Chapter 1
Assessing the State of Smoke Science

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Abstract Recent large wildfires in the USA have exposed millions of people to smoke, with major implications for health and other social and economic values. Prescribed burning for ecosystem health purposes and hazardous fuel reduction also adds smoke to the atmosphere, in some cases affecting adjacent communities. However, we currently lack an appropriate assessment framework that looks past the planned versus unplanned nature of a fire and assesses the environmental conditions under which particular fires burn, their socio-ecological settings, and implications for smoke production and management. A strong scientific foundation is needed to address wildland fire smoke challenges, especially given that degraded air quality and smoke exposure will likely increase in extent and severity as the climate gets warmer. It will be especially important to provide timely and accurate smoke information to help communities mitigate potential smoke impacts from ongoing wildfires, as well as from planned prescribed fires. This assessment focuses on primary physical, chemical, biological, and social considerations by documenting our current understanding of smoke science and how the research community can collaborate with resource managers and regulators to advance smoke science over the next decade.

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1.1 Recent Trends

Data from the National Interagency Fire Center show that annual area burned by wildfires in the USA has increased in recent decades (NIFC 2021). Smoke generated from these fires is of particular concern because it is harmful to human health and can have significant economic implications for nearby communities. In recent years, air quality impacts due to wildfires in the USA have exposed tens of millions of people to elevated and sometimes hazardous concentrations of particulate matter, specifically particulate matter with aerodynamic diameter $\leq 2.5\ \mu m$ ($PM_{2.5}$), the smoke pollutant of most concern in relation to human health (Chap. 7).

Smoke can affect broad geographic areas, well beyond the actual wildfires. In 2017, numerous large wildfires in the western USA generated smoke plumes that were transported across North America and resulted in $PM_{2.5}$ concentrations that reached unhealthy to hazardous levels (based on the USEPA Air Quality Index(AQI) in many areas (Fig. 1.1). Although US air quality has been improving for decades, largely due to implementation of the Clean Air Act, the effects of wildfires in the past decade have been acute, and in some regions, wildfire smoke has led to a reversal in the general trend toward cleaner air (McClure and Jaffe 2018). Periodic pulses of high $PM_{2.5}$ from smoke are typically much higher than ambient $PM_{2.5}$ concentrations otherwise seen in both rural and urban areas. In 2017 and 2018, many cities in the western USA experienced their all-time highest $PM_{2.5}$ concentrations due to the number of wildfires burning simultaneously (Laing and Jaffe 2019). Very high $PM_{2.5}$ concentrations can also occur in the southeastern USA, although less frequently than in the western USA.

Although most smoke is associated with wildland fires[1] within the USA, fires in other countries can also affect US air quality. In 2017, high $PM_{2.5}$ concentrations in the Pacific Northwest were associated with large fires in British Columbia, Canada (Laing and Jaffe 2019). These same fires were associated with smoke transport to Europe and, locally, strong thunderstorm–pyrocumulonimbus activity, which injected smoke into the stratosphere (Baars et al. 2019). In addition, large fires in Quebec, Canada, have significantly affected air quality in the northeastern USA (DeBell et al. 2004); smoke from fires in Mexico and Central America can affect Texas (Mendoza et al. 2005; Kaulfus et al. 2017); and fires in Siberia can affect air quality in the western USA (Jaffe et al. 2004; Teakles et al. 2017).

[1] Throughout this document "wildland fire" is used to encompass both wildfires and prescribed fires. The individual terms are used only when they specifically refer to that specific source of smoke.

