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NWCG Smoke Management Guide for Prescribed Fire

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The *NWCG Smoke Management Guide for Prescribed Fire* contains information on prescribed fire smoke management techniques, air quality regulations, smoke monitoring, modeling, communication, public perception of prescribed fire and smoke, climate change, practical meteorological approaches, and smoke tools. The primary focus of this document is to serve as the textbook in support of NWCG's RX-410, Smoke Management Techniques course which is required for the position of Prescribed Fire Burn Boss Type 2 (RXB2). The Guide is useful to all who use prescribed fire, from private land owners to federal land managers, with practical tools, and underlying science. Many chapters are helpful for addressing air quality impacts from wildfires. It is intended to assist those who are following the guidance of the NWCG's *Interagency Prescribed Fire Planning and Implementation Procedures Guide*, PMS 484, https://www.nwcg.gov/publications/484, in planning for, and addressing, smoke when conducting prescribed fires.

For a glossary of relevant terminology, consult the *NWCG Glossary of Wildland Fire Terminology*, PMS 205, https://www.nwcg.gov/glossary/a-z. For smoke management and air quality terms not commonly used by NWCG, consult the *Smokepedia* at https://www.frames.gov/smokepedia.

The National Wildfire Coordinating Group (NWCG) provides national leadership to enable interoperable wildland fire operations among federal, state, tribal, territorial, and local partners. NWCG operations standards are interagency by design; they are developed with the intent of universal adoption by the member agencies. However, the decision to adopt and utilize them is made independently by the individual member agencies and communicated through their respective directives systems.

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Foreword

Colin Hardy and Janice Peterson

The challenge of minimizing the impacts of smoke on the public while expanding the role of fire in land management has never been greater, as air quality standards tighten and the wildland urban interface expands with people looking to live in natural environments with clean air. Recent dramatic increases in the average number of acres burned by wildfire per year have led to increased awareness that wildfire smoke impacts are a reality that must be addressed. Prescribed fire, a vital tool to improve ecosystem health and lessen the potential impacts of wildfire, is gaining support even among unlikely allies such as clean air agencies. But this tentative support will only continue and expand if fire practitioners commit to continuously learning and applying the best science and methods for protecting air quality as well as emphasizing public communications and outreach to address concerns. In the near future, changes in climate leading to shifting ecosystems and fire regimes will provide new challenges. This edition of the *Smoke Management Guide for Prescribed fire* builds on previous versions with updated knowledge of fire and air quality science, policy, and tools. New concepts presented for the first time include chapters on smoke management communications, public perceptions of smoke from wildland fire, wildland fire and climate change, and the practical use of meteorological tools and indices for smoke management. This guidebook will serve to educate current and future generations of fire practitioners and smoke managers by building upon the good work of earlier efforts.

The challenge—and the potential—for wildland fire management in the 21st century is perhaps best described by the vision statement adopted by the Wildland Fire Leadership Council (WFLC):

"To safely and effectively extinguish fire, when needed; use fire where allowable; manage our natural resources; and as a Nation, live with wildland fire."

This vision frames the *National Cohesive Wildland Fire Management Strategy* effort (Cohesive Strategy) initiated by the Federal Land Assistance, Management and Enhancement (FLAME) Act of 2009. The Cohesive Strategy takes a holistic approach to the future of wildland fire management, and identifies three primary, national goals:

- **Restore and Maintain Landscapes**, making them resilient to fire-related disturbances.
- Create **Fire-adapted Communities**.
- Ensure safe, effective, and efficient **Wildfire Response**.

The imperative for appropriate and effective management of smoke from wildland fire is embedded in all three of these goals. The Cohesive Strategy approach is considered holistic because achievement of these goals, as well as the associated smoke management implications embedded in each, is only possible through collaborative engagement—the "all-hands/all-lands" paradigm on which implementation of the Cohesive Strategy is firmly grounded. This approach has already found considerable traction in the context of smoke management and air quality, as demonstrated by the growth and strength of recent partnerships. Adding to the legacy of contributors and partners who have worked together around smoke management (USDA, DOI, EPA, DOD, state forestry agencies and tribes) are new partners such as CDC, NOAA, NASA, NGOs, and academic institutions.

In 1976, the first comprehensive synthesis of knowledge about wildland fire emissions and management strategies to mitigate smoke effects was developed for the Southern US. The *Southern Forestry Smoke Management Guidebook* (Mobley 1976) was directed at southern forest-land managers, and begins by noting that prescribed fire is "an indispensable tool of the forest manager." Then, as now, forest and resource managers in the South have been leaders in the use of fire—in the mid-1970s, nearly 3 million acres were burned by prescription in the South each year. At the time, both the need for, and the science about wildland fire emissions and smoke management were largely focused in the South, and the new guide benefitted from a strong consortium of contributors, ranging from Regional Forest Service managers, to the strength of science at the Southeastern Forest Experiment Station, to contributions from both academic and industrial forestry collaborators. The authors fully recognized and acknowledged the many limitations to what they could provide so limited the scope of the guidebook to three primary subjects:

1. Broad breakdown of southern fuels
2. Single prescription fires
3. Predictions of particulate emissions only.

Despite the limitations, this regional effort set the stage for what might be possible at a national scale.

The same year as the *Southern Forestry Smoke Management Guidebook* was published, the National Wildfire Coordinating Group (NWCG) was formed and authorized through a charter signed by the Secretary of Interior and the Secretary of Agriculture. As the name suggests, NWCG was chartered as the nationally-recognized organization by which training, qualifications, standardization, and guidance for fire management could be coordinated and promulgated. One of 13 original NWCG Working Teams was the Prescribed Fire and Fire Effects Working Team, which launched an effort to create guidelines for planning and managing smoke from prescribed fire to achieve air quality requirements through improved smoke management principals. The outcome was the first guide to focus on national smoke management principles—the *Prescribed Fire Smoke Management Guide* (NWCG 1985). That guide expanded greatly on both the scope and depth of information provided in the earlier Southern Guidebook, covering smoke management objectives and regulatory requirements, smoke production, smoke management strategies, and smoke monitoring and evaluation.

The 1985 national guide served both land and air resource managers well for many years, and was ultimately used as the course textbook for a NWCG Smoke Management Course prototyped as “RX-95” in 1988. The course was renamed “RX-450” in 1994. By the mid-1990s, the NWCG working team (renamed the Fire Use Working Team) recognized that, while fire use programs were increasing, concerns were also elevating regarding associated costs such as smoke management problems. In direct response to the escalating tension between increases in sources of smoke and the impacts on public health and safety, the NWCG team commissioned a new guide titled *Smoke Management Guide for Prescribed and Wildland Fire* (Hardy *et al.* 2001). A six-person steering committee directed the contributions of 16 authors to produce the 2001 guide, a collaboration underscored in the guide’s introduction, which states “Minimizing the adverse effects of smoke on human health and welfare while maximizing the effectiveness of wildland fire is an integrated and collaborative activity.” The 2001 guide included best practices and techniques synthesized from three regional workshops held across the US specifically for that purpose. Like the 1985 guide before it, the 2001 guide has been the national standard for both fire practitioners and air resource managers, and has stood as the reference textbook for the current smoke management training course RX-410. This new update of the Smoke Management Guidebook, sponsored by NWCG Smoke Committee, is the work of 31 authors and 8 editors/compilers. It is intended to again be used as the textbook for smoke management training courses across the country and will serve managers well for years to come.

