Chapter 8
Resource Manager Perspectives on the Need for Smoke Science

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Abstract Smoke from wildland fire is a significant concern to resource managers who need tools, knowledge, and training to analyze, address, and minimize potential impacts; follow relevant rules and regulations; and inform the public of possible effects. Successful navigation of competing pressures to appropriately use fire on the

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landscape to manage fire-adapted and fire-dependent ecosystems, while protecting public health and other air quality values, depends on credible science and tools conceived of and developed in partnership between managers and the research community. Fire and smoke management are made even more complex by the current

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condition of ecosystems as a result of fire exclusion and the future implications of a changing climate. This chapter describes the scope of smoke management, social and regulatory contexts, and pathways through which scientific information and tools can improve the accuracy and timeliness of management and communication with the public.

Keywords Air quality · Emission reduction techniques · Modelling · Prescribed fire · Public health · Smoke · Wildfire

8.1 Introduction

In many parts of the USA, fire-prone ecosystems have been altered by a combination of past management and changing environmental conditions. Accumulation of wildland fuels from decades of wildfire exclusion (including suppression) is contributing to increased wildfire size and severity across much of western North America (Schoennagel et al. 2017). As a result, smoke impacts have been severe and widespread in recent decades, with serious consequences for human health, economic impacts from lost tourism, and visibility impairment on roads and at airports (Chaps. 4 and 7). In addition, climate change is contributing to greater amplitude of seasonal weather extremes and altered ecosystem functions (Box 8.1). Wildfire season is starting earlier in the year and ending later. If a warmer climate does indeed cause more area burned by wildfires (Abatzoglou and Kolden 2013; Jolly et al. 2015), an increased frequency of degraded air quality, or "smoke waves" (Larkin et al. 2015; Liu et al. 2016), is likely. Communities have become more aware of how to prepare for wildfire, but the concept of being prepared for smoke is new and not yet widespread. Smoke exposure cannot be eliminated, but with preparation and planning, people can take actions to mitigate adverse effects of wildland fire smoke.

Box 8.1 Managing Smoke in a Changing Climate
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Climate change is expected to cause more frequent wildfires across larger areas of the USA, altering vegetation patterns and ecosystem function (Reidmiller et al. 2018; Vose et al. 2018; Halofsky et al. 2020). Extreme fire weather is expected to become more frequent, affecting primarily the arid and semiarid west, but also affecting the upper Midwest and portions of the northeastern

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and southern USA (Barbero et al. 2015). Annual area burned in the western USA may increase by 2–6 times by the mid-twenty-first century compared to historical area burned in the twentieth century, depending on ecosystem and local climate (Kitzberger et al. 2017; Litschert et al. 2012; McKenzie et al. 2004). If a warmer climate does indeed cause more area burned by wildfires, an increased frequency of degraded air quality, or "smoke waves" (Liu et al. 2016), is likely. Given these projections of increased emissions, a greater number and magnitude of human impacts from smoke could be expected in the future.

A range of environmental changes resulting from climate change may affect future smoke emissions. Longer fire-weather seasons will have commensurately longer periods of drier (dead and live) fuels (Jolly et al. 2015). As the frequency and extent of drought increases, lower soil moisture will accentuate the influence of soil organic matter (and mineral soil in very intense fires [Bormann et al. 2008]) on smoke chemistry and carbon dynamics (Martínez Zabala et al. 2014; Mayer et al. 2020), potentially limiting use of prescribed fire. A better understanding is needed of how climate change will alter the flammability of surface fuels, particularly on how pre-fire soil moisture and fine fuels influence the size and intensity of wildfires (Krueger et al. 2015).

Because more frequent fires will lead to more frequent smoke effects (Peterson et al. 2020), planning for and managing smoke emissions and dispersion will become increasingly difficult and require agencies and communities to consider new approaches to: (1) managing wildfires, (2) timing of management actions such as prescribed fire, and (3) mitigating health and economic risks from large wildfires through the effective use of fire. Air quality agencies will need to consider the potential increased emission load when approving a planned burn.

As extreme weather becomes more common, better meteorological data will be needed to respond to its effects. The Remote Automated Weather Station (RAWS) system deploys stations across forested areas, but real-time meteorological data are needed to guide fire management. Most national forests are above 200 m elevation in the eastern USA and above 1200 m in the western USA, but climate trends modeled by NOAA rely chiefly on meteorological data from low-elevation stations, contributing to potential errors.

Smoke management practices may need to be revised in some cases to address the potential effects of climate change but will generally not need to be greatly altered. However, a comprehensive approach to smoke would benefit fire and air quality management in this changing environment. Williamson et al. (2016) proposed the concept of a smoke regime, a transdisciplinary framework that would take into account the collective consequences of numerous smoke-related elements including the risk factors for each type of fire (wildfire and prescribed fire). These, combined with human population attributes such as exposure, size, vulnerability, and mitigation, could be used to describe overall population health impact.

Recognition is growing that prescribed fire—when carefully planned, timed, and managed—can reduce wildfire risk and lower potential environmental and public health impacts as compared to the unplanned nature of wildfires (WFLC 2020). Prescribed fire can help reduce fuels, enhance ecosystem resilience, and enhance community safety; however, smoke from prescribed fire can be a serious health threat for some individuals and is often a nuisance, even to those who are unlikely to have adverse health impacts. Prescribed fires offer the opportunity to adjust the timing of fire and some ability to manage the amount of smoke and its path, thereby potentially reducing the overall impacts of wildland fire emissions on public health and welfare (WFLC 2020).

In some places, federal land managers are tentatively using some naturally ignited wildfires to allow more fire on the landscape, although this approach can be controversial and difficult to implement. In California, a fee is assessed for wildfires used in this way. Air quality regulations focus on planned ignitions (prescribed fire) but do little to address unplanned ignitions (wildfire), although wildfire impacts are much worse in both magnitude and duration.

Managers need to take into account and minimize smoke impacts to remain within legal constraints for air quality protection and protect the public. In order to maintain societal support for use of prescribed fire, it can also be beneficial for managers to provide the public with information on the goals and effects of fire use (Olsen et al. 2014). Fire that mimics historic wildfire timing, size, and intensity can contribute to desired ecosystem functions. Alternatives to burning can be more socially desirable as immediate impacts of smoke can be avoided (Shindler and Toman 2003). Although smoke is reduced in the short term, land managers have little scientific evidence that using alternative techniques accomplishes the goals of reducing emissions while simultaneously sustaining desired ecosystem process and functions (Thompson et al. 2018). In addition, most alternatives to fire are more costly than prescribed fire and may have negative environmental effects of their own, such as soil compaction from the use of heavy equipment. Managers are challenged to understand how use of different emission reduction techniques affect forest structure following prescribed fire and how the techniques may work individually and in combination.

Managers have a responsibility to analyze the effects of fire management decisions, inform the public about planned actions that affect air quality, and alert the public during active smoke events that may affect human health. Ultimately, public support for actions taken to manage wildlands depends on sharing credible information about potential smoke effects from active fire management, including possible air quality implications of taking no action. Efforts to develop state-of-science smoke analysis tools, and to provide smoke science information to managers, play a vital role in managing ecosystems, while protecting people and communities from the impacts of smoke.

8.2 Managing Wildland Fire to Improve Ecosystem Conditions While Minimizing Smoke Impacts

Mandated in the Federal Land Assistance, Management, and Enhancement Act of 2009 (FLAME Act; US Congress H.R. 1404), an intergovernmental planning group involving stakeholders and the public adopted a national vision for wildland fire management for this century: "To safely and effectively extinguish fire when needed; use fire where allowable; manage our natural resources; and as a nation, to live with wildland fire" (National Science and Analysis Team 2014). Prescribed fire helps reduce fuel accumulation and improve ecosystem conditions, and scientific documentation can support efforts to increase use of prescribed fire as envisioned by the National Cohesive Wildland Fire Management Strategy (Cohesive Strategy). Analysis of when and where prescribed fire is most effective and most necessary helps managers maximize the benefits of fire, while considering alternatives to put less smoke in the air. In addition to prescribed fires, managers may utilize natural ignitions but need information to weigh short- and long-term benefits and costs of these fires, especially potential smoke impacts.

8.2.1 Smoke Concerns and Barriers to Prescribed Fire

Wildland fire management options to improve ecological conditions, including prescribed fire, have been supported by research and federal fire management policy and guidance for decades. However, resource managers have not been able to utilize these options at the larger spatial scales needed to increase ecological resilience in the West (Stephens et al. 2016; Thompson et al. 2018; Kolden 2019; Schultz et al. 2019). Two likely reasons for this include risk aversion and a systemic set of incentives that lead to an emphasis on minimizing short-term impacts while accepting negative future tradeoffs, thus deferring fire and smoke risk into the future (Maguire and Albright 2005; Schultz et al. 2019).

Fundamental changes in how the fire management community thinks about, learns from, plans for, and responds to wildfires may be needed before change is seen in the amount of fire on the landscape (Thompson et al. 2018). A recent survey of prescribed fire practitioners found that air quality was one of the top three perceived impediments to implementing prescribed fire (Melvin 2018), suggesting that there also will be a need to develop more effective options for mitigating wildfire smoke and air quality impacts.

A comprehensive set of signatories to the Cohesive Strategy (National Science and Analysis Team 2014) including federal, state, tribal, county, and municipal governments has established goals to increase the use of prescribed fire. However, prescribed fire may not always be the right tool for some locations and sociopolitical environments. To prioritize the use of fire and address potential short-term smoke emissions, managers need to answer numerous questions, including: (1) when and where is fire an irreplaceable tool?, (2) how do seasonal shifts in the use of prescribed fire affect the function of fire in an ecosystem?, and (3) where and how will the use of prescribed fire affect wildfire risk?

Current fire and air quality analysis tools are not always well suited to these needs. A significant amount of research has been completed to help estimate fuel consumption (Chap. 2) and emissions (Chap. 5) from various types of fires. However, because of the site- and unit-specific nature of prescribed burning operations, additional research and tools are needed to assist in local planning and reporting.

8.2.2 Applying Prescribed Fire Across Large Landscapes

Large areas of the western USA are far out of range of the natural fire cycle (based on historical conditions) and are at risk of experiencing high-intensity wildfires that can spread into communities and degrade other values of wildlands (Morgan et al. 2001). The current pace and spatial scale of prescribed fire cannot keep up with the need for reducing fuels, fire intensity, and smoke (Vaillant and Reinhardt 2017). Applying prescribed fire across larger landscapes, thousands of hectares instead of hundreds of hectares at a time, would also provide ecological benefits and return the role of more frequent fire (Schweizer et al. 2017).