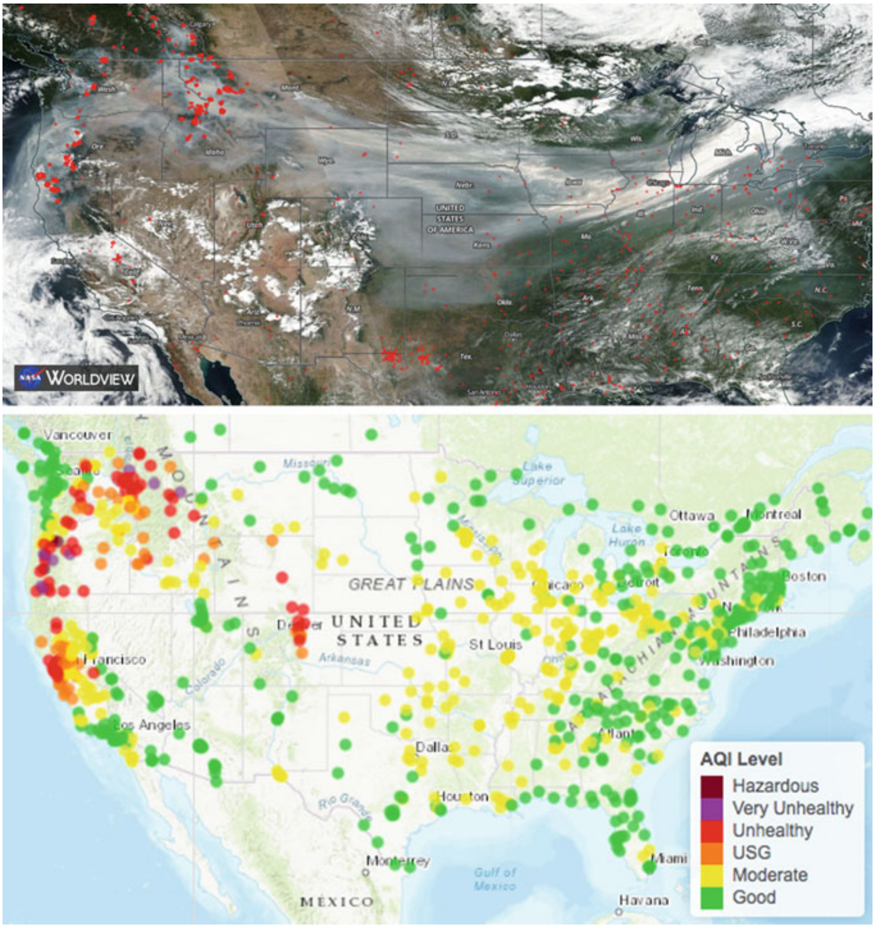

Fig. 1.1 Observed smoke on September 4, 2017. NASA Worldview (https://worldview.earthdata.nasa.gov) image (upper) showing fire hotspot detections from the VIIRS and MODIS satellite instruments, along with visible satellite imagery from the VIIRS instrument between 1200 and 1400 local time. Bright white areas are clouds; grayer areas are smoke. 24-h average $PM_{2.5}$, shown as the corresponding air quality index (AQI) category colors (lower), based on surface PM sensors collected in the USEPA AirNow system (https://www.airow.gov) (From Jaffe et al. (2020))

These increasingly broad and adverse effects of wildland fire smoke have led to growing interest in (1) assessing the state of science in relation to smoke and (2) improving smoke science in order to develop information and tools that can better inform management decisions (e.g., forest treatments and prescribed burning) and mitigate potential smoke impacts of future wildland fires.

1.2 Environmental and Social Context

Wildland fire is an essential ecological process that influences the structure and function of most North American ecosystems. The scale of fire phenomena differs across the nation, with consequences for both emissions and effects of smoke. Wildland fire smoke can affect at least some part of the USA throughout the year (Fig. 1.2). In winter, fires are found mainly in the Southeast, typically as prescribed, low-intensity understory burns to rejuvenate grasses and forbs and prepare seed beds for new tree seedlings, as well as reduce understory growth in pine forests. As spring approaches, fire detections move north and west, with increased prescribed fires on rangelands in the central USA. In Alaska, the wildfire peak is typically in May and June, and summer is the peak wildfire season for the western USA. Late fall can be a time of many wildfires in California and the Southeast. This progression of fire throughout the seasons and ecosystems across the USA has implications for the overall quantity, duration, and human impacts of the emitted smoke (Table 1.1).