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CHAPTER 1–OVERVIEW

1.1 The Air Quality and Smoke Management Imperative

Peter Lahm

There are many reasons to protect and improve air quality in the United States. Many of these are the same factors that compel land managers to manage smoke proactively as they use fire to meet ecological and fuel hazard reduction objectives. Balancing prescribed fire objectives while managing smoke to protect air quality has been a challenge for many years. And that challenge is growing in a modern society which is now supportive of worldwide emission reductions to combat climate change. Fire managers should be aware of the overarching issue that drives the need to manage smoke from prescribed fire—regulators and members of the public value clean air and often perceive the use of fire as discretionary. Concern about smoke can also be driven by a personal sensitivity to air pollutants. All of these factors are important when considering the drive to reduce all sources of air pollution — a fundamental tenet of pollution control rules and regulations. The challenge facing stewards of wildlands and practitioners of prescribed fire is to successfully balance the need to use fire with the need to protect air quality. Even though the vital role of fire and its irreplaceable disturbance function in many ecosystems is well understood by land managers and many of the public, land managers are well served by understanding the drivers for protecting air quality and the need to recognize the air quality and smoke management imperative.

Health Risks of Smoke

The recognition that certain amounts and types of air pollution can harm the health of the general public, as well as sensitive individuals, and lead to premature mortality and illness is a compelling driver of public policy, laws and regulations. This is reflected in the long-standing efforts in the United States to reduce air pollution from all sources, and is the primary driver for the Clean Air Act (CAA) (104 Stat. 2399). Understanding air quality regulations is crucial to success whenever prescribed fires are conducted. One in three households in the United States has someone with a respiratory issue or illness. This number of households with respiratory issues is supported with 7.3% prevalence of asthma, 6.3% prevalence of cardio-obstructive pulmonary disease, 20% prevalence of chronic rhinitis, and lesser prevalence of pneumonia, lung cancer and other related conditions (Garbe 2015). The number of Americans with asthma is increasing despite significant air quality improvements over the life of the CAA and its air quality standards. These numbers should underscore the likelihood that someone with significant health issues will be affected by smoke from a prescribed fire. Some of these households are in the growing wildland urban interface where use of prescribed fire and fuel treatments is critical to reduce risk of catastrophic wildfire. This public health situation will challenge even the most experienced prescribed fire practitioner.

Worldwide, biomass burning (which includes agricultural burning, prescribed fire and wildfire) has been estimated to cause 180,000 premature deaths per year. One study (Lelieveld *et al.* 2015) estimates 2,500 such deaths per year in the United States, mostly tied to elevated levels of fine particulate matter (particulate matter smaller than 2.5 microns aka $PM_{2.5}$). Other global annual mortality estimates are even higher (Johnston *et al.* 2012). Beyond premature mortality, significant respiratory and cardiovascular effects such as asthma attacks, respiratory infections, acute and chronic changes in pulmonary function, and increased hospital admissions are hallmarks of air quality effects of smoke from biomass burning (Goldammer 2015). Biomass burning and the resulting emissions are significant contributors to climate change through a variety of mechanisms including deforestation, greenhouse gas emissions, increasing emissions of short-lived climate forcing air pollutants such as black carbon (EPA 2012) and loss of forest carbon sequestration capability. These effects are a driving factor behind global coordination efforts to address biomass burning and wildfire (Goldammer 2015).

In the United States, wildfire smoke is recognized as a significant contributor to exceedances of the National Ambient Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA) to protect public health and welfare (EPA 2016a). This is a recent trend in part because the NAAQS have become more stringent over time based on periodic review as required by the CAA and now allow only small increases in pollutants from background air pollution levels. The duration, areal extant, and concentration of wildfire smoke in the United States has been increasing. Meanwhile, emissions from other sources of air pollution such as industrial facilities, electric power generation and mobile sources have all been dramatically declining. The small margin between naturally occurring background levels of air pollutants and the NAAQS is now a concern for prescribed fire users as well. Historically, the potential that a prescribed fire could contribute to an exceedance of a NAAQS was remote. This is no longer the case. To highlight the significance of wildfire emissions in the United States, in the 2011 National Emissions Inventory (EPA 2014), agricultural burning, wildfire and prescribed fire made up 34% of the nation's annual fine particulate emissions; science supporting new emission factors would bump that number to 48% (O'Neill 2015, Urbanski 2015). This category has grown in importance when compared to other pollution sources. Combined, these factors have contributed to an increased focus on the significance of wildfire emissions and have supported a perception change leading to increased understanding of the role of fire on wildland ecosystems for both ecosystem health and resilience but also for fuels and hazard reduction. Wildfire smoke is being recognized as a larger contributor to chronic public exposure to fine particulate matter and there is now some developing commitment to address the issue in the context of air quality rules and regulations.

The EPA, through rules developed in 2015 and 2016, has indicated an understanding of the importance of prescribed fire to help address catastrophic wildfire and its attendant public health effects and disruption of life. How these messages from the lead federal agency for environmental protection are accepted by the public and the state air quality regulatory community is yet to be determined, but they are valuable to the land management community as they seek to use and/or increase use of prescribed fire. This recognition may lead to more opportunities to use prescribed fire. A key challenge for land managers using prescribed fire is to manage smoke appropriately by reducing emissions and their effects on the public.

Safety Risks of Smoke

Smoke from wildland fire can pose risk to public health, in general, but is of particular concern for sensitive individuals. The Clean Air Act aims to protect the public's health from air pollution, but smoke from wildland fire can threaten public safety in a variety of ways. When high levels of wildfire smoke remain for long durations, the potential for risk to public health and safety is real. Although not a common situation, smoke from wildfire can trigger life-threatening responses and those responses are not always simultaneous with the peak smoke exposure. This is especially true for sensitive individuals with some heart conditions. This risk as a result of a potential air quality impact should be considered within the realm of safety when it directly threatens life. The same situation occurs when smoke from a wildland fire crosses roads and meteorological conditions support the formation of total visibility obscuring "super-fog." What may initially be an annoyance and perhaps a minor traffic hazard that can be mitigated with appropriate signage, light smoke crossing a road can rapidly escalate to life-threatening opaque "super-fog" which can trigger fatal automobile accidents. Members of the public and fire personnel have lost their lives in the tragic situation when thick smoke from wildfires or prescribed fires obscures visibility on a roadway.

Fire personnel exposure to high levels of smoke near the combustion front can, under some meteorological conditions, lead to absorption of carbon monoxide (CO) in the blood which can impair decision-making capability. Very high levels of CO can lead to death. Understanding the symptoms and proper response to CO exposure is important as this safety threat to fire personnel can occur on wildfires as well as prescribed fires. Such direct threats support the importance of being well-trained. These effects comprise an important part of the air quality and smoke management imperative.

The Air Quality and Smoke Management Imperative: Addressing the Health and Safety Risks of Wildland Fire Smoke

Smoke from wildfire can threaten public as well as fire personnel health and safety. These air quality effects are now being recognized as a serious issue by the public and by governmental agencies. Historically, wildfire smoke effects were not given much focus in the air quality regulatory process because the NAAQS were not frequently exceeded. When responding to wildfires, managers rarely focused on smoke effects to the public as they were generally considered uncontrollable. According to the EPA's Exceptional Event Rule (EPA 2016b), air quality effects from wildland fire smoke captured on official air quality monitors and contributing to an exceedance of air quality standards for health can be excluded from affecting determination of whether an area meets NAAQS or could be declared as in non-attainment. This discounting occurs even though public health is directly affected. Additionally, wildland managers have begun assessing their responses to wildfires in the context of risk which allows for consideration of many environmental effects, safety concerns and likelihood of success when developing management response, strategies and tactics.