However, air quality laws and limited land management resources make it unlikely that prescribed fire and alternatives to burning can be utilized to the extent that would be desirable for ecosystems. Managers need to both understand and communicate tradeoffs among the options of fire use, alternatives to burning, and restoration of desired ecological functions (e.g., resilience to future fire and climate change) in fire-prone ecosystems. This information will help resource managers better assess how to burn larger areas while minimizing air quality impacts. Support for burning large areas will depend on evidence that current approaches are inadequate, that larger burn areas will provide greater ecosystem benefits, and that large burns can be done safely and with acceptable smoke impacts.

8.2.3 Utilizing Wildfires and Natural Ignitions

Federal wildfire policy allows for a range of responses to a wildfire, from monitoring to full suppression (with all options along this spectrum available depending on assessment of each individual fire) while prioritizing firefighter and public safety first and using sound, risk-based decisions as the foundation for all fire management activities (National Science and Analysis Team 2014).[1] Each fire management

[1] In reality, the range of response options available to federal managers on individual land management units may be constrained by options spelled out in existing planning documents, some of which are many years old and may not reflect current priorities for wildland fire management.

strategy considers associated risks, short- and long-term tradeoffs, levels of uncertainty of effects on resources and assets, probability of success, and potential duration. For example, in remote locations, selecting a monitoring strategy for a wildfire with resource objectives may be an appropriate decision, having little immediate risk and exposure to firefighters, lower costs, and low smoke impacts. But those impacts may be of longer duration, and uncertainty about future smoke emissions increases over time.

In areas where communities or other highly valued resources and assets are threatened, selection of a full suppression strategy is likely. When firefighters actively engage in suppressing fire, their risk and exposure are high, cost per unit of time is high, and smoke impacts are relatively low or of short duration if the fire is quickly controlled. However, in fire-prone ecosystems, this potentially defers impacts, including for air quality, to future years (Box 8.2). Quantifying ecological and air quality tradeoffs in a manner that is understandable for policy makers and the public is a challenging proposition, requiring the assistance of scientists, because smoke impacts from prescribed fires are no more welcome than from wildfires.

Box 8.2 Managing Fires for Resource Benefits in California

Under California law (Title 17), lightning ignitions managed for multiple objectives, including resource benefit, are classified and regulated as prescribed fires. This law does not reflect contemporary federal definitions for wildland fires. The California law requires close coordination, compliance, and mitigation measures with local and state air quality regulatory authorities. Resource managers are often scrutinized and criticized for not aggressively suppressing all unplanned ignitions and for allowing smoke to adversely impact communities. This perspective often fails to recognize that absence of fire defers smoke to a later date when emissions and risk of impacts may be higher.

One option for reintroducing the natural role of fire is to aggressively suppress fewer wildfires. However, this could lead to smoke impacts with considerably longer durations than for prescribed burning. If prescribed fire is applied at a much larger scale, then smoke impacts can more easily be spaced out over time. Some studies have suggested that both wildfires allowed to burn for resource objectives and prescribed fires have substantially lower smoke impacts than large, fast-spreading wildfires (North et al. 2012; Schweizer and Cisneros 2017). However, Navarro et al. (2018) compared emissions from a number of studies and determined there is little difference in emissions between wildfires and prescribed fires for a given area. In any case, wildfires managed for resource objectives and prescribed fires are more able to align emission pulses with times of best dispersion, providing greater control of smoke impacts (Long et al. 2017).

8.2.4 Implications of Wildfire Response Actions and Suppression for Air Quality

Wildfire suppression and management may include the tactical use of intentionally ignited burnout operations to deprive an advancing wildfire of fuels. Although this technique can stop or slow wildfire spread, there are air quality implications that can be difficult to assess, raising questions about whether (1) aggressive use of intentionally ignited fires for wildfire control results in a significant decrease in the duration and/or size of the wildfire and air quality impacts, and (2) the public will support more smoke in the short term if it means fewer air quality impacts over the long term.

Fire management and suppression decisions must always be made with safety in mind. Although it is easier to understand risks to wildland firefighters during suppression actions, public health and safety considerations from smoke are more difficult to understand and communicate; better integration in decision-making would improve wildfire management.

8.2.5 Alternatives to Burning—Evaluating Emissions Reduction

Alternatives to burning (e.g., mechanical thinning, grazing) are considered in nearly every decision to use prescribed fire, and there is often pressure to increase the use of alternatives to reduce smoke impacts. Alternatives to burning cannot always be scaled to the extent needed to foster a resilient ecosystem because of the buildup of fuels from fire exclusion, particularly with the additional stress of climate change (Bradstock et al. 2012; Flannigan et al. 2009; Vaillant and Reinhardt 2017). In addition, surrogates of fire may not provide the same ecological benefits of fire (Keeley et al. 2005; Klocke et al. 2011; Kobziar et al. 2018). For example, undergrowth brush mastication reduces fuel loading but does not provide the heat needed to release seeds from the cones of serotinous pine species (e.g., lodgepole pine [*Pinus contorta* var. *latifolia*]). In this case, mastication would meet the societal need of reducing fire risk and smoke but not the ecological need for tree regeneration.

Information on the cost and benefits of large-scale emission reduction techniques using alternatives to burning is limited. Alternatives to burning can be expensive and may create additional, if different, air quality impacts (e.g., dust from mastication, transportation emissions associated with thinning or milling). Research is needed to quantify the effect of different emission reduction techniques. For example, allowing fires in remote areas or wilderness to progress with minimal intervention may reduce smoke exposure to nearby communities (Schweizer et al. 2019b), but little is known about collateral air quality impacts.

The ecological role of smoke and the effects of altering the smoke cycle with suppression are poorly understood. For example, one study found that loss of ground-level cooling due to smoke potentially increased stream temperatures and reduced the benefits of cold water to fisheries (David et al. 2018). Further study is needed to understand the tradeoffs of different fire management techniques, particularly when the decision to ignite is being used in part for air quality considerations (e.g., good smoke dispersal) (Schweizer et al. 2020).

Managers need emission reduction techniques that have a high probability of minimizing air quality impacts, along with a description of possible unintended consequences to other ecosystem processes. A rigorous procedure to evaluate tradeoffs and costs when choosing emission reduction techniques or alternatives to burning will ensure that those techniques align with land management goals. Numerous prescribed fire emission reduction techniques have been identified and described (Peterson et al. 2020), although effectiveness and applicability of specific techniques to specific locations, fuel types, meteorological conditions, lighting patterns, and land management objectives are uncertain.

8.2.6 Effects of Fuel Moisture on Emissions and Dispersion

Moisture content of components of wildland fuelbeds can affect consumption and emissions in different ways (Chaps. 2 and 5). The ability to target fuelbed components for consumption during prescribed fire while leaving other components largely in place can result in reduced emissions. A prescribed fire in moist fuels may result in less fuel consumed and less smoke, although if insufficient heat is produced, the smoke plume may stay near the ground, resulting in greater smoke impacts. Successful consumption of targeted fuelbed components can help to meet ecosystem objectives and ensure good smoke dispersion.

8.2.7 Fuel Type, Fuel Loading, and Fuel Consumption

Although good information about the type and amount of fuel burning is fundamental to fire management and smoke estimations, most vegetation datasets are not available at a sufficiently fine spatial scale to inform project implementation. LANDFIRE, although good for national and regional discussions, does not meet the needs of fuel managers for project planning and accurate smoke forecasting. There is no national product that maps actual fuels (species, fuel loading, moisture, etc.) that can be used for prescribed fire project planning. In addition, most datasets are not kept current, meaning they may be out of date within just a few years due to disturbances across the landscape. Without a maintenance loop, one-time data become unusable, and often after a few years, another one-time dataset is created for another project, leading to inefficiency. Research could help develop project-level data collection methods and standards for national vegetation layers that are updated annually, depending on disturbance extent.

Although some stand-scale models calculate smoke components (e.g., particulate matter [PM] emissions) (Rebain 2010), they do not account for most ecosystem processes and disturbance interactions. Incorporating feedbacks among ecosystem processes, disturbance interactions, and changing fuel and fire conditions would likely improve the accuracy of smoke production and transport modeling (Chaps. 4, 5, and 6). Incorporating feedbacks among climate change, vegetation, fire, and smoke will improve models used in smoke management and inform management strategies to minimize smoke impacts (McKenzie et al. 2014). Several in-progress studies are linking models such as Quic-Fire to complex, three-dimensional fuel properties, fire effects, and ecosystem responses and recovery through time, thus improving predictions of how future fires will influence smoke production and dispersion.

Current wildfire data collection, typically via ICS 209,[2] does not address fire intensity, severity, or unburned islands within the fire perimeter, which can result in overprediction of smoke emissions and impacts. Emissions estimates compiled after a fire is over, using area blackened rather than area within a fire perimeter, would be more accurate.

Another challenge is that each agency and landowner has their own prescribed fire standards for reporting post-burn fuel consumption. For example, in Utah, area blackened is reported with no estimate of severity or percent consumption, thus potentially overestimating actual emissions. Many other states have the same challenge. Lack of consistent data standards also affects reported annual emissions data, which differ for wildfire and prescribed fire, and for different agencies and states.

It is relatively straightforward to model fuel consumption for prescribed fire because a planned fire typically has known environmental variables. Wildfire fuel consumption is more challenging due to the need for field measurements during wildfires for model development. Remote sensing methods that use other parameters, such as heat release or fire radiative power, to ascertain fuel consumption may be the best option for wildfires (Chap. 5).

8.2.8 Techniques for Minimizing Smoke Impacts

Prescribed fire planning typically considers ways to reduce smoke impacts, and managers use various techniques to influence fire behavior in ways that maximize smoke transport and dispersion. Identifying the probability of finding best days to burn for smoke dispersion based on meteorological averages and trends can help managers and burners anticipate and maximize good dispersion windows. Robust, simple meteorological analysis tools would help managers customize burn techniques to take advantage of favorable weather conditions (e.g., inversions, winds at various

[2] An incident status summary (ICS 209) is used for reporting specific information on incidents of significance. The ICS 209 is an important reporting tool giving daily snapshots of the wildland fire management situation and individual incident information including costs, critical resource needs, fire behavior, and size.

levels, precipitation). Clarity is needed on appropriate and effective use of weather parameters (mixing height, ventilation indices, air quality alerts, air stagnation, etc.) and the performance and validation of a point fire-weather matrix (e.g., Atmospheric Dispersion Index, Low Visibility Occurrence Risk Index) and enhanced availability of such parameters for all landowners and managers.