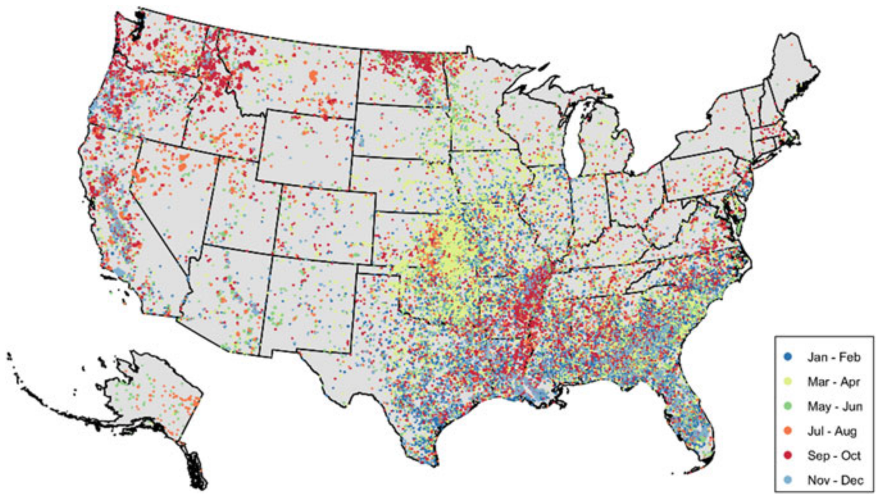

Fig. 1.2 Progression of fires throughout the year using 2017 MODIS hotspot fire detections. (*Source* U.S. Forest Service, from Jaffe et al. (2020))

Table 1.1 Summary of wildland fire for different regions in the USA. Adapted from Jaffe et al. (2020)

Region[a]	Typical fire season	Wildfire characteristics
Alaska	May–Jun	Mostly lightning- caused; high interannual variability in fire depending on the occurrence of dry weather; largest fires >100,000 ha
Eleven western contiguous states, minus California, Arizona, and New Mexico	Jun–Sep	Mostly lightning- caused in mountains; high fuel loadings in many dry forests can facilitate intense fires; largest fires >100,000 ha
California	Oct–Nov Jun–Sep	Many lightning- caused in Sierra Nevada, mostly human-caused elsewhere; high fuel loadings in many dry forests can facilitate intense fires; largest fires >100,000 ha
Arizona and New Mexico	May–Jun	Combination of lightning- and human-caused; fires often driven by interannual variation in fuel production (e.g., grasses); largest fires >100,000 ha
Great Plains	Apr–Jul	Mostly human- caused, some lightning-caused; largest fires are rarely >10,000 ha
Midwest and Northeast	Apr–Jun	Mostly human- caused; dependent on dry spring weather; fires are small
Southeast	Feb–Nov	Mostly human- caused, some lightning-caused; largest fires are usually <10,000 ha, although fires in 2016 burned more than this

[a] Hawai‘i and USA-affiliated areas are not included because they comprise a very small portion of fire and smoke occurrence

Humans have a long history of using fire and it is difficult to separate human influence from the natural occurrence of fire on the landscape (Pyne 1997). For centuries, Native Americans used fire as a tool for multiple purposes, including agriculture, managing wildlife habitat and hunting grounds, and cultural practices. As a result of lightning fires and Native American burning, as well as agricultural clearing fires by European settlers, dense and extended periods of smoke were a fairly common occurrence prior to 1900 in many places in the USA. In the 1800s, smoke from wildland and agricultural fires in Oregon hindered navigation on the Columbia River and was credited with contributing to increased illness (Pyne 1997).

The practice of suppressing most wildfires was introduced in the late 1800s. Over time, this policy has contributed to elevated fuel loadings that are one factor contributing to increasing fire size in recent years (Ryan et al. 2013). Fire suppression (and other forms of fire exclusion [e.g., agriculture]) have meant that up until about 1990, less fire has occurred on the landscape than in pre-European settlement times (Leenhouts 1998), resulting in less smoke in the air (Brown and Bradshaw 1994). Recent episodes of smoke across the USA in the last two decades have been driven by large wildfires, and this may be, to some extent, a return to conditions that have not existed since the implementation of widespread fire suppression. A key challenge for forest managers therefore is how to address the fuel accumulation that has occurred as a result of fire suppression (Calkin et al. 2015), while addressing the potential impacts of smoke on a growing human population.