As the presence of wildfire and the effects of smoke have increased, there has been proactive response to this threat and the risks to health and safety. The Forest Service, with interagency partners such as the National Park Service, has developed the Wildland Fire Air Quality Response Program which directly addresses risks posed by smoke. The program maintains a national cache of smoke monitoring equipment and supports operational smoke modeling efforts conducted by the Forest Service Pacific Northwest Research Station's AirFire Team, both of which are useful in wildfire and prescribed fire applications. Monitoring and modeling can help fire managers, regulators, and the public understand the magnitude of air quality effects; and forecast future effects so that the public and fire personnel can respond accordingly and, when needed, take actions to reduce their exposure. Most important has been the development of technical specialists called air resource advisors (ARAs) who are increasingly deployed to incident management teams on large wildfires. Air resource advisors are trained to predict and warn about smoke effects, and advise on opportunities to reduce exposure (Lahm 2015). Such air quality messaging and pre-exposure forecasting has been found to be effective especially for those who are sensitive to high air pollution levels (Rappold *et al.* 2014).

The focus on these serious wildfire smoke effects has helped the public and governmental agencies become more aware of the risk to air quality they pose but also to emphasize distinct benefits of proactive fuels management including use of prescribed fire.

Figure 1.1.1 compares daily fine particulate concentrations of a prescribed fire with a significant wildfire in California for Washoe County in Nevada. The distant wildfire air quality effects are substantially greater than those of a planned, localized prescribed fire on a day-to-day basis (Hunter 2016). There are many reasons for the difference in effects but the potential management of prescribed fire smoke effects with its limited fuel consumption and emissions stands in stark contrast to the severe air quality effects of the catastrophic wildfire.

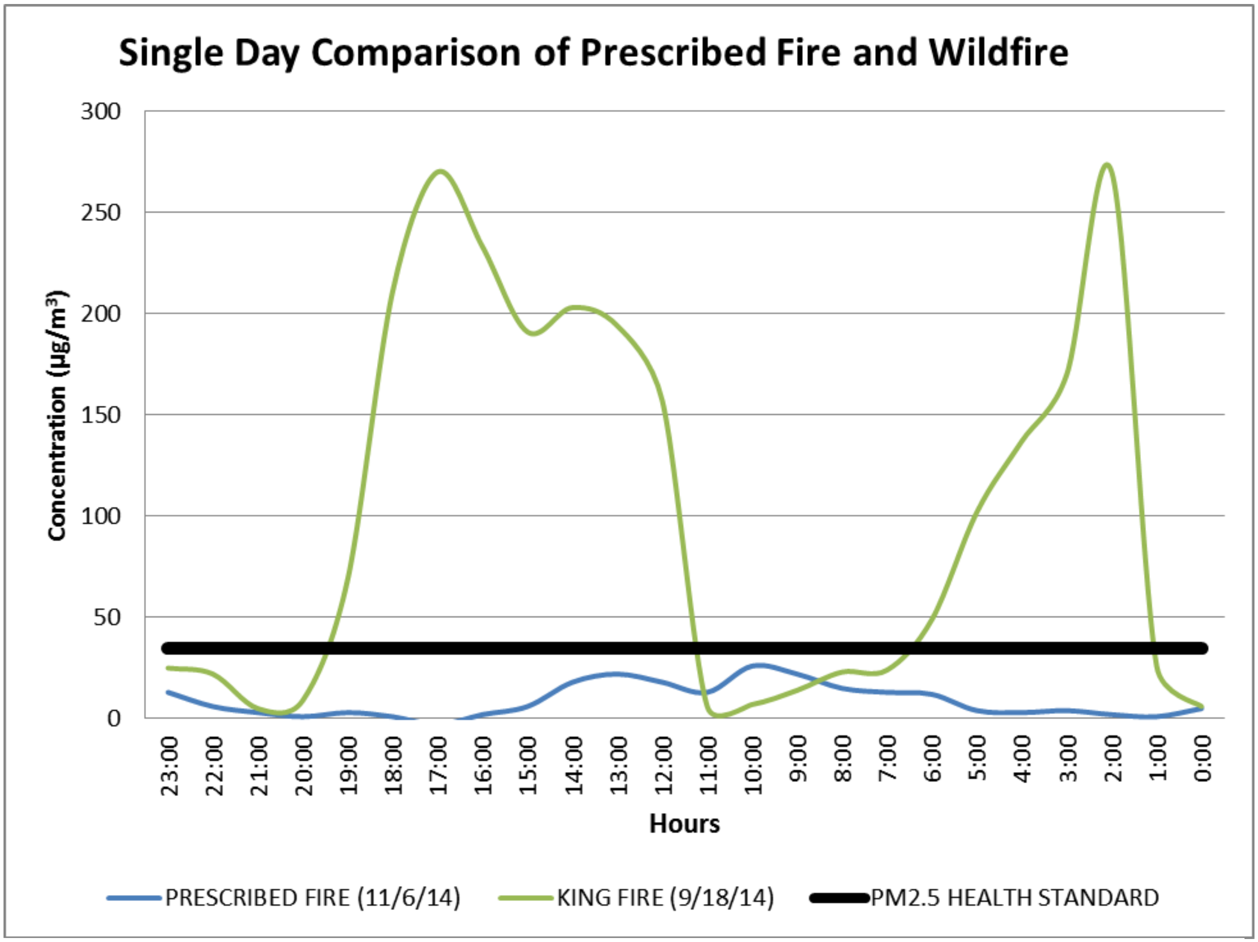

Figure 1.1.1. Daily fine particulate concentrations in Washoe County, Nevada of a prescribed fire as compared to a significant wildfire in California.

Because the effects of wildfire are more commonly understood in terms of air quality, the vision to offset such effects with the use of prescribed fire has been gaining support. Prescribed fire was conducted on about 8.9 million acres of U.S. forest land in 2014 (Melvin 2015). A similar survey in 2011 reported 7.9 million acres burned (Melvin 2012). This wildfire versus prescribed fire trade-off of effects may lead to increased use of prescribed fire to help reduce wildfire effects which are far more environmentally damaging than just air quality degradation. A key question to be asked is if this opportunity for more prescribed fire is realized, is the wildland management community prepared to proactively manage smoke?

There are some answers to the question about increasing use of prescribed fire. The number of states offering education and training leading to certification of prescribed fire managers increased by 41% between 2012 and 2015 to a total of 24 (Melvin 2015). At this time the survey didn't explicitly explore the smoke management content of the certification course in these states but many are known to cover the topic. Air resource advisors are not currently requested for large multi-day prescribed fires, but they could prove useful in providing information that addresses public and regulatory concerns. Research into wildland fire smoke has dramatically increased across academia and federal agencies. The Fire Science Exchange Network of the Joint Fire Science Program, funded by the U.S. Department of the Interior and the U.S. Department of Agriculture, Forest Service, has supported many scientific papers and webinars focused on smoke issues and has consistently invested in wildland fire smoke-related research (Riebau and Fox 2010).

Being equipped with the best approaches to smoke management and understanding the air quality effects of prescribed fires and how they can be mitigated is central to any fire program. Proactively engaging with the public who may be affected by smoke and understanding their concerns, whether for an asthmatic child or the value they place on unimpaired visibility at their favorite vista, is critical. Demonstrating that, when fires are planned and conducted, smoke is considered and managed will help in addressing air quality concerns while meeting fire objectives. The air quality and smoke management imperative is driven by health and safety risks which will only increase driven by more stringent air quality standards supported by medical findings on the human health effects of air pollution. Increasing effort to protect visibility in class I areas and where smoke is considered a public nuisance are also drivers. And, as has been understood for many years, the increasing number of people living in the wildland urban interface adds another important challenge. Integrating consideration of smoke effects into all facets of wildland fire management is an important step for addressing public and air regulatory concerns.