Further research is needed on the effects of ignition techniques and ignition speed on plume rise, dispersion, smoke quantity, smoke dispersion, and air quality impacts, including effectiveness in producing desired outcomes. Firing patterns can affect prescribed fire emissions. Similar-sized units with the same fuelbeds burned under the same atmospheric conditions may display disparate downwind impacts based on the timing and technique used for burning. To better understand the effects of fire patterns on emissions, the following questions need more scientific study:

- What are the effects of different firing methods on emissions and heat release?
- What effect does aerial ignition have on emissions compared to hand ignition?
- How do emission profiles during each stage of combustion compare across different firing techniques?
- How does firing technique affect plume rise and downwind dispersion?

8.2.9 Components of Wildland Fire Smoke

Land managers and air quality regulators are somewhat limited in understanding the full range of potential smoke impacts on air quality. Fine particles in smoke understandably get much of the research attention, but other components in smoke are important and need to be quantified (Bytnerowicz et al. 2016; Clinton et al. 2006). Ratios of coarse-to-fine PM are extremely volatile during the course of a day and throughout the duration of a fire (Schweizer et al. 2019a). Wildland fire can contribute to ozone formation (Chaps. 1, 6) but can also reduce radiative production over urban areas, thus suppressing ozone formation (Burley et al. 2016; Bytnerowicz et al. 2010; Preisler et al. 2005). Smoke also contains other components that are health hazards (Chap. 6), but research and methods for estimating them are limited. Pollutants in smoke may remain aloft for days and travel hundreds of kilometers from the fire before affecting distant communities. Further research into the mixture and aging of the emitted air pollutants is needed (Chaps. 5 and 6).

8.2.10 Soils and Emissions

A better understanding of how organic soil moisture and other soil properties interact to affect emissions and smoke chemistry is needed (Chaps. 5 and 6). Emissions from organic soil combustion are shaped by current and antecedent meteorological conditions (Weise and Wright 2014) and by the composition and relative amounts of combustible vegetation, soil organic matter, and mineral soil. Understanding soil moisture influences on fire behavior, particularly smoldering and glowing combustion, in combination with fuel moisture levels can inform fire suppression and prioritization of fuel reduction activities. In addition, using prescribed fire when there is high moisture content of the organic horizon can be an effective emissions reduction technique if prescribed fire managers have the ability to predict this condition.

A better understanding of soil characteristics could also inform potential differences in human health impact from wildfire versus prescribed fire smoke. A low-moisture organic horizon releases more heat, promoting faster, more complete combustion and higher emissions of volatile organic compounds and gases. Not accounting for combustion of the organic horizon can result in underprediction of smoke emissions (Zhao et al. 2019).

Soil moisture is monitored primarily across agricultural lands, and in situ stations measuring soil moisture are expensive to implement and maintain. Integrating soil characteristics, drought monitoring, and soil moisture measurements with fire and fuels models would allow fire managers to more effectively analyze emissions under drought conditions and prioritize actions to mitigate fire and emissions risks.

8.2.11 Remote Sensing and Data for Fuels, Fire, and Smoke

Remote sensing of vegetation and fuel characteristics needed for estimating fuel consumption and smoke has resulted in advances for fire detection and smoke modeling. The Smoke and Emissions Model Intercomparison Project (SEMIP) analysis found that the largest sources of uncertainty in estimating fire emissions come from uncertainties in overall fuel loading, fuel loading in specific fuel categories, overall area burned, and area burned by type of fire (Larkin et al. 2012). Dense clouds of smoke can inhibit the ability of remote sensing to detect fires, meaning that some fires may be missed entirely or their size is underestimated.

A new area of remote sensing that is ripe for study comes from the rapid expansion of unmanned aerial vehicles or drones for wildfire surveillance, prescribed fire ignition, and other uses. The interest in these tools offers the opportunity to explore this technology for gathering data on such things as fuel loading, fuel consumption, and area burned.

Accurately linking vegetation and fuels to smoke and emissions is critical (Chaps. 2 and 5). Pre- and post-fire parameters are often measured in research projects but rarely during prescribed fires or wildfires. Large, high-quality datasets like those produced for the Fire and Smoke Model Evaluation Experiment (FASMEE; Prichard et al. 2019) (Fig. 8.1), the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) (Peterson and Hardy 2016), and other integrated campaigns need to be prioritized. FASMEE is a multiagency, interdisciplinary effort to identify and collect measurements of fuels, fire behavior, fire energy, meteorology, smoke, and fire effects that will be used to evaluate and advance fire and smoke models. This knowledge will promote better predictions of the production and spread of smoke and effects on human health and safety, as well as inform allocation

Fig. 8.1 Crown fire behavior and effects were intentionally created in an experimental burn on the Fishlake National Forest (Utah), implemented in 2019 as part of the Fire and Smoke Model Evaluation Experiment (FASMEE) (Photo by Kreig Rasmussen)

for firefighting resources. FASMEE currently focuses on only a few fuel types, and similar work is needed across other fuel types to provide a scientific foundation for implementing fuel treatments and managing smoke at large spatial scales.

Mapping fuel structure, composition, and condition (moisture and decay) along with behavior of the fires that consume those fuels is a priority research area (Parsons et al. 2011; Rowell et al. 2020) (Chaps. 2, 5 and 6). This fuel characterization can then be linked to combustion phases (smoldering and flaming) and their respective links to emission factors (Prichard et al. 2020; Chap. 5).

Empirical and computational fluid dynamics (CFD) models offer promise in estimating spatial and temporal patterns of smoke dispersion (Chap. 4). The fuel inputs to these computationally intensive applications are amenable to remotely sensed data that is increasingly available to managers on the ground (e.g., Moran et al. 2020).

8.2.12 Prescribed Fire Tracking Data

As prescribed burning activity increases, the ability to conduct real-time airshed analysis will also rise. Regional tools will be needed that track fire activity and assess the potential for additive downwind impacts from multiple burn units. The Airshed Management System (AMS) in Montana and Idaho, formed over 40 years ago to manage and limit the impacts of smoke from prescribed fire, may be a model for other states (https://mi.airshedgroup.org).

Prescribed fire data collection differs by land management organization. Data collected by federal agencies differs from that collected by states. Lack of data and parameter definitions discourages collaboration. More states are developing local systems (e.g., California, Florida, North Carolina, South Carolina, Washington) to track smoke and prescribed fire permits, and identify adjacent fire locations (Box 8.3), although other states have minimal information available, especially for agricultural burning and its contribution to smoke impacts.

Box 8.3 Prescribed Fire Tracking in California

Smoke management is coordinated year-round in California and depends in part on a system called the Prescribed Fire Information Reporting System (PFIRS 2020). PFIRS provides land managers and air regulators an opportunity to assess burning statewide and manage airsheds accordingly. PFIRS is designed to simplify and expedite communications on planned burns and their approvals and provide a public platform for viewing statewide burning for participating air districts. Land managers can use PFIRS to submit Smoke Management Plans, requests for ignition, and post-fire area burned.

8.2.13 Fire Emissions and the National Emissions Inventory

The US Environmental Protection Agency (USEPA) conducts the National Emissions Inventory (NEI) every three years, collecting data from point, area, mobile, and biogenic sources to assess air emissions status and trends throughout the USA. Emission inventories form the basis for rules and regulations designed to improve ambient air quality. Accurate emissions information allows the USEPA and state air regulatory agencies to focus air quality improvement on anthropogenic sources. Although it is relatively easy to calculate emissions from a point source, such as a coal-fired power plant or a paper mill, determining emissions from all prescribed fire activities over a large landscape is more difficult. Many fires are not reported, and states and the USEPA often rely on satellite detections to identify fire locations.

8.3 Wildland Fire and Smoke Decision Tools

Accurate emissions information is critical to managers for burn planning, dispersion modeling (Chap. 4), and emissions inventory (Chap. 5). Fire managers assess emissions to compare alternatives and evaluate the scale of a proposed management activity. Knowing the quantity of emissions that will be produced is needed for making informed decisions on whether to go forward with a burn. Dispersion model outputs are used to inform "go/no-go" decisions and to communicate air quality information to the public. In some locations, emissions must be reported to local, state, and/or federal agencies as part of emission inventory efforts.

Predictive tools that can help managers identify air quality implications of decisions, are critical for wildland fire use and management. Although existing tools provide valuable information, more research, development, and testing are needed to reduce uncertainty in predictions of smoke dispersion and impacts (Chaps. 4, 5, and 6). Improved models would facilitate wildfire and prescribed fire management decisions and better enable managers to proactively communicate likely smoke impacts to communities.

Better smoke modeling and decision support tools help managers take maximum advantage of meteorological windows in which fire use goals can be accomplished while protecting air quality. Determining where prescribed fire may be most useful, assessing the potential for scaling burn units to larger parcels, and having accurate emissions information and modeling platforms that evaluate downwind impacts from multiple burn units can help managers identify opportunities to improve the condition of natural resources while protecting air quality and human health.

When considering potential emissions and smoke impacts from a proposed prescribed fire activity, managers use emissions analyses in several ways:

- During the planning process to assess emissions, compare alternatives, and evaluate the scale of a proposal.
- During burn implementation, to make informed decisions on whether to go forward with a burn event, and whether to curtail an activity already initiated.
- As a communication tool for conveying smoke impact information to the public.
- In some areas, emissions are reported to local, state, and/or federal agencies as part of emission inventory efforts.

8.3.1 Multiple Fires and Airshed Analysis

Many tools help managers assess the downwind smoke impacts from their own burn unit, but no tools are available to assess fire activity across a geographic area in real or near-real time. The most widely used tools to predict downwind smoke impacts generally model effects for only one burn at a time. Workarounds exist to add other nearby burn activity to a modeling output but are time consuming and cumbersome. In the future, user-friendly tools will be needed to assess impacts from all fire activity within an airshed on a given day. Regional tools are needed that track proposed fire activity in real time and assess the potential for additive downwind impacts from multiple burn units.

8.3.2 Fire Growth Models and Smoke Dispersion

Current smoke dispersion models have built-in assumptions regarding wildfire growth, so emissions estimates are unable to take into account that a fire may grow at different rates or shrink in response to weather conditions, available fuels, terrain, or suppression actions. Fire behavior models (contained within the Wildland Fire Decision Support System and Interagency Fuel Treatment Decision Support System) provide fire growth predictions that could be integrated into smoke models, facilitating more accurate predictions of upcoming smoke impacts (Chaps. 2 and 3).