Although 98% of wildfires are currently suppressed before reaching 120 ha (Calkin et al. 2005), annual area burned by wildfires is increasing (Dennison et al. 2014). In the decade between 1991 and 2000, wildfires burned an average area of 1.46 million ha y^{-1}, whereas in the most recent decade (2011–2020) wildfires burned an average area of 3.04 million ha y^{-1} (NIFC 2021). This is mainly due to an increase in large fires that are difficult to control (Dennison et al 2014).

One study has suggested that climate change is contributing to the increased size of wildfires in the western USA (Abatzoglou and Williams 2016), although this study did not consider how fuels and other factors affect wildfire (Dennison et al. 2014). Rising temperatures affect fuel moisture and the length of the fire season (Jolly et al. 2015; Freeborn et al. 2016; McKenzie and Littell 2017). The effects of climate change on area burned will differ by ecosystem and fuel conditions (Littell et al. 2009), with larger areas burned by wildfire in some regions and longer durations of poor air quality due to smoke (Pechony and Shindell 2010; Vose et al. 2018). Changes in fuel composition, loading, and areal extent (Chap. 2) may lead to regional variability that alters the effects of climate change, especially after mid-century. For example, if large wildfire patches comprise an increasing proportion of the landscape, they may limit fire spread.

Prescribed fire—*planned ignition in accordance with applicable laws, policies, and regulations to meet specific objectives* (NWCG 2020)—is an important land management tool that can be used for several management objectives including fuel reduction and ecosystem health. All potential smoke production from such burning must be considered in the context of human health and air quality standards (Chap. 7). Prescribed fires occur under environmental conditions more amenable to fire control (Chaps. 2 and 8) and, depending on the state, may need to be permitted under a smoke management plan to ensure that smoke exposure will not exceed air quality standards or affect sensitive populations.

The ability to plan for when and where a prescribed burn will happen provides some control over the duration, overall amount, and spatial extent of smoke production, although unexpected atmospheric conditions (e.g., a change in wind direction) can result in smoke dispersion into nearby communities (Chap. 4). When a large number of prescribed fires are planned to occur simultaneously, they can create accumulated smoke impacts, making collaboration among burners advisable (Chap. 8).

A final challenge in relation to wildland fire smoke is that wildland fires do not occur in a vacuum. Rather, they occur in landscapes with expanding human populations, increasing the potential for social impacts for both rural and urban areas. Although health impacts are usually the primary concern, smoke can adversely affect a range of social values beyond health (e.g., transportation and tourism) (Chap. 7) and affect areas far beyond the fire perimeter. For example, in 2016, the Chimney Tops fire near Gatlinburg, Tennessee, a major tourism center, caused 15 deaths and burned 2500 homes. It also exposed large populations beyond the immediate area to severely degraded air quality for weeks: monitors in many cities in the southeastern USA had daily $PM_{2.5}$ averages that exceeded 100 $\mu g\ m^{-3}$, a level of exposure that greatly increases risk for people with compromised respiratory function and other medical conditions (Jaffe et al. 2020; Chap. 7). In addition, fires that burn human infrastructure may produce toxins from building materials into the smoke (Chap. 6).

1.3 Overview of This Assessment

This assessment builds on previous integrated analyses of wildland fire and smoke (e.g., Sommers et al. 2014). To better address the growing societal impacts discussed above, an improved understanding of smoke dynamics is needed to more accurately predict the location, extent, and likely effects of smoke, as well as how to effectively mitigate any adverse effects. Because understanding how fire influences air quality is a complex process due to high variability among fires in the quantity and composition of emissions, this will require the compilation of knowledge from diverse scientific disciplines.