Where there is smoke there is fire, and so fire management includes addressing air quality risks caused by smoke. This is especially true when using prescribed fire. For prescribed fire, the consideration of smoke is critical for public and regulatory credibility, from the planning of a prescribed fire through its implementation including contingency measures to address unplanned effects. All of these air quality factors will drive the focus to respond to the effects of wildland fire smoke more than ever. Whether smoke effects downwind of a wildfire are addressed with messages developed by an air resource advisor or when conducting a prescribed fire while utilizing Basic Smoke Management Practices, addressing smoke effects will need to become integrated into every facet of wildland fire management. A lynchpin to addressing the future role of fire, whether through wildfires or use of prescribed fire, will depend upon land managers proactively responding to public concerns about air quality.

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1.2 The Need for Prescribed Fire

Mark Melvin and Dennis Haddow

Fire is a natural ecological process that has played a key role in shaping many North American landscapes for millennia. Before European settlement, about 60% of the North American landscape was dependent on frequent surface fires. These fires were the result of both natural ignitions or anthropogenic uses of fire for a variety of reasons including driving game animals, managing crops, and clearing trails for travel (Johannessen *et al.* 1971, Lewis 1973). Whatever its source, fire was the primary disturbance that shaped and maintained plant communities across the continent. Today, prescribed fire is the surrogate for historical fire and is necessary for maintaining the ecological integrity and sustainability of many landscapes. Prescribed fire is a fire intentionally ignited by management actions in accordance with applicable laws, policies, and regulations to meet specific objectives. It is applied in a professional manner to fuels on a specific land area under selected weather conditions to meet predetermined, well-defined objectives. The degree of difficulty in implementing an individual prescribed fire is often determined by its location and complexity. Regardless of either, prescribed fire planning and implementation should be conducted in a socially and politically acceptable manner.

When applied appropriately, prescribed fire provides many benefits to the environment as it maintains wildlife habitat; plant species composition and forest structure; water and soil quality; and nutrient cycling. Besides these benefits, the modern-day use of prescribed fire has societal benefits because it reduces hazardous fuel loads, protects communities from wildfire, improves forage for grazing, controls some forest diseases, expands options for management of threatened and endangered species, and can make both natural and artificial forest restoration easier. Perhaps the most important public benefit of healthy forests is their improved resiliency to climate change and drought (Mori *et al.* 2013).

The specific objective(s) for any well-planned prescribed fire is determined by the land owner/land manager and the resources being managed. Although prescribed fires may only have a single resource objective, they typically have multiple benefits. For example, a well-planned prescribed fire can reduce hazardous fuels while also improving wildlife habitat. Another prescribed fire intended to maintain wildlife habitat can help shift and restore forest structure. A land manager who is familiar with the effects of fire on the ecosystem being managed, can skillfully and artfully apply fire at the right time and intensity to meet well defined resource management objectives.

Millions of acres in the United States are treated successfully each year with prescribed fire; however, improper planning or inappropriate or careless use of prescribed fire can have unintended and damaging effects on the resource being managed. In extreme cases, the effects are catastrophic, and damage public trust of fire as a useful resource management tool. If either planning or implementation is inadequate, prescribed fire can severely affect public health and safety, cause property loss, and damage natural resources. Prescribed fire is a complex land management tool, and should be used only with adequate planning and by trained land managers under favorable, conservative conditions.

The Role of Prescribed Fire in Minimizing the Effects of Wildfire

Prescribed fire is often the most cost-effective tool available to land managers for reducing fuel loads and minimizing the threat and severity of wildfire. Although the number of large wildfires has been decreasing (NIFC 2014a), the acreage burned by large wildfires is increasing (figure 1.2.1).

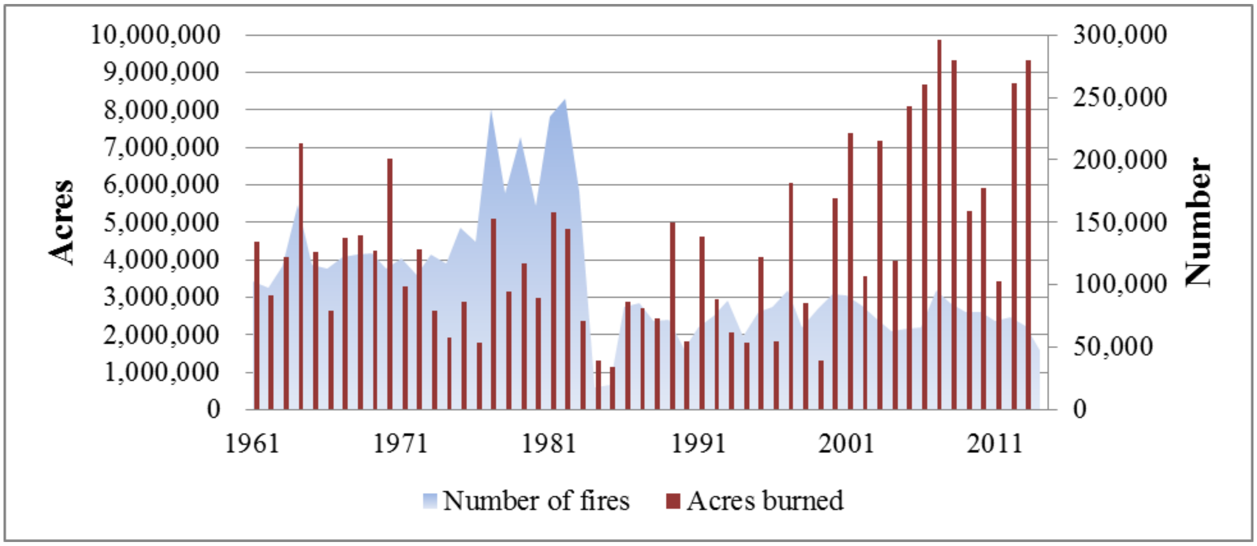

Figure 1.2.1. From 1961 to 2013 the number of individual fires decreased while the total acres burned increased (NIFC 2014a).

In modern U.S. history, application of wildfire suppression policies has changed preexisting fire regimes (occurrence, frequency, size, and severity). In the absence of fire, natural vegetation succession has been altered; thus, changing forest structure and increasing the risk of catastrophic wildfire. Fighting wildfires in the 21st century costs taxpayers billions of dollars annually; in fact, annual suppression costs have been increasing dramatically (figure 1.2.2). During the 1980s the federal firefighting budget was in the range of $200 million to $300 million, only topping a $500 million dollars during the massive wildfires in Yellowstone National Park in 1988. In 2000, the bill exceeded $1 billion for the first time. In 2013, federal land managers spent $1.7 billion fighting wildfires (NIFC 2014b).

