina” OR “North Dakota” OR Ohio OR Oklahoma OR Oregon OR Pennsylvania OR “Rhode Island” OR “South Carolina” OR “South Dakota” OR Tennessee OR Texas OR Utah OR Vermont OR Virginia OR Washington OR “West Virginia” OR Wisconsin OR Wyoming OR “Washington DC” OR “Washington D.C.” OR “D.C.” OR “District of Columbia”*