Emission characteristics vary as a function of the amount and type of fuel, meteorology and burning conditions (Chap. 2), fire behavior (Chap. 3), and smoke dispersal (Chap. 4); therefore, emissions (Chap. 5) for individual fires are often uncertain and difficult to predict. In addition to $PM_{2.5}$, smoke contains numerous gaseous compounds, some of which are harmful to people, including nitrogen oxides, carbon monoxide, ozone, methane, and hundreds of volatile organic compounds (Chap. 6). This chemical complexity makes wildfire smoke different from typical industrial pollution. In addition, once emitted, wildland fire smoke undergoes chemical transformations in the atmosphere, which alter the mix of compounds and generate secondary pollutants, such as ozone and secondary organic aerosols (Chap. 6); some of these secondary compounds appear to be more toxic than the primary emissions (Wong et al. 2019).

Ultimately, given that the social impacts of smoke are the foundation for these scientific needs, a better understanding of the full range of human health and economic costs of smoke is needed (Chap. 7). Complex interactions among wildland fires, climate change, and other factors mean that the different disciplines of smoke science need sufficient integration to ensure credible and consistent projections of physical phenomena and human impacts through space and time. Clear linkages between what resource managers and regulators need and what is being produced through scientific research is also critical (Chap. 8).

The technical capability of smoke measurement and modeling has increased significantly over the past decade. Our understanding of acute human health effects has also increased, partially in response to big smoke events and partially in response to concerns about effects on wildland firefighters who are exposed to smoke for weeks at a time during the course of their work. This scientific knowledge is encouraging, but greater accuracy is needed in all aspects of smoke science to better mitigate future health and economic impacts.

To that end, we are now at a critical point in the development of smoke science. Several large-scale field projects, focused on comprehensive measurements and modeling (detailed in subsequent chapters) have been recently completed or will be completed within the next few years (e.g., FASMEE; Prichard et al. 2019). These experiments include simultaneous satellite-, aircraft-, drone-, and ground-based sensors which, along with fuel measurements, should significantly improve our knowledge about a number of smoke phenomena.

Accompanying this potential wealth of data will be the need to develop new assessment frameworks through which we can compare and evaluate characteristics of different types of fires, their smoke consequences, and opportunities for planning and managing fires to reduce smoke impacts. However, this information will be meaningful only with a better understanding of the health and economic effects of smoke and identification of which actions most effectively mitigate those effects. Williamson et al. (2016) articulated the principles of a potential framework for guiding scientific and management needs associated with fire and smoke, but more effort is needed to develop this framework.

Poised on the cusp of a new wave of technically advanced smoke research and a surge in new data, it is imperative that we summarize the current state of science for wildland fire smoke as a foundation for integration of new information. The subsequent chapters of this book assess that state of science as follows:

- Fuels and consumption (Chap. 2)
- Fire behavior and heat release (Chap. 3)
- Smoke plume dynamics (Chap. 4)
- Emissions (Chap. 5)
- Smoke chemistry (Chap. 6)
- Social Considerations: Health, Economics, and Risk Communication (Chap. 7)
- Resource manager perspectives on the need for smoke science (Chap. 8).

Chapters 2 through 6 focus on physical, chemical, and biological factors that affect fire and smoke. Chapter 7 examines the existing knowledge on key impacts, particularly human health, all of which rely on a better understanding of the physical and chemical nature of smoke, as well as on improved knowledge of human sensitivities and responses to smoke to understand social and economic consequences. We note here that the social costs of smoke are significant and include documented increases in cardiovascular issues, premature mortality, and direct health costs in the billions of dollars annually (Fann et al. 2018). A summary of management and regulatory issues related to smoke science is presented in Chap. 8, which can be used to inform research and facilitate science-management collaborations in the future.

Although this assessment is, by necessity, divided into the primary components of smoke science, authors of the above chapters have integrated among components as much as possible. This assessment emphasizes recent discoveries, linking to projects and lines of inquiry that are in progress or soon will be. Recommendations for future research are included in each chapter.

This is an exciting time for the science and management of smoke in the USA and other parts of the world, and we anticipate rapid progress in the years ahead. As smoke will likely become a more pervasive issue in a warmer climate with more extensive wildfires, it is also a critical time for the smoke science community to continue to make progress. Our hope is that collaboration at all levels will improve effectiveness of the research process and timeliness of integration into useful applications, ultimately benefiting the health and welfare of all communities affected by smoke.

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