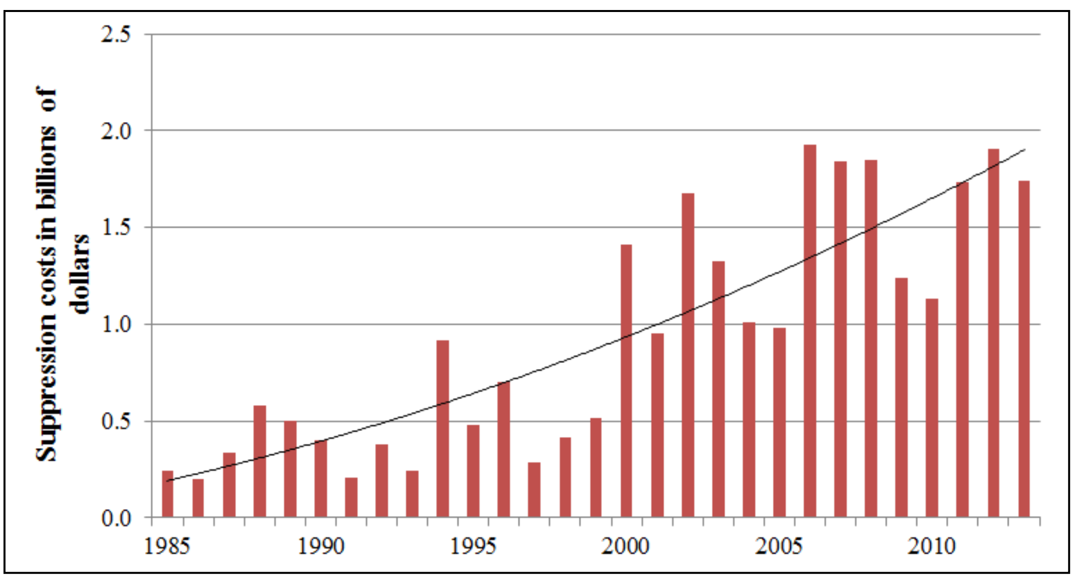

Figure 1.2.2. Increases in federal fire suppression costs from 1985 through 2013 (NIFC 2014b).

These figures do not include residual damage costs to the public. When considering the cost of damage to public and private property, disruptions to and displacement of communities, watershed damage, short and long-term public health concerns, air pollution, soil degradation, and other resources costs can be at least 3-20 times greater than the firefighting budget itself. (Fann *et al.* 2018, Western Forestry Leadership Coalition 2009) Wildfire has the greatest potential of any air pollution source in the country to rapidly release high concentrations of particulate matter and degrade air quality. Concentrations of air pollutants from wildfires have been measured at levels significantly above the established EPA public health standards and can be life-threatening for sensitive individuals, such as the very old, the very young, and those with preexisting medical conditions.

There are definite air quality tradeoffs between wildfires and prescribed fires. Although prescribed fires do emit smoke, it is possible to choose the timing and dispersion of emissions so that harmful effects on public health and safety can be minimized. By applying emission reduction techniques during planning and implementation of a prescribed fire, it is possible to significantly reduce the amount of smoke produced as compared to what would have been emitted by a wildfire burning over the same landscape (See Chapter 4.2 Techniques to Reduce Emissions from Prescribed Fire).

The Role of Prescribed Fire in Maintaining Ecosystem Function and Health, and Providing Societal Benefits

Prescribed fire is an important tool for maintaining natural ecosystems as well as providing societal benefits such as improving wildlife habitat, recovery of threatened and endangered species, disease control, etc. The important natural role of fire in ecosystems has been well documented and is an area of continuing research. For example:

Disease Control

Certain pathogens that reduce growth in pines and other species can be controlled, or eliminated, by the use of prescribed fire (Phelps *et al.* 1978). One example of this is brown-spot needle blight and the longleaf pine (*Pinus palustris*). Only longleaf pine needles in the seedling stage are affected by the blight, and longleaf pine seedlings greater than 1 year old are fire tolerant. This fire tolerance is a unique characteristic among all of the Southern pines, and allows the affected needles to be burned away. Once the diseased needles on young pine trees have been consumed by fire, the blight is controlled, and the seedlings can continue to store carbohydrates in their roots.

Maintaining Wildlife Habitat

The major effects of fire on wildlife are indirect and pertain to changes in food availability and groundcover structure. Prescribed fires can increase the amount and availability of high-quality browse, thereby improving forage habitat for deer and other wildlife. Bobwhite quail (*Colinus virginianus*) and turkey (*Meleagris spp.)* favor early successional food species and semi-open or open forested conditions that can be created and maintained by burning (Main and Richardson 2002, Rosene 1969, Stoddard 1931). In fact, many habitats that bobwhite quail avoid, or are entirely absent from, are areas that have not burned in the previous 3 years. Use of prescribed fire supports habitats for animals such as big horn sheep (*Ovis canadensis*) by providing open areas for grazing where they are not as vulnerable to predators (Hobbs and Spowart 1984) (figure 1.2.3).

It also improves habitat for marshland birds and other animals by increasing food production and availability.

Plant Diversity and Response

Figure 1.2.3. Bighorn Canyon National Recreation Area personnel working on a prescribed fire to restore bighorn sheep habitat. Photo courtesy of the National Park Service.

Fire can affect plants positively or negatively depending on the species and fire return intervals. In ecosystems with low intensity and high fire frequencies, fire is essential to maintain natural plant communities. These systems tend to be the most biologically rich in North America. The longleaf pine ecosystem of the southeast coastal plain is a good example; over 50 species per square meter have been documented, making it the most bio-diverse ecosystem outside of the tropics (Peet and Allard 1993). Some plants are so sensitive to fire that they cannot carry out their life cycle in its absence. Wiregrass (*Aristada stricta*) is found throughout a large portion of the longleaf eastern range and will not flower and set viable seed unless burned during the growing season.

In the West, lodgepole pine (*Pinus contorta*) sheds cones that are glued shut with resin. Its seeds cannot be released until this resin is melted by the heat from a fire (Schoennagel *et al.* 2003) (figure 1.2.4). Leaves of chaparral are coated with flammable oils which encourage hot fires required for germination of their heat-activated seeds (Countryman and Philpot 1970, Keeley 1987). Ponderosa pine (*Pinus ponderosa*) grows a thick, corky bark and sheds lower branches to protect itself from ground fires that historically kept the understory clear of competing brush and conifers (Graham and Jain 2006).

Figure 1.2.4. Lodgepole pine cones are glued shut with sticky resin that is melted by the heat of a fire so seeds can be released.

Recovery of Threatened and Endangered Species

Many animal species are dependent on fire and have had their habitat reduced because of fire exclusion. One example, the Kirtland's warbler (*Setophaga kirtlandii*) (figure 1.2.5) is often called the "bird of fire" because of its strict reliance on the fire-dependent jack pine forest for nesting (USFWS 2012). Kirtland's warblers are specific about where they nest only utilizing large stands of dense jack pine (*Pinus banksiana*) trees that range between 5 and 16 years of age.

The advent of modern forest fire suppression has brought about significantly smaller and much less frequent fires which has degraded this habitat structure. Reintroducing prescribed fire improves habitat and helps to restore Kirtland's warbler populations.

Figure 1.2.5. Kirtland's Warbler (*Setophaga kirtlandii*) relies upon fire-dependent pine species for habitat (US Fish Wildlife Service 2012). Photo courtesy of Joel Trick, US Fish and Wildlife Service.

Summary

Fire is inevitable, irreplaceable, and essential to the functioning of many ecosystems in the United States. Plant and animal species depend on fire for their survival. Fire managers must consider a complex web of policy, legal statutes, and liability concerns, as well as public safety, health, and acceptance; however, when applied appropriately, prescribed fire can benefit ecosystems and society without the potentially catastrophic effects of wildfire.

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1.3 The Effects of the Social-Wildland Interface on Wildland Fire Management

Thomas Zimmerman

Wildland Fire Management and Societal Expansion—Embracing Growth and Maintaining Balance

Wildland fire management is undoubtedly the single natural resource management program with the highest risk, most complexity, and greatest potential for serious negative outcomes. Successful fire program management requires careful planning and sound implementation. Wildland fire management programs typically involve: (1) suppression of wildfires, (2) management of naturally ignited wildfires, and (3) application of planned prescribed fires.