8.3.3 Background Air Quality Conditions

As most smoke dispersion models assume a clean atmosphere at initiation, including background air quality will improve their accuracy (Chaps. 5 and 6). This is especially important with respect to ozone impacts from wildfires which, unlike PM impacts, can be highest at a significant distance from the fire (Jaffe and Wigder 2012, Chap. 6). Including background air quality in models would help support states during exceptional events. With proper analysis and documentation, air quality data showing high smoke impacts from wildfires and some prescribed fires may be excluded from the record and prevent exceedance of an air quality standard. Understanding and including background air quality conditions can improve smoke impact forecasting and decisions about when to use prescribed fire so it does not cause air quality exceedances.

8.3.4 Smoke Models for Fire Planning

Most smoke models rely on current or near-term meteorology for dispersion predictions, however, managers often need to plan for fire use months or years in advance. Managers are increasingly provided outputs from advanced atmospheric forecast models linked to fire spread and fuel consumption models. These "coupled" models may resolve some of the more complex interactions between fuel consumption and emission production and dispersion. However, ensuring these outputs are evaluated to sufficiently resemble real-world observations is difficult (Chap. 5).

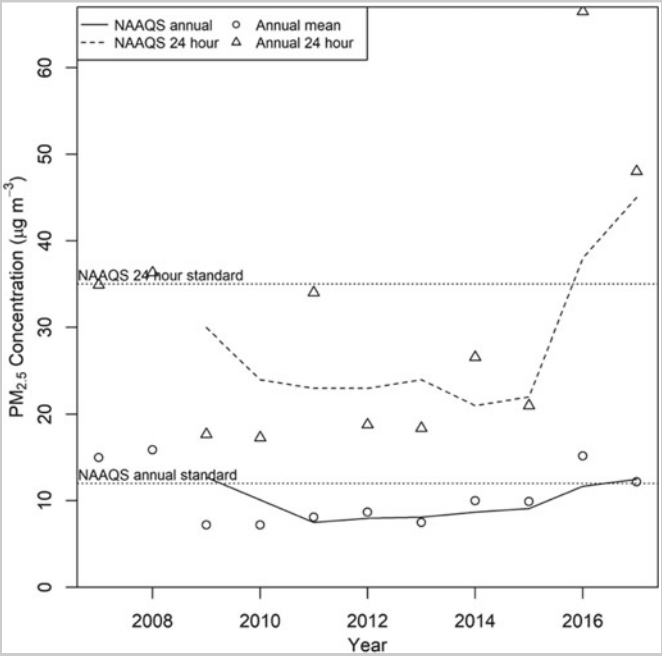
8.3.5 Use of Air Quality Measurements

State air quality monitoring networks typically emphasize areas with significant populations, so small towns and rural areas may have little permanent, high-quality monitoring of air quality. Significant smoke episodes may go unquantified in these areas, so the true impact of smoke may be unknown. An assessment of the air quality monitor network could be undertaken using a similar approach to the recent Remote

Automated Weather Station (RAWS) network assessment (Brown et al. 2012) and would be useful in creating a more robust flow of monitoring data (Box 8.4).

Box 8.4 Why Conduct Long-Term Monitoring for Smoke?

Rural monitoring sites can provide a local assessment of the public health burden of smoke, directly testing if fire management tactics are reducing smoke impacts. The USDA Forest Service has operated a rural site monitoring $PM_{2.5}$ in the community of Kernville, California, since 2007. This site has experienced a significant amount of smoke several times since then, with the annual 98th percentile for $PM_{2.5}$ exceeding the 35 µg m^{-3} National Ambient Air Quality Standard (NAAQS) (see figure below). After high smoke exposure in 2007 and 2008, the site had lower smoke exposure in 2009 and 2010. This helped resource managers decide to manage the Lion Fire in 2011 largely for ecological benefits. Low smoke exposure occurred from 2012 to 2015, followed by the second Lion Fire in 2017 which had the highest smoke exposure (98th percentile) ever observed at the Kernville monitoring station. Fire managers took this high exposure into account when planning for wildland fire in succeeding years.



Estimates of air quality conditions at Kernville compared to annual and 24-h NAAQS for $PM_{2.5}$ from 2007 to 2017.

Information on rapidly changing smoke conditions can be used for early alerts to managers and the public to prepare for coming changes in air quality. Portable air quality monitoring instrumentation can help provide timely information during rapidly changing air quality conditions that often occur during smoke events. This information is important for developing health messages for schools, athletic directors, and other outdoor event planners when making decisions about outdoor activities. There are several types of inexpensive, portable monitoring instruments that can support managers. Testing and calibration of portable instruments based on comparison with official state monitors could improve accuracy.

8.3.6 Air Quality Impacts of Prescribed Fire Versus Wildfire

Assessing a quantitative difference between wildfire and prescribed fire emissions is challenging due to disparate $PM_{2.5}$ monitoring methods. Wildfire smoke tends to travel and disperse over much larger regions and for longer periods, whereas prescribed fire smoke tends to be more local and transient. Wildfire smoke measurements often are made a few to several hundred kilometers from the source, focusing on communities near the fire or more distant urban centers, whereas prescribed fire smoke tends to be measured much closer to the fire. Comparing emissions from a number of studies, Navarro et al. (2018) found little difference in emissions magnitude between wildfire and prescribed fire. This is counterintuitive to the concept that prescribed fire implies reduced fuel consumption and emissions. This highlights the importance of on-going research collaborations between wildland fire management and air quality agencies to further assess emission differences between fire types.

8.3.7 Smoke Model Performance and Accuracy

Fire and air quality managers need to know which smoke models work best and are most accurate in different wildland fire situations. Differences in terrain, seasonal weather patterns, local drainages, and other factors contribute to smoke dispersion, meaning that smoke models must be performance tested utilizing local topography and meteorology. Identifying major drainages and typical weather patterns in specific geographic locations would improve predictions of smoke plumes for local forecasting.

Smoke model testing using various fuel types, fuel loading, and topography would help in forecasting smoke impacts from firing operations and for locations where several prescribed burns are being conducted at the same time. These simulations would help to more accurately forecast air quality and inform decisions about the amount of burning that can be conducted in an area while avoiding an exceedance of an air quality standard.

All smoke model outputs have uncertainty due to inadequate meteorological or air quality inputs, physical or statistical inadequacies, or a lack of computational power that requires parameterizations (or "shortcuts") to produce an output. Transparency about the levels of smoke forecast uncertainty is critical for decision makers to effectively identify management actions most likely to lead to desired air quality outcomes. Managers will generally need assistance from scientists to quantify and communicate about uncertainty.

8.3.8 Long-Range Forecasts and Projections for Planning and Early Warning

Managers need more confidence in long-duration smoke forecasts to support use of fire in ecosystem restoration efforts, especially given anticipated effects of climate change. Current smoke prediction tools are typically short-term forecasts covering up to 72 h, which is useful for active wildfire incidents and daily tactical planning for prescribed fire. However, a number of environmental factors can be monitored or forecasted to provide an early warning of potential conditions beyond this short period, either from a wildfire or prescribed fire perspective. Several operational and experimental tools used by the scientific community could meet these management needs, but managers may not be aware of the practical applications of these tools or know how to access or use them. Focused efforts are needed to increase learning opportunities and develop more intuitive delivery systems for these tools.

8.3.9 Tools and Data Needs for the Future

Moving forward, managers may increase the use of prescribed fire across the landscape as well as increase the size of units and area burned. For example, instead of burning 100 ha in one 6-h period, they may want to burn 400 ha in that same time period. With larger burn areas, more pollutants are emitted, more heat is generated, and plume dynamics change. This may have implications for smoke impacts in nearby communities as well as communities farther downwind of the burn unit (Chap. 4) and additional planning tools, especially regarding smoke management and impacts on downwind communities, will be needed. In addition, how burns conducted by private landowners, which account for the majority of prescribed fire in the USA, are accounted for and integrated into such planning will need consideration as these systems develop.

Geographic screening or simple smoke dispersion models that are used during the burn planning process are not adequate to address hourly and cumulative airshed effects, although the conservative outputs are effective in predicting worst-case smoke management issues. More complex modeling tools that rely on forecast meteorology can provide robust outputs that help to facilitate go/no-go decisions for prescribed fire and help communicate impacts from wildfire. Ideally, managers would have access to complex modeling outputs earlier in the burn planning phase. This may include longer forecast intervals or the ability to generate realistic prescribed burn scenarios with more complex smoke models based on archived gridded meteorological data.

8.3.10 Identifying Areas at High Risk from Wildfire and Smoke

There have been multiple efforts to identify and map areas with high wildfire risk to help prioritize fuels management efforts. Depending on who is using the data and how the data are applied, there are multiple definitions of what constitutes "high wildfire risk," ranging from the "Wildfire Risk to Communities" website (https://wildfirerisk.org) to "Firesheds" and potential operational delineations (PODs). They address biophysical needs for treatment (Stratton 2020) but do not incorporate shared stewardship agreements, collaborative group involvement in projects, or risks caused by emissions and possible smoke impacts.

Wildfire risk analyses do not generally include public health vulnerability assessments related to smoke impacts. A public health vulnerability screen for smoke could include age, medical history, and similar information. This information could then be incorporated in project planning, early warnings, etc. Better tools that describe expected smoke outcomes and show the risk tradeoff between smoke from treatments versus potential smoke/wildfire impacts without treatments would provide a foundation for facilitating the restoration of fire. Identification of communities at risk from smoke could then be taken a step further to identify and map areas at greatest need of treatment based on reducing risk to public health vulnerabilities.

There is currently no standard process to identify and contact individuals whose health may be at most risk from smoke. Understandably, these are often the people most concerned about potential prescribed fire smoke impacts. However, with preparation and effective outreach, those who are most at risk can act to protect themselves and efforts to make communities "smoke ready" are just beginning (see Sect. 8.5).

Descriptions of smoke and air quality outcomes are needed long before implementing a prescribed burn. Communities need to be informed of expected smoke outcomes, the implications of first entry versus maintenance smoke levels, and the relevance of fire planning and smoke prediction. A smoke planning tool that has public-level graphics that are understandable for planning purposes and effectiveness outcomes is critical. The BlueSky Playground tool (Larkin et al. 2009) is a good start, but predicting smoke impacts is constrained by the capability of current predictive meteorological models. Some method is needed to predict future smoke impacts from prescribed fires in specific areas using estimates of historically determined probable meteorology. In addition, animated screens to show estimated smoke impacts throughout the life of the fire as video graphics could provide a valuable public communications tool.