Wildland fire management program development has taken place in a highly dynamic environment. Expanding objectives, evolving goals, emerging strategies and tactics, developing policy, improving scientific and technological information, and increasingly inflexible expectations have framed program growth. Fire management has steadily progressed from its early focus on fire control with the goal of total fire exclusion, into today's blend of application of prescribed fire, and flexible management of wildfires that allows suppression to include protection and resource benefit objectives to be achieved concurrently (figure 1.3.1).

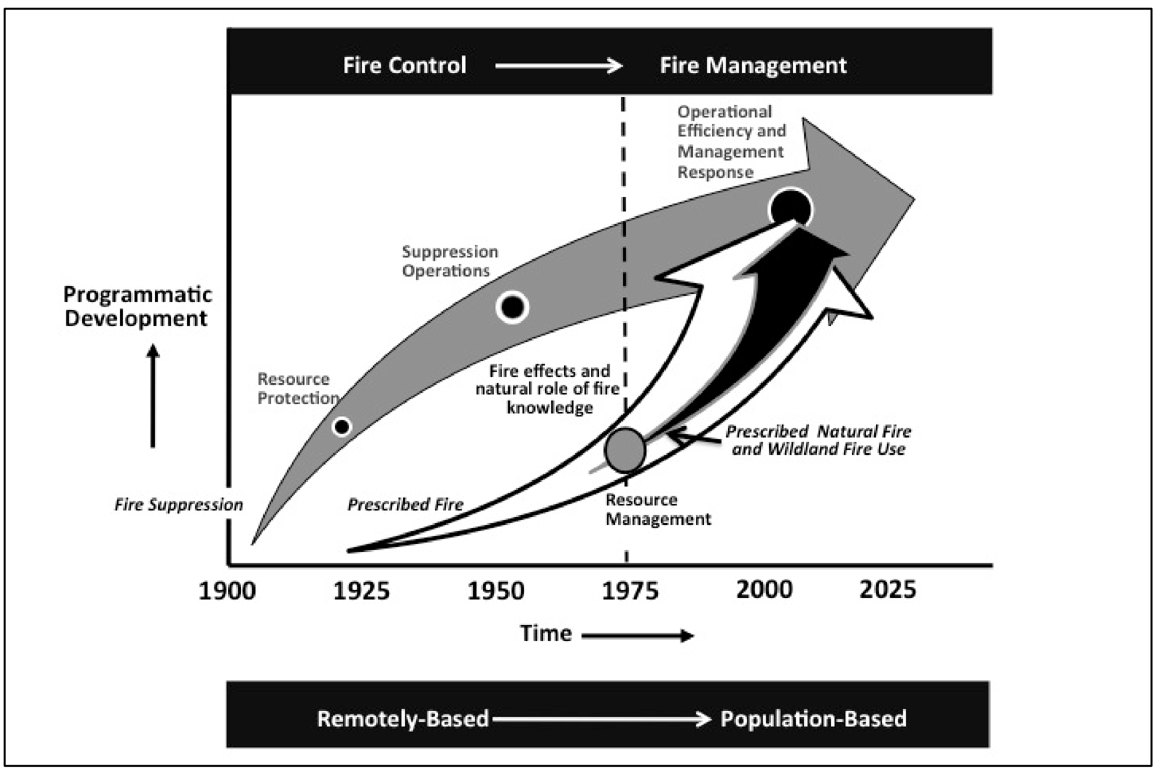

Figure 1.3.1. Wildland fire management programs have evolved from a primarily suppression approach in the 1900s to the mix of suppression, prescribed fire, and use of natural fire that we see today (modified from Zimmerman 2011).

The primary emphasis of early fire management was resource protection. As fire programs matured, suppression operations became increasingly important and wildfire suppression methods became more organized and refined. Soon, prescribed fire, ignited by management actions to meet specific beneficial objectives, began as an important fire program component. But, for some time, prescribed fire remained only a subordinate component of the overall wildfire control program. The management of smoke to minimize effects on air quality was considered part of natural resource management. At this time the majority of fire management activity was far away from populated areas and garnered little if any public scrutiny. Smoke management concerns and activities received only cursory attention.

This focus on resource management promoted greater importance and acceptance of fire as a tool, and served to accelerate knowledge of fire effects, fire history, and the natural role of fire and allowed the introduction of the use of naturally ignited wildland fires for beneficial objectives (formerly called prescribed natural fire and wildland fire use). These activities all led to recognition of the need for a more integrated resource management program. Prescribed fire and wildfire suppression eventually converged into the single program of fire management (DeBruin 1974, Gunzel 1974, van Wagtendonk 2007) (figure 1.3.1).

Factors fueling this change are related to program scope and magnitude. As the fire environment, social and political expectations, ecological concerns, economic concerns, and physical capabilities expand; challenges and risks inescapable to wildland fire management are increasing in complexity and extent. Proximity to wildland urban interface areas, critical infrastructure, (power grids, energy production and transport facilities, drinking water supplies); visibility from communities, highways, and recreation areas; and readily accessible information from commercial and social media place greater attention on nearly all fires and management response activities. These elements can limit management options, potentially conflict with ecological objectives, and contribute significantly to program complexity.

Knowledge of the natural role of fire and fire ecology as well as a century of fire management experience shows us that fire exclusion is not a viable long-term option. It is clear that as challenges of the future become more difficult to address, past fire management practices may not be effective. Changing processes and improving organizational effectiveness have been suggested as necessary to keep pace (NWCG 2009). As fire management moves into the future, focus on improving program efficiency while accomplishing both protection and resource management objectives will be needed. Wildland fire must be a component of wildlands, but it must be managed, balanced with societal needs, and integrated with the use of non-fire fuels management techniques. Of particular importance is smoke management. Strategies and tactics applied in response to smoke management requirements must be balanced with careful consideration of ecological, social, economic, and political effects of wildland fire management.

The Framework for Wildland Fire Management

Wildland fire management is subject to a comprehensive set of guiding statements and directions that dictate both management and incident requirements. These statements consist of mission statements, goals, guiding principles, agency rules, doctrinal principles, objectives, and requirements. For federal agencies, this guidance comes in the form of agency mission and program mission statements, *Review and Update of the 1995 Federal Wildland Fire Management Policy* (USDI-USDA 2001), *Fire Suppression: Foundational Doctrine* (Hollenshead *et al.* 2005), agency policy and statutes, and land and resource management objectives and requirements. The amount of detail and direction in the various guiding documents varies across all land management agencies and organizations, including state and local land managers; but, a common message is that fire is recognized as a highly important ecological factor as well as a social issue. Key guidance statements provide increasing endorsement and advocacy for moving wildland fire management beyond the traditional suppression approach and further integrating it into land and resource management.

Fire in Wildlands

Fire occurrence, frequency, and severity is influenced by short- and long-term weather, climatic variations, the physical setting (dominant topographical and terrain features), and fuels (composition, structure, amount, moisture content). These factors interact to influence fire behavior, fire location and timing, and how fire influences components of the natural environment.

Wildland fires affect all elements of the wildland environment and the social-wildland interface. How fire affects environmental components varies considerably. Location and timing are often most important in determining specific effects. Wildland fire can generate ecological effects that can be beneficial or detrimental, visual effects that can be minimal and even mesmerizing or very disturbing, and social effects that are damaging or disastrous.