8.4 Health, Safety, and Societal Impacts of Smoke

Smoke effects are a significant public health concern, particularly in relation to short-term $PM_{2.5}$ exposures which can lead to adverse respiratory and cardiovascular effects, including increased mortality (Chap. 7). Smoke can also have significant economic impacts on communities (e.g., business closures, displacement of tourism activities) but these are poorly quantified (Chap. 7) and a better understanding of both short- and long-term economic impacts due to smoke exposure is a critical need for scenario planning. Other social values that can be affected by smoke that managers need to take into account when making management decisions include safety impacts for transportation and visibility impairment in Class I areas.[3]

8.4.1 What is a Smoke-Affected Day?

"Smoke-affected day" is a term used in air quality management, fire management, and smoke health effects research. In air quality management, defining a day as smoke-affected allows the state or local agency to apply to have that day qualify as an "exceptional event." An exceptional event is a cause of poor air quality that is largely outside of human control such as a wildfire, volcano, or dust storm. By definition, an exceptional event is (1) something not reasonably controllable or preventable, (2) caused by human activity that is unlikely to recur at a particular location or a natural event, and (3) determined by the USEPA to qualify as an exceptional event (Environmental Protection Agency, 40 CFR Parts 50 and 51, 3 October 2016). The state air agency needs to prepare a demonstration showing that the event met the exceptional event criteria and prove a causal relationship between the event and the exceedances of air quality standards. Unless the event has regulatory significance (i.e., is likely to contribute to exceedance of an air quality standard), the local USEPA Region would not process the demonstration or remove the data from the official design value.

In Idaho and Montana, smoke-affected days have been used to determine wildland fire management strategies, and several national forests have used smoke-affected days in their press releases to explain the decision not to allow seasonal prescribed

[3] The Clean Air Act Amendments of 1977 gave special air quality and visibility protection to national parks larger than 6000 acres (2430 ha) and wilderness areas larger than 5000 acres (2020 ha) that were in existence at the time. These are called Class I areas.

burning. In health studies, the term "smoke-affected day" is used to define population exposure for the purpose of evaluating health outcomes. There is no standard approach for defining what constitutes a wildfire smoke-affected day in the health effects literature. Research to define wildfire smoke-affected time periods is needed to validate epidemiological methods (Doubleday et al. 2020).

8.4.2 Effects of Smoke Exposure on Human Health for Different Exposure Scenarios

Health effects from individual wildfire events are generally described by 24-h average exposures, or multiple events across a single location (Adetona et al. 2016; Reid et al. 2016). However, although existing research has identified a number of factors associated with smoke and increased susceptibility to poor health outcomes (e.g., preexisting health conditions, specific life stages, and lower socioeconomic position) (Chap. 7), it is largely unknown how health effects of smoke exposure, for both firefighters and the public, may differ for different scenarios. These scenarios include (1) very-high concentration of smoke exposures across short durations (hours), (2) high concentration smoke exposures across limited durations (days to weeks), and (3) repeated high- to very-high exposures over the course of a fire season and multiple fire seasons (years). The duration and smoke concentration of an event are important, because they can lead to higher cumulative exposures to air contaminants (Navarro et al. 2018). This knowledge would be helpful for public health advisories and for making decisions about timing of prescribed fires and interpreting air quality sensor data.

8.4.3 Health Effects of Constituents of Smoke Beyond Particulate Matter

Wildland fire smoke is a complex mixture of individual air contaminants including many hazardous air pollutants (HAPs) from smoke and ash (Adetona et al. 2016; Chap. 6). Most epidemiologic studies have focused on exposure to particulate pollution, but some studies have found wildland fire smoke to be related to various health effects from ozone, carbon monoxide, and HAPs (Chap. 7). In addition, increased residential development increases the likelihood of large wildfires that burn structures where smoke is produced by sources other than vegetation, increasing the risk of adverse health impacts for the public and firefighters (Radeloff et al. 2018).

8.4.4 Smoke and Mental Health

Smoke from wildland fires may also have impacts on the mental health and emotional stress of communities. These impacts have been studied to some degree in the general context of fires, but the literature related to smoke is limited. To better understand the full health burden of smoke exposure, and to take steps to prevent or to reduce the mental health effects of a prolonged smoke event, it is important to understand (1) which aspects of a smoke event are associated with adverse mental health effects, (2) which strategies prevent or reduce those effects, and (3) the groups of people who are most likely to experience these effects, so that interventions can be directed to them. This information would assist in developing and deploying interventions to prevent or reduce smoke-related effects.

8.4.5 Smoke and Visibility Reduction on Roadways

Roadway visibility effects from heavy smoke can result in serious injuries or fatalities of the public and fire personnel. Better forecast tools can aid managers in their efforts to protect public safety by estimating the potential for smoke-caused impairment on roadways and at airports. The conditions that lead to dangerous levels of visibility impairment from smoke are relatively well understood. An especially dangerous occurrence is a mixture of smoke and high humidity known as "superfog" (Chaps. 4 and 7). Managers need methods that will help them anticipate and predict the occurrence of superfog and similar phenomena.

8.4.6 Visibility Conditions in Class I Areas

Visibility is a protected value in Class I areas as required by the federal Clean Air Act. States develop state implementation plans (SIPs) that contain regulatory measures used to protect visibility. Comparisons of current levels of visibility impairment due to wildland fire versus natural or historic visibility impairment from wildland fire inform this issue. As "natural" background visibility, including pre-suppression smoke levels, is poorly understood (Ford et al. 2018; Hamilton et al. 2018), research is needed to define historic visibility conditions, or what is "natural." If the frequency and extent of wildfires continue to increase, visibility likely will be even more reduced during large events. Although it is expected that greater use of prescribed fire could minimize duration and intensity of future visibility impairment, this needs to be empirically assessed.

8.5 Outreach and Messaging About Smoke

Science on wildland fire and smoke is an important foundation for effective outreach that can provide the public with information about smoke concentrations and episodes, potential health risks, and actions they can take to protect themselves (Chap. 7). Identifying potentially affected public sectors and engaging in targeted education and outreach also can assist in gaining the social license needed to support wildland fire management decisions. Effective communication requires trust, often based on existing relationships and procedures. Key stakeholders need to understand fire management decisions and their implications, preferably developed through collaborative efforts in which partners and the public have input into decisions. To facilitate discussions, research is needed to better identify the tradeoffs associated with periodically reduced air quality resulting from wildland fires.

Good outreach and transparent communications are critical to ensuring that appropriate information reaches the general public, especially to those most at-risk from smoke. Some populations are more adversely affected by smoke than others, however, research is needed to better understand how individuals who are most at-risk acquire, absorb, and act on information on projected smoke impacts**.** The Smoke Ready Community concept is an effort being developed by the federal government (USEPA, Centers for Disease Control and Prevention, US Forest Service) to reduce the public health burden of wildland fire smoke by integrating public health communication into wildland fire emergency management and preparedness.

8.5.1 Smoke Ready Interventions

Communities and individuals can undertake a number of actions to prepare for eventual smoke episodes and minimize health effects and community disruption. Managers can help prepare the public for smoke events by providing timely information about air quality, health effects, and exposure reduction measures. Common messaging about smoke and health precautions provides the public with information on how to protect themselves during smoke events (e.g., staying indoors, closing doors and windows, utilizing a "clean room," utilizing filtration devices if available) (Chap. 7).

Information provided to communities during smoke events include (1) data on pollutants of concern (especially fine PM and ozone), (2) expected timing and duration of smoke episodes, (3) predicted severity of smoke impacts using the AQI, (4) where and how to access real-time air quality advisories. Certain locations in communities (schools, hospitals, long-term care facilities, and athletic programs) are at a higher risk of adverse smoke outcomes and should be identified prior to wildfire season and provided with information on how to protect themselves during wildfire season. There is a need to understand barriers for different groups in taking appropriate protective actions to mitigate smoke impacts including how to best reach underserved communities.

8.5.1.1 Respirator Use by the Public

Various methods to help protect people from smoke are available, although effectiveness, expense, and public acceptance can be challenging. Respirators, such as an N95 mask, are in common use, inexpensive, and could be quite effective with proper training. To date, these have largely been used in occupational settings and with fit testing respirators can be quite effective. Few studies have assessed respiratory protection in the absence of fit testing, which is how they likely would be used by the general public.

N95 facepiece respirators are safe for healthy people and those with mild chronic illnesses. The few studies that have assessed adults wearing respirators during mild exercise or wearing them for multiple hours at a time suggest that respirators increase facial temperature and can be uncomfortable for this reason, but physiological parameters do not seem to change markedly (Harber et al. 2009; Rebmann et al. 2013; Roberge et al. 2010). However, if widespread use of filtering-facepiece respirators is to be recommended, larger studies are needed on their use under a variety of conditions (including different levels of exercise). There is also a paucity of data to clarify which people are too ill to use respirators and, in the absence of further study, they should be recommended only for people with the cognitive and physical ability to remove the respirator if they feel lightheaded or short of breath.

8.5.1.2 School-Based Information

Because children are a particularly at-risk population, scientific knowledge on how to provide healthy air at schools during smoke events will be a necessary component for communities to be smoke ready. Research-based guidance to schools is needed on:

- Use of low-cost air sensors to determine air quality in indoor and outdoor spaces.
- Air quality thresholds for determining appropriate indoor and outdoor activities, including recess and athletic practices.
- Ways to maximize indoor air cleaning using existing HVAC systems or supplemental air filtration for different building types.
- Use and effectiveness of different models of portable air cleaners (must not produce ozone).
- Best ways to predict smoke levels in different spaces during smoke events.
- Use of short-term air quality measurements (1-h average or less) for health protective behavioral messages.

8.5.1.3 Medical Professionals and Other Partners

Medical professionals are key partners and trusted communicators in preparing communities for smoke events. Outreach and education for medical professions to become proficient in smoke effects and interventions help facilitate protection of public health. Tools that can be used to reach the public during smoke events and increase the effectiveness of messaging include (1) "Wildfire Smoke: A Guide for Public Health Officials" and related factsheets (https://www.airnow.gov/wildfire-smoke-guide-publications), (2) "Particle Pollution and Your Patients' Health" web course (https://www.epa.gov/pmcourse), and (3) "Wildfire Smoke and Your Patients' Health" web course (https://www.epa.gov/wildfire-smoke-course).

Additional resources are needed for medical professionals who treat members of at-risk groups prior to or during smoke events. For instance, factsheets and online courses could be developed for older adults and people with heart or lung disease that include discussion of the risks of smoke exposure and how to prevent or reduce effects. Even simple tools that can be used in medical offices such as posters, care-plan forms, and magnets with exposure reduction measures would help to disseminate information.