Prior to organized wildfire suppression in the United States, temperature and precipitation patterns, natural (lightning and volcanoes) and human sources were responsible for fire ignition in wildland ecosystems. Cultural burning practices of Native Americans before Euro-American settlement were responsible for most fire activity in many vegetation types (Barrett and Arno 1982, Stewart 1951). Lightning-ignited fires, although always present, were more variable and dependent upon temperature and precipitation patterns. More frequent lightning ignitions occurred during periods of higher temperatures (Swetnam 1993). The constant historical presence of wildland fire is documented through charcoal layers in lakes and bogs, fire scars of fire tolerant trees, and in the morphological and life history of many native plants and animals (Hardy *et al.* 2001).

Interrelationships of Fire and the Natural Environment

Basic interrelationships of wildland fire and the natural and social environment can be defined through four fundamental principles including:

- Differences in fire behavior and distribution affect natural and invasive species diversity and vegetation.
- Fire affects nearly every ecological process in an ecosystem including regeneration, growth and mortality, decomposition, nutrient cycles, resilience to climate change, response to insects and disease, and hydrology.
- Fire affects societal values and can lead to public scrutiny and concern, and ultimately alter wildland fire program requirements.
- Human use of fire leads to effects on ecosystems that are both intended and unintended.

Fire as a natural process is influenced by a variety of factors including fire frequency, fire intensity, and severity; how fires burn through vegetation strata or the type of fire; and area burned by fire. Fire frequency is the average number of years between fires. Fire intensity is the rate at which a fire is producing thermal energy. Severity is the effect that a fire has on the materials (or fuels) it is burning.

The structure and properties of fuels, including live or dead state and horizontal and vertical continuity, strongly influence the initiation, propagation, and behavior of fire. Fuelbeds consist of as many as six strata: tree canopy; shrubs/small trees; low vegetation; woody fuels; moss, lichens, and litter; and ground fuels (duff and humus) (Sandberg *et al.* 2001). Fires burn in three forms: ground, surface, and crown fires.

Ground fires or residual smoldering fires are an important but frequently overlooked component of wildfires (Frandsen 1991). Fuels consumed in this type of burning consist of soil organic horizons (duff); mosses, lichens, and litter; and woody fuels along the ground like sound and rotten logs, stumps, and wood piles (figure 1.3.2a). This type of burning takes place slowly, can persist for long periods of time (weeks or months), and can result in sustained smoke production as well as harmful ecological effects. These fires reduce organic matter and can damage or kill tree roots, generate high levels of soil heating, and cause formation of hydrophobic layers on soil surfaces that resist water infiltration and promote soil erosion.

Figure 1.3.2. Examples of fire types and intensity: (a) ground fires (can be low intensity but long duration), (b) low intensity surface fire, (c) moderate to high intensity surface fire with some tree crown involvement, and (d) high intensity stand replacing crown fire. Photos courtesy of: US Forest Service, Boise National Forest (a,c,d); and US Forest Service, Gila National Forest (b).

Surface fires burn in surface fuels such as low vegetation and woody fuel, but also moss, lichen, and litter. This fuel complex generally supports flaming combustion and exhibits highly variable flame lengths, spread rates, and energy release. Surface fires can ignite ladder fuels that carry fire into tree canopies. Surface fires reduce low vegetation, remove competing vegetation, reduce downed dead fuels, and can reduce the prospect of future fires that may burn at higher intensity levels and expand into more intense and severe fires (figure 1.3.2b).

Crown fires burn through the crown fuel stratum (figure 1.3.2c, 1.3.2d). Their duration and extent is dependent on spatial continuity and density of tree canopies, wind, physical slope and aspect, air and fuel temperature, and relative humidity. Crown fires can burn as fires that consume crown fuels of single or groups of trees without spreading from crown to crown. High intensity crown fires can be limited to scattered patches of trees but ignited by wind driven firebrands under high wind conditions; or through tree crowns concurrently and with dependence on surface fires. Crown fires can also burn through tree crowns independent of surface fires, nearly always in the presence of strong winds. Crown fires burn through all fuel strata at high intensity levels and can remove much, or all, of the tree canopy.

Crown fires cause the most dramatic immediate visual changes. These fires are normal in some vegetation types. However, in other vegetation types, crown fires are considered to be a huge threat to ecological values as well as human values. In areas near urban improvements, high intensity crown fires—regardless of potential ecological benefits or negative effects—pose great threats to societal infrastructure and human health and safety. Because crown fires generally burn a large area in a single or a few burning periods and consume a lot of fuel, they generate large quantities of smoke.

The area burned by wildfires historically is highly variable. Periods of higher precipitation result in greater production of fine surface vegetation fuels which then facilitate wider spread of fires during intermittent dry years (Swetnam 1993). In other areas, terrain features and vegetation diversity create situations that constrain fire sizes. During the 20th century, fire prevention and suppression goals resulted in reduction of accidental human-caused fires and suppression of most natural ignitions at very small sizes. This in turn has had an unintended consequence of altering vegetation and fuel complexes, affecting ecosystem health, and increasing the likelihood of large, more intense wildfires under the right combination of conditions.

Not restoring fire's role as a natural process across landscapes has brought increased threats to natural and cultural resources and community infrastructure, increased risks to firefighters, and the large size and resultant volume of burning fuel brought large scale smoke management concerns. This situation is occurring worldwide; figure 1.3.3[1] shows some recent examples of large scale burning in Idaho and Arizona, USA; Mexico; and Portugal; and associated smoke production.

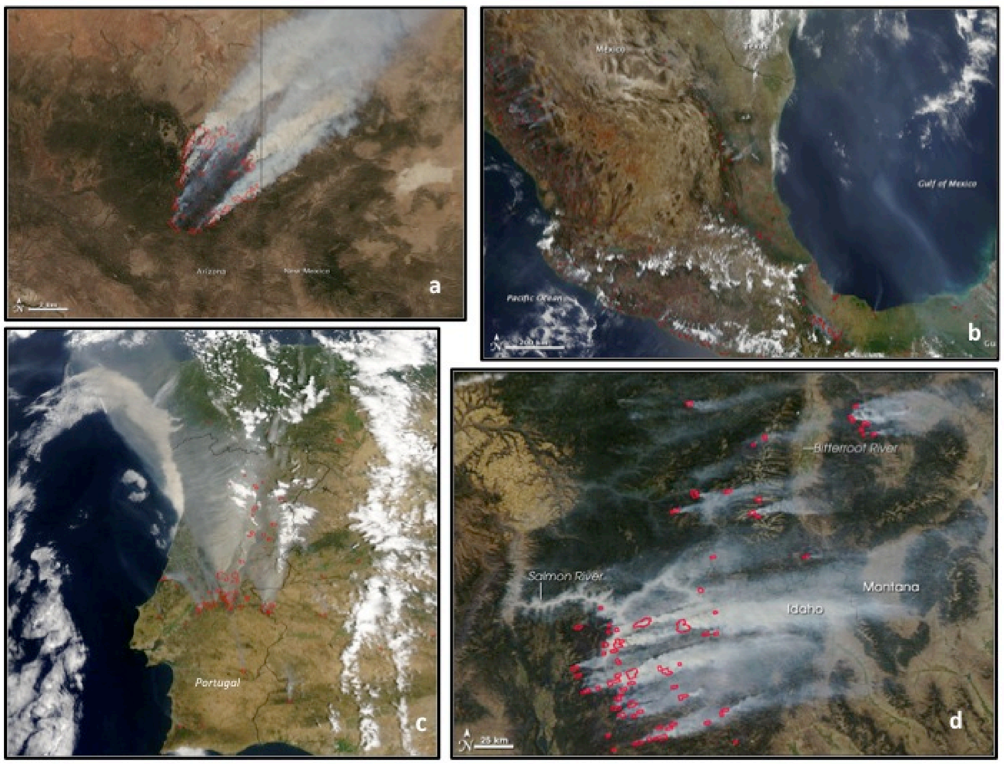

Figure 1.3.3. Large scale wildfire burning and associated smoke production at various locations around the world over recent years (a) Arizona in 2011; (b) Mexico in 2011; (c) Portugal in 2003; (d) Idaho and Montana in 2007.

Fire influences a web of ecological processes that affect vegetation growth and survival (Brown 2000). Ecological effects of fire can be difficult to evaluate. Some are obvious and immediately visible, but other effects may be quite subtle and slow to appear. Characterizing fire effects into first and second orders is a means to help understand this web of processes. First order effects are the direct effects of fire such as soil heating, tree mortality, and smoke production. Second order effects are more indirect and not totally a result of fire but the result of the combination of fire and interactions with other processes (Brown 2000) such as regeneration, nutrient cycle changes, and wildlife habitat and activity changes.

[1] Imagery provided courtesy of NASA Earth observatory and Jesse Allen, by using data provided courtesy of the University of Wisconsin's Space Science and Engineering Center MODIS Direct Broadcast system (photo a); Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC (photo b); Jacques Descloitres, MODIS Rapid Response Team at NASA GSFC (photo c); MODIS Rapid Response Team, Goddard Space Flight Center (photo d).

The collective state of knowledge of ecological effects of fire, the natural role of fire, and fire history has never been greater. The body of science dedicated to these topics has expanded considerably in the last 50 years and information can be found in numerous textbooks, government publications, and knowledge syntheses (Agee 1993, Arno 1980, Biswell *et al.* 1973, Brown and Smith 2000, Cooper 1960, Covington and Moore 1994, Swetnam 1993, Wright and Bailey 1982).

Fire regimes are used to describe general characteristics of fires in specific vegetation types. They describe aspects of typical fires such as intensity, how it burns (ground, surface, or crown), frequency, season, size, and area burned. From this information, a useful perspective on the historical occurrence and function of fire can be developed. Such a perspective can aid managers in developing management strategies and management plans, help communicate the historical role of fire to both technical and non-technical audiences (Brown 2000), and can establish a solid frame of reference for ascertaining shifts in fuel and vegetation complexes and subsequent fire activity because of land management activities.

Fire regimes have been described and re-defined over recent years based on similar, but slightly different criteria. A comparison of fire regime classifications by numerous authors is available in Brown (2000). Schmidt *et al.* (2002) identified five fire regimes defined by fire frequency and severity which is used currently as a reference for making comparisons against current conditions. They developed three fire regime condition classes (FRCCs) (table 1.3.1), which represent qualitative descriptions of the degree of departure from historical fire regimes. Such departures could possibly result in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings. This condition class system is useful for land management planning and communication on the state of current conditions. Specifically, this information can serve as an ecological reference for identifying needs and opportunities to treat vegetation and fuel conditions to address natural resource, political, and social concerns.

Table 1.3.1. Fire regime condition classes (from Schmidt *et al.* [2002]).

Condition class	Fire regime
Condition class 1	Fire regimes are within historical ranges and the risk of losing key ecosystem components is low. Vegetation attributes (species composition and structure) are intact and functioning within historical ranges.
Condition class 2	Fire regimes have been moderately altered from their historical range. The risk of losing key ecosystem components is moderate. Fire frequencies have departed from historical frequencies by one or more return intervals (either increased or decreased). This results in moderate changes to one or more of the following: fire size, intensity and severity, and landscape patterns. Vegetation attributes have been moderately altered from their historical range.
Condition class 3	Fire regimes have been significantly altered from their historical range. The risk of losing key ecosystem components is high. Fire frequencies have departed from historical frequencies by multiple return intervals. This results in dramatic changes to one or more of the following: fire size, intensity, severity, and landscape patterns. Vegetation attributes have been significantly altered from their historical range.

Fire Regimes

A natural fire regime is a general classification of the role fire would play across a landscape in the absence of modern human intervention but including the possible influence of aboriginal fire (Brown and Smith 2000). Five discrete, mutually exclusive fire regime groups have been defined, each describing a combination of fire frequency and severity (below). These groups are used in landscape assessment, and for inferring the frequency and severity of fires to calculate fire regime condition class.

Group	Frequency	Severity	Severity Description
I	0-35 years	Low/mixed	Generally ≤ 25% dominant overstory replacement.
II	0-35 years	Replacement	Replacing 75% of the dominant overstory.
III	35-200 years	Mixed/low	Mixed severity, can include some low severity
IV	35-200 years	Replacement	High-severity fires
V	≥ 200 years	Replacement/ any severity	Generally replacement, can include any severity

For additional information on Fire Regime Groups or Fire Regime Condition Class refer to Barrett *et al.* (2010)

Interrelationships of Fire and the Social-Wildland Interface

Human management of fire, regardless of specific objectives, wields intended and unintended influence on ecosystems. This, in turn, stimulates action, sometimes difficult to control and occasionally producing unrealistic or dramatic swings in focus.

Human activity, such as expansion of urban developments, general increases in societal expectations, and management practices (including land management policies, fire suppression, timber harvesting, livestock grazing, introduction and establishment of exotic plant species, and introduced insects or diseases) in combination with long-term droughts and climate shifts is affecting ecosystems around the world. Ecosystems are experiencing loss of species diversity, decreases in site growth quality, expansion of the wildland urban interface, increases in size and severity of wildfire, and altered fire regimes.

Figure 1.3.4. Mountain pine beetle-caused mortality in Colorado lodgepole pine forests (US Forest Service, Rocky Mountain Research Station).

Loss of species diversity and site degradation are resulting from extensive forest mortality from epidemic levels of insects and diseases. Long-term drought and warming temperatures may be a major contributor to this situation. Over 20 years ago, a forest health emergency was identified in parts of the Western U.S. due to tree mortality (American Forests 1992). This situation has continued to worsen and native pine forests from New Mexico to British Columbia are being killed at record levels by mountain pine beetle infestations (Robbins 2008). Recent mountain pine beetle outbreaks in Colorado are threatening the majority of the state's lodgepole pine (*Pinus contorta*) forests (figure 1.3.4). The area burned by wildland fire in the United States could be increasing every year (NWCG 2005). Acres burned by wildfire in the past are difficult to estimate as reporting, data availability, and agency protocols have been inconsistent. Figures 1.3.5-1.3.7 highlight apparent trends in burned area for the period from 1916 to 2000. Annual acres burned follow a very discernible trend (Figure 1.3.5) (Hardy *et al.* 2001). Acres burned annually by wildfire trends from a moderately high level early in the 20th century to its lowest level roughly from 1940 to 1980 and then shows an increasing trajectory through the end of the century. In figure 1.3.6, national data collected at the National Interagency Fire Center (NIFC) display more variability of burned acres since 2000 in both Alaska and the contiguous United

States. In figure 1.3.7, NIFC data averaged over five-year periods since 1990, show what appears as an increasing trend in burned acres.

There are strong indicators that average area burned in the contiguous United States before European settlement could have been much higher than estimates for the last 100 years; possibly as much as ten times higher (Leenhouts 1998). While acres burned by wildfire have increased over the last three decades, this amount may still be much lower than historical levels. Increasing burned area brings the