8.5.2 Air Quality Conditions and Advisories

Tools that are easy for the public to understand (e.g., simple displays of current air quality conditions) motivate appropriate protective actions during smoke episodes. The Air Quality Index (AQI) is a nationally uniform index for reporting and forecasting daily air quality conditions across the USA. As smoke events become longer, in some cases lasting weeks or months, the concentrations at which effects occur during these longer-duration events are often uncertain. The AQI is designed to caution the public about daily pollution exposures. But when smoke lingers for days or weeks, should additional cautionary language, including additional exposure reduction measures, be recommended sooner?

Several national products provide air quality managers and the public with information to track and understand smoke impacts in most areas of the country. The multiagency AirNow website (www.airnow.gov) is administered by the USEPA and reports air quality using the AQI. The AirNow program accepts, stores, and displays monitoring data provided by state, local, and federal air quality agencies. Agencies submit continuous PM data to AirNow from over 1,200 $PM_{2.5}$ monitors and 500 PM_{10} monitors, plus temporary monitors, on an hourly basis. These data are available to the public via an interactive map on airnow.gov and through email notifications, software widgets, and smart-phone apps. The Fire and Smoke Map (Fig. 8.2), a joint USEPA and USFS effort, has data layers with information from ambient $PM_{2.5}$ monitors, satellite smoke plumes, and fire detections from the National Oceanic and

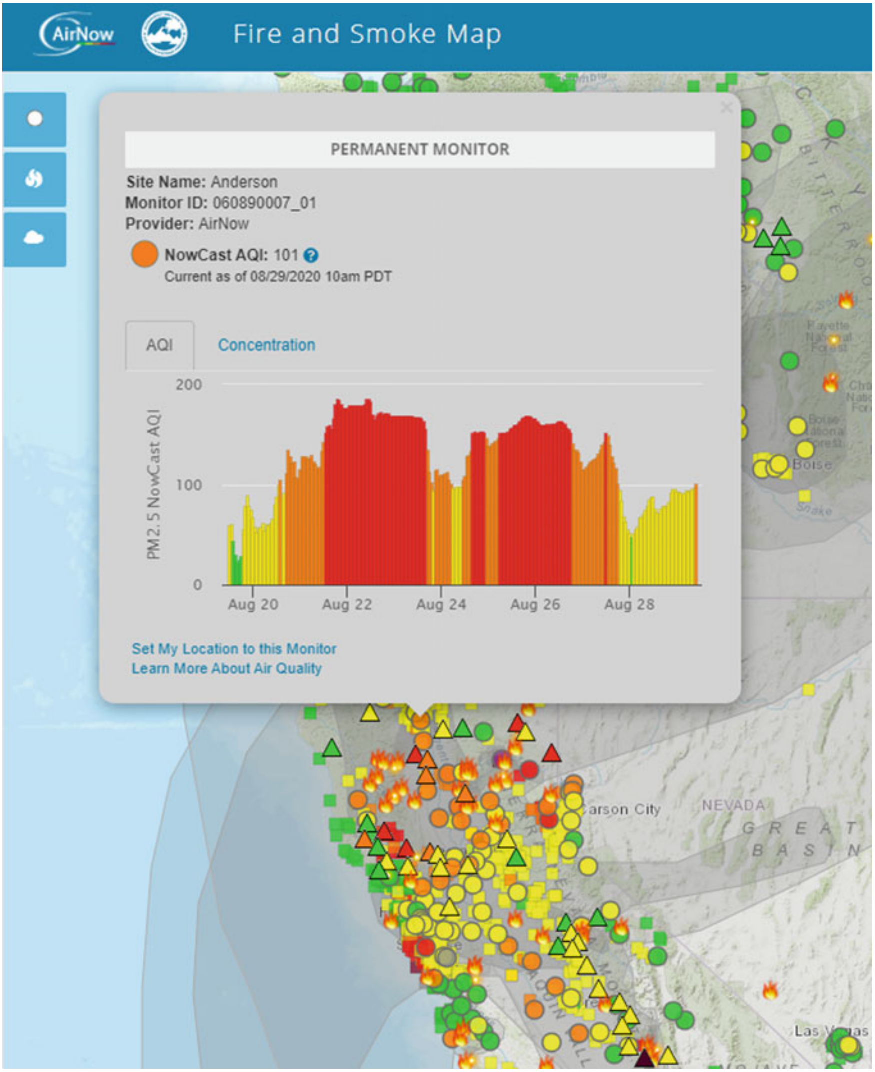


Fig. 8.2 Fire and Smoke Map—developed in partnership with the USEPA and US Forest Service with input from state, tribal, and local air regulatory agencies—provides air quality and wildland fire information for the public in a single location

Atmospheric Administration (NOAA) Hazard Mapping System, as well as smoke advisories and information about the location of the nearest monitors, smoke plumes, and fire detections.

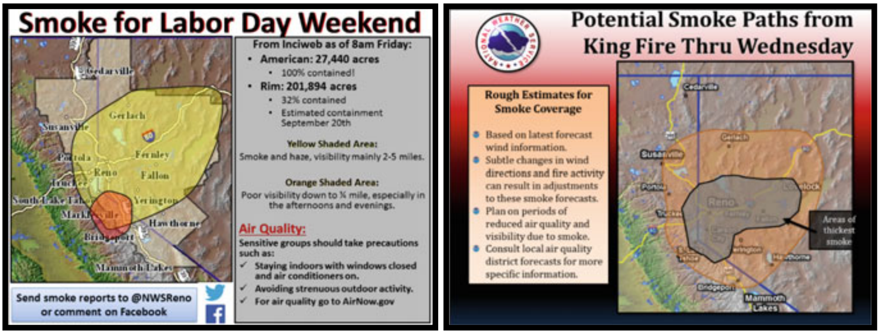


Fig. 8.3 Social media posts by the National Weather Service office in Reno, Nevada, during the 2013 American Fire and Rim Fire (left), and the 2014 King Fire (right)

8.5.3 National Weather Service

Partnerships with the National Weather Service (NWS) and/or state air quality forecasters help inform the public of potential smoke impacts. The NWS National Air Quality Forecast Capability develops and implements operational air quality forecast guidance for ozone, smoke, dust, and $PM_{2.5}$. Local NWS offices deliver air quality predictions to the public and air quality management agencies to inform health warnings and individual actions to limit exposure to poor air quality, and the NWS can issue an air quality alert when warranted, although they do not use standard AQI categories (Fig. 8.3). Air quality agencies and health departments benefit from partnerships with the NWS and land managers that develop and share consistent messaging through various media platforms when smoke puts public health at risk.

8.5.4 Interagency Wildland Fire Air Quality Response Program and Air Resource Advisors

Recognition of the growing impact of wildland fire smoke on public health and safety has resulted in a proactive response led by the USDA Forest Service and partner agencies and authorized by the Dingell Act of 2019. The Interagency Wildland Fire Air Quality Response Program works to directly assess, communicate, and address risks posed by wildland fire smoke to the public and fire personnel. Informed by smoke science and tool development, the program depends on four primary components: (1) specially trained personnel, known as an Air Resource Advisor (ARA) (Box 8.5), (2) air quality monitoring, (3) smoke concentration and dispersion modeling, and (4) coordination and cooperation with agency partners.

Box 8.5 Air Resource Advisors

Air Resource Advisors (ARAs) are technical specialists trained to support wildland fire response efforts by addressing smoke and air quality concerns of both the public and fire personnel. ARAs are often assigned directly to wildfire incident management teams and work closely with incident personnel with expertise in meteorology, fire behavior, safety, planning, and public information. ARAs provide expertise in air quality rules and regulations, smoke dispersion modeling, air quality monitoring techniques, health effects of smoke, and public communications. The primary public outreach product produced by ARAs is the daily smoke outlook (Fig. 8.4), which provides (1) a text discussion of the status of nearby fires, (2) an hourly bar chart of Air Quality Index (AQI) (NowCast) from nearby monitors for the prior day, (3) the AQI for the prior day at each nearby location of interest, (4) AQI predictions for the next two days, and (5) any relevant comments by location.

Predicting the AQI for the coming day at a specific location requires a range of scientific concepts and tools. This is illustrated by the approach used by ARAs:

(1) Start with satellite-detected fire size and location.
(2) Crosswalk this information with a fuels map to assign fuel type and fuel loading.
(3) Link this to models that calculate fuel consumption and plume rise.
(4) Access meteorological predictions to disperse smoke downwind and estimate ground-level concentrations of $PM_{2.5}$.
(5) Communicate this information to the public in a form that is understandable and will motivate the public to take precautions to protect their health.

8.6 Transfer of Smoke and Air Quality Science and Tools to Managers

Effective technology transfer between researchers and practitioners is vital for continued improvement of best management practices and to ensure that science findings and new tools are used on the ground. Scientists working on wildland fire smoke are encouraged to emphasize outreach and technology transfer to landowners, managers, line officers, and agency administrators about smoke management techniques, smoke production and dispersion model use, air quality rules and regulations, air quality and smoke monitoring, and reporting of smoke impacts. Technology transfer can be prioritized by asking the following questions:

- How can burners and managers be effectively engaged in defining scientific objectives?
- Which communication and delivery methods are most effective for different audiences and products?

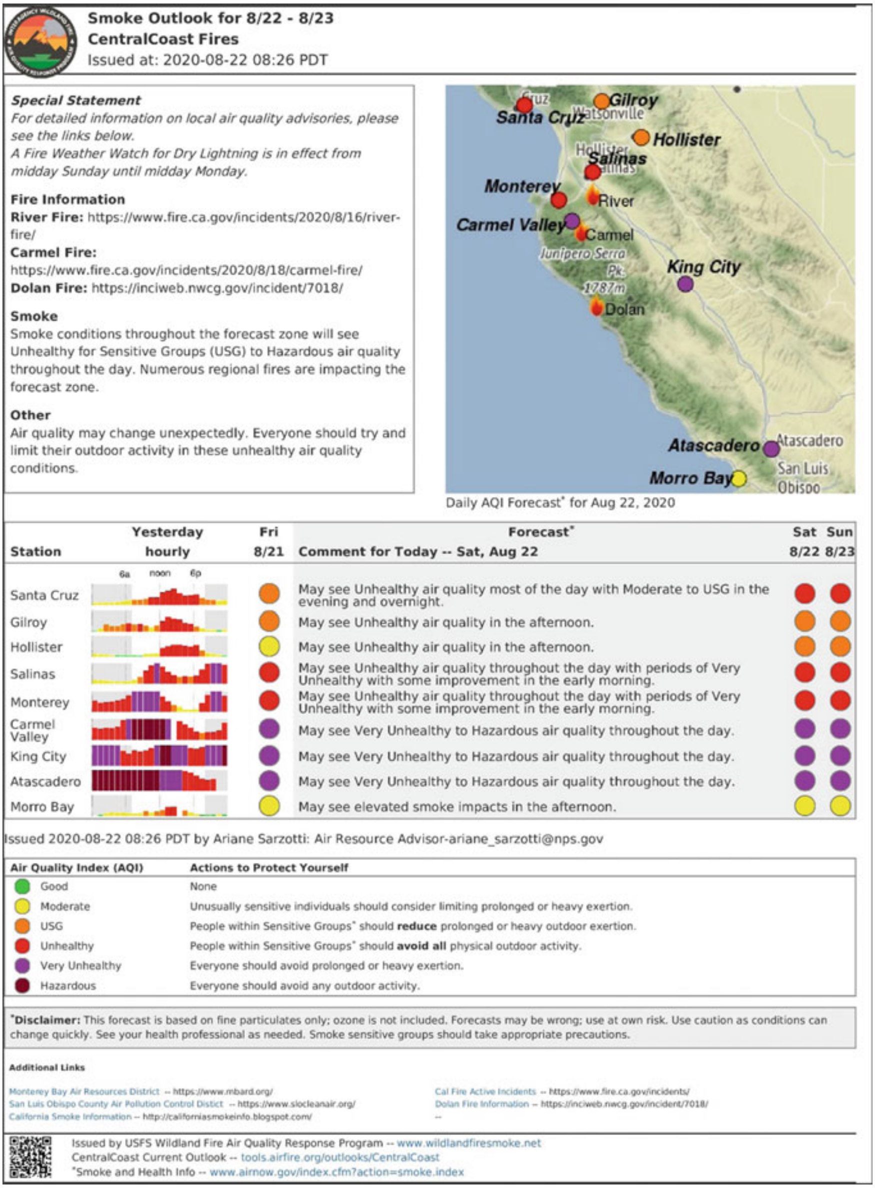


Fig. 8.4 "Daily smoke outlook" for a portion of the southwestern USA, produced by an Air Resource Advisor assigned to a wildland fire. A large amount of fire and smoke science and tool development underlies production of this one-page communications product

- Which outreach approaches (e.g., training courses, webinars, lay-audience newsletters, conferences) effectively communicate new science and products to managers in addition to publishing a research paper?

In order to maximize effectiveness, science-management connections need to be continuous and mainstreamed in the fields of fire and air quality. Greater involvement of field-level resources can help to identify (1) new research needed, (2) the best tools for making sound decisions, and (3) more effective systems for communicating new information.

8.6.1 Formal Fire and Smoke Training Opportunities

Many federal and state fire practitioners are required to attend several in-person training courses sponsored by the National Wildfire Coordinating Group (NWCG). Incorporation of new science and best management practices helps meet the needs of the Interagency Prescribed Fire Planning and Implementation Procedures Guide (NWCG 2017), which is used to ensure prescribed fires comply with the Clean Air Act. In addition to field training and documentation of critical competencies, the following coursework is required to become qualified as a prescribed fire practitioner: Prescribed Fire Plan Preparation (RX341), Smoke Management Techniques (RX410), and Fire Program Management (M-581). These courses integrate discussions on smoke management, air quality indicators, program direction and policy, and use of models to calculate emissions and dispersion. In addition, specialized national training courses, such as those for ARAs and prescribed fire line officers, are designed for those who provide smoke impact forecasts and ignition approval.

As in-person discussion among scientists, landowners, and managers is mutually beneficial, opportunities are needed for scientists and managers to come together to jointly identify priority needs and best management practices. Fire and smoke specialists need to be active participants in understanding climate change effects on wildland fire behavior, smoke emissions, and ecosystem management decisions. Expanding the traditional NWCG community to include climate scientists would better prepare fire managers to monitor climate change indicators and thresholds that trigger a change in action.

8.6.2 Informal Training and Collaboration Opportunities

Managers benefit from scientists bringing the latest research and analytical processes to smoke-related projects, such as updates to a state smoke management plan, analysis of a complex National Environmental Policy Act (NEPA) project, scientifically defensible comparisons of air quality impacts from prescribed fire versus wildfire, or implications of policy on wildland fire.

Agency administrators may be unaware of what they need to know about smoke management. Supplementing existing regional training with smoke management and air quality knowledge would ensure that up-to-date information is used. Research needs can be identified by encouraging more active dialogue among scientists, program managers, administrators, practitioners, and state air quality regulators.

8.6.3 Websites, Webinars, Etc.

Websites, webinars, newsletters, and lessons-learned documents are an increasingly popular way to reach a large and diverse audience and introduce private to federal practitioners and other interested parties to new research and tools. Recorded webinars can be viewed repeatedly and on a schedule that suits the individual.

A major source for fire-related research documents, summaries, newsletters, and recorded webinars is the Joint Fire Science Program (JFSP) and its associated Fire Science Exchange Network (https://www.firescience.gov/JFSP_exchanges.cfm), which regionalizes access to information for 15 areas of the USA (Fig. 8.5). These networks include practitioners and scientists from federal, state, private, and tribal entities. The ability to access the latest publication, workshop, science finding, or management need is important for all parties involved. Although the JFSP and

Fig. 8.5 Fire Science Exchange Network (https://www.firescience.gov/JFSP_exchanges.cfm) encompasses 15 geographic areas of the USA (see text for details)

exchanges address all wildland fire science topics, smoke science and management are emphasized only in specific research projects.

Other fire science organizations maintain websites and send research summaries via subscription newsletters, including common sources such as US Forest Service research stations, the Association for Fire Ecology, and the International Association of Wildland Fire. None of these is specific to smoke-related science, although all share smoke content.

A good resource for smoke-specific information, documents, websites, and training materials is the Emissions and Smoke Portal (https://www.frames.gov/smoke/home), sponsored by the NWCG Smoke Committee and hosted on the Fire Research and Management Exchange System (FRAMES) website which provides categorized hosting of all things fire and fuels.

8.6.4 *Learning Pathways*

Fire practitioners frequently seek additional information through a series of learning pathways within the fire community. By following the adult learning pathways of tactile interactions, virtual course delivery, and fire community-based sharing, there is a higher likelihood of connecting science and management.

Most modeling software is available on the FRAMES website. Links to the Wildland Fire Learning Portal (https://wildlandfirelearningportal.net/) and Northwest Knowledge Network (https://www.northwestknowledge.net/home) connect users to online coursework and information. Effective learning pathways for smoke management tools and science will always benefit both the scientific and management communities. Smoke management and modeling are available through the Wildland Fire Learning portal, a central location for sharing new science, new modeling tools, and best management practices. In-person training and interactive presentations at a regional or local level can be an effective way for scientists and managers to share new information, tools, and science.

8.6.5 *Maintaining Contact*

For both scientists and managers, attending a single conference or training course is not enough to ensure a scientific finding or tool is well integrated into a management process. Continual interactions, training, updates, and feedback are needed. Scientists can provide training when models are developed and updated, develop guidance documents and online hosting, and provide notices of model updates and enhancements.

8.7 Managing Smoke in a Changing Environment

Ecosystems and fire regimes will continue to change in response to a warmer climate (Halofsky et al. 2020, Box 8.1). Environmental risks from climate change are becoming more evident and happening quickly, requiring resource managers to incorporate climate considerations and adjust how they manage fire and natural resources. Because of expected increases in emissions, combined with increasing evidence of a multitude of potential health impacts associated with smoke exposure, effective smoke management and communication will be a priority.

Because more frequent fires will lead to more frequent smoke effects from wildfire (Peterson et al. 2020), planning for and managing smoke emissions and dispersion likely will become increasingly difficult. The management and mitigation of smoke impacts rely on continued advancements in the field of smoke science, including our understanding of smoke emissions and predictive modeling tools. Community preparedness for smoke from wildfire and prescribed fire will be critical, and managers will need to incorporate new knowledge and tools into decision-making and in their work with stakeholders, communities, and policy makers; appropriate protective actions and evaluation of the benefits of new management approaches will be needed. Active learning through testing of new approaches can accelerate the learning process, and an open dialogue with all stakeholders can help to identify effective local solutions that will improve smoke management and protect key social values.

References

Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the western United States. Int J Wildland Fire 22:1003–1020

Adetona O, Reinhardt TE, Domitrovich J et al (2016) Review of the health effects of wildland fire smoke on wildland firefighters and the public. Inhalation Toxicol 28:95–139

Barbero R, Abatzoglou JT, Larkin NK et al (2015) Climate change presents increased potential for very large fires in the contiguous United States. Int J Wildland Fire 24:892–899

Bormann BT, Homann PS, Darbyshire RL, Morrissette BA (2008) Intense forest wildfire sharply reduces mineral soil C and N: the first direct evidence. Can J for Res 38:2771–2783

Bradstock RA, Cary GJ, Davies I et al (2012) Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: insights from landscape-scale simulation. J Environ Manage 105:66–75

Brown TJ, Horel JD, McCurdy GD et al (2012) What is the appropriate RAWS network? PMS 1003, Report to the National Wildfire Coordinating Group. https://www.nwcg.gov/sites/default/files/publications/pms1003.pdf. 3 Sept 2020

Burley JD, Bytnerowicz A, Buhler M et al (2016) Air quality at Devils Postpile National Monument, Sierra Nevada Mountains, California, USA. Aerosol Air Qual Res 16:2315–2332

Bytnerowicz A, Cayan D, Riggan P et al (2010) Analysis of the effects of combustion emissions and Santa Ana winds on ambient ozone during the October 2007 southern California wildfires. Atmos Environ 44:678–687

Bytnerowicz A, Hsu Y-M, Percy K et al (2016) Ground-level air pollution changes during a boreal wildland mega-fire. Sci Total Environ 572:755–769

Clinton NE, Gong P, Scott K (2006) Quantification of pollutants emitted from very large wildland fires in Southern California, USA. Atmos Environ 40:3686–3695
David AT, Asarian JE, Lake FK (2018) Wildfire smoke cools summer river and stream water temperatures. Water Resour Res 54:7273–7290
Doubleday A, Schulte J, Sheppard L et al (2020) Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: a case-crossover study. Environ Health 19:4
Flannigan MD, Krawchuk MA, de Groot WJ et al (2009) Implications of changing climate for global wildland fire. Int J Wildland Fire 18:483–507
Ford B, Val Martin M, Zelasky SE et al (2018) Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. GeoHealth 2:229–247
Halofsky JE, Peterson DL, Harvey BJ (2020) Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. Fire Ecol 16:4
Hamilton DS, Hantson S, Scott CE et al (2018) Reassessment of pre-industrial fire emissions strongly affects anthropogenic aerosol forcing. Nat Commun 9:3182
Harber P, Bansal S, Santiago S et al (2009) Multidomain subjective response to respirator use during simulated work. J Occup Environ Med 51:38–45
Jaffe DA, Wigder NL (2012) Ozone production from wildfires: a critical review. Atmos Environ 51:1–10
Jolly WM, Cochrane MA, Freeborn PH et al (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nat Commun 6:1–11
Keeley JE, McGinnis TW, Bollens KA (2005) Seed germination of Sierra Nevada postfire chaparral species. Madroño 52:175–181
Kitzberger T, Falk DA, Westerling AL et al (2017) Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. PloS One 12:e0188486
Klocke D, Schmitz A, Schmitz H (2011) Fire-adaptation in *Hypocerides nearcticus* Borgmeier and *Anabarhynchus hyalipennis hyalipennis* Marquart and new notes about the Australian "Smoke Fly" *Microsania australis* Collart (Diptera: Phoridae, Therevidae and Platypezidae). Open Entomol J 5:10–14
Kobziar LN, Pingree MRA, Larson H et al (2018) Pyroaerobiology: The aerosolization and transport of viable microbial life by wildland fire. Ecospheres 9:e02507
Kolden CA (2019) We're not doing enough prescribed fire in the western United States to mitigate wildfire risk. Fire 2:30
Krueger ES, Ochsner TE, Engle DM et al (2015) Soil moisture affects growing-season wildfire size in the Southern Great Plains. Soil Sci Soc Amer J 79:1567–1576
Larkin NK, Abatzoglou JT, Barbero R et al (2015) Future megafires and smoke impacts (Final report JFSP-11-1-7-4). Boise: Joint Fire Science Program. https://www.firescience.gov/projects/11-1-7-4/project/11-1-7-4_final_report.pdf. 1 July 2020
Larkin NK, O'Neill SM, Solomon R et al (2009) The BlueSky smoke modeling framework. Int J Wildland Fire 18:906–920
Larkin NK, Strand TM, Drury SA et al (2012) Smoke and emissions model intercomparison project (SEMIP): Creation of SEMIP and evaluation of current models (Final report, JFSP 08-1-6-10). Boise: Joint Fire Science Program. https://www.firescience.gov/projects/08-1-6-10/project/08-1-6-10_final_report.pdf. 1 July 2020
Litschert SE, Brown TC, Theobald DM (2012) Historic and future extent of wildfires in the Southern Rockies ecoregion, USA. For Ecol Manage 269:124–133
Liu JC, Mickley LJ, Sulprizio MP et al (2016) Particulate air pollution from wildfires in the western US under climate change. Clim Change 138:655–666
Long JW, Tarnay LW, North MP (2017) Aligning smoke management with ecological and public health goals. J for 116:76–86
Maguire LA, Albright EA (2005) Can behavioral decision theory explain risk-averse fire management decisions? For Ecol Manage 211:47–58

Martínez Zabala LM, Celis García R, Jordán López A (2014) How wildfires affect soil properties: a brief review. Cuadernos De Investigación Geográfica 40:311–331
Mayer M, Prescott CE, Abaker WE et al (2020) Influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. For Ecol Manage 466:118–127
McKenzie D, Gedalof Z, Peterson DL et al (2004) Climatic change, wildfire, and conservation. Conserv Biol 18:890–902
McKenzie D, Shankar U, Keane RE et al (2014) Smoke consequences of new wildfire regimes driven by climate change. Earth's Future 2:35–59
Melvin M (2018) National prescribed fire use survey report (Technical Report 03–18). Coalition of Prescribed Fire Councils. https://www.stateforesters.org/wp-content/uploads/2018/12/2018-Prescribed-Fire-Use-Survey-Report-1.pdf. 4 June 2020
Moran CJ, Kane VR, Seielstad CA (2020) Mapping forest canopy fuels in the Western United States with LiDAR–Landsat covariance. Remote Sens 12:1000
Morgan P, Hardy CC, Swetnam TW et al (2001) Mapping fire regimes across time and space: understanding coarse and fine-scale fire patterns. Int J Wildland Fire 10:329–342
National Science and Analysis Team (2014) The national strategy: The final phase in the development of the National Cohesive Wildland Fire Mangement Strategy. https://www.forestsandrangelands.gov/documents/strategy/strategy/CSPhaseIIINationalStrategyApr2014.pdf. 10 Mar 2021
National Wildfire Coordinating Group (NWCG) (2017) Interagency prescribed fire planning and implementation procedures guide (PMS 484). https://www.nwcg.gov/publications/484. 15 Sept 2020
Navarro KM, Schweizer D, Balmes JR, Cisneros R (2018) A review of community smoke exposure from wildfire compared to prescribed fire in the United States. Atmosphere 9:1–11
North M, Collins BM, Stephens S (2012) Using fire to increase the scale, benefits, and future maintenance of fuels treatments. J for 110:392–401
Olsen CS, Mazzotta DK, Toman E, Fischer AP (2014) Communicating about smoke from wildland fire: challenges and opportunities for managers. Environ Manage 54:571–582
Parsons RA, Mell WE, McCauley P (2011) Linking 3D spatial models of fuels and fire: effects of spatial heterogeneity on fire behavior. Ecol Model 222:679–691
Peterson J, Lahm P, Fitch M et al (2020) NWCG smoke management guide for prescribed fire (PMS 420–3/NFES 001279). National Wildfire Coordinating Group. https://www.nwcg.gov/sites/default/files/publications/pms420-3.pdf. 10 Mar 2021
Peterson DL, Hardy CC (2016) The RxCADRE study: a new approach to interdisciplinary fire research. Int J Wildland Fire 25:i–i
Prescribed Fire Information Reporting System (PFIRS) (2020) [WWW Document]. https://ssl.arb.ca.gov/pfirs. 1 July 2020
Preisler HK, Grulke NE, Bytnerowicz A, Esperanza A (2005) Analyzing effects of forest fires on diurnal patterns of ozone concentrations. Phyton 45:33–39
Prichard SJ, Larkin NS, Ottmar RD et al (2019) The fire and smoke model evaluation experiment: a plan for integrated, large fire-atmosphere field campaigns. Atmosphere 10:66
Prichard SJ, O'Neill SM, Eagle P et al (2020) Wildland fire emission factors in North America: synthesis of existing data, measurement needs and management applications. Int J Wildland Fire 29:132–147
Radeloff VC, Helmers DP, Kramer HA et al (2018) Rapid growth of the US wildland-urban interface raises wildfire risk. Proc Natl Acad Sci USA 115:3314–3319
Rebain SA (2010) The fire and fuels extension to the forest vegetation simulator: updated model documentation (Internal report, revised 23 March 2015). Fort Collins, U.S. Forest Service, Forest Management Service Center
Rebmann T, Carrico R, Wang J (2013) Physiologic and other effects and compliance with long-term respirator use among medical intensive care unit nurses. Am J Infect Control 41:1218–1223
Reid CE, Brauer M, Johnston FH et al (2016) Critical review of health impacts of wildfire smoke exposure. Environ Health Perspect 124:1334–1343

Reidmiller DR, Avery CW, Easterling DR et al (eds) (2018) Impacts, risks, and adaptation in the United States: fourth national climate assessment, vol II. U.S. Global Change Research Program, Washington, DC

Roberge RJ, Coca A, Williams WJ et al (2010) Physiological impact of the N95 filtering facepiece respirator on healthcare workers. Respir Care 55:569–577

Rowell E, Loudermilk EL, Hawley C et al (2020) Coupling terrestrial laser scanning with 3D fuel biomass sampling for advancing wildland fuels characterization. For Ecol Manage 462:117945

Schoennagel T, Balch JK, Brenkert-Smith H et al (2017) Adapt to more wildfire in western North American forests as climate changes. Proc Natl Acad Sci USA 114:4582–4590

Schultz CA, Thompson MP, McCaffrey SM (2019) Forest Service fire management and the elusiveness of change. Fire Ecol 15:13

Schweizer DW, Cisneros R (2017) Forest fire policy: Change conventional thinking of smoke management to prioritize long-term air quality and public health. Air Qual Atmos Health 10:33–36

Schweizer D, Cisneros R, Buhler M (2019a) Coarse and fine particulate matter components of wildland fire smoke at Devils Postpile National Monument, California, USA. Aerosol Air Qual Res 19:1463–1470

Schweizer D, Cisneros R, Navarro K (2020) The effectiveness of adding fire for air quality benefits challenged: a case study of increased fine particulate matter from wilderness fire smoke with more active fire management. For Ecol Manage 458:117761

Schweizer D, Cisneros R, Traina S, Ghezzehei TA, Shaw G (2017) Using National Ambient Air Quality Standards for fine particulate matter to assess regional wildland fire smoke and air quality management. J Environ Manage 201:345–356

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

Shindler B, Toman E (2003) Fuel reduction strategies in forest communities: a longitudinal analysis of public support. J for 101:8–15

Stephens SL, Collins BM, Biber E, Fulé PZ (2016) U.S. federal fire and forest policy: emphasizing resilience in dry forests. Ecosphere 7:e01584

Stratton RD (2020) The path to strategic Wildland fire management planning. Wildfire, Jan–Mar 24–31

Thompson MP, MacGregor DG, Dunn CJ et al (2018) Rethinking the wildland fire management system. J Forest 116:382–390

Vaillant NM, Reinhardt ED (2017) An evaluation of the Forest Service hazardous fuels treatment program—Are we treating enough to promote resiliency or reduce hazard? J Forest 115:300–308

Vose JM, Peterson DL, Domke GM et al (2018) Forests. In: Reidmiller DR, Avery CW, Easterling DR et al (eds) Impacts, risks, and adaptation in the United States: Fourth national climate assessment, vol II. U.S. Global Change Research Program, Washington, DC, pp 232–267

Weise DR, Wright CS (2014) Wildland fire emissions, carbon and climate: characterizing wildland fuels. For Ecol Manage 317:26–40

Wildland Fire Leadership Council (WFLC) (2020) Joint vision and key messsages on relative benefits of prescribed fire to wildfire. https://southernfireexchange.org/joint-vision-statement-on-relative-benefits-of-prescribed-fire-to-wildland-fire. 10 Mar 2021

Williamson GJ, Bowman DMS, Price OF et al (2016) A transdisciplinary approach to understanding the health effects of wildfire and prescribed fire smoke regimes. Environ Res Lett 11:125009

Zhao F, Liu Y, Goodrick S et al (2019) The contribution of duff consumption to fire emissions and air pollution of the Rough Ridge Fire. Int J Wildland Fire 28:993–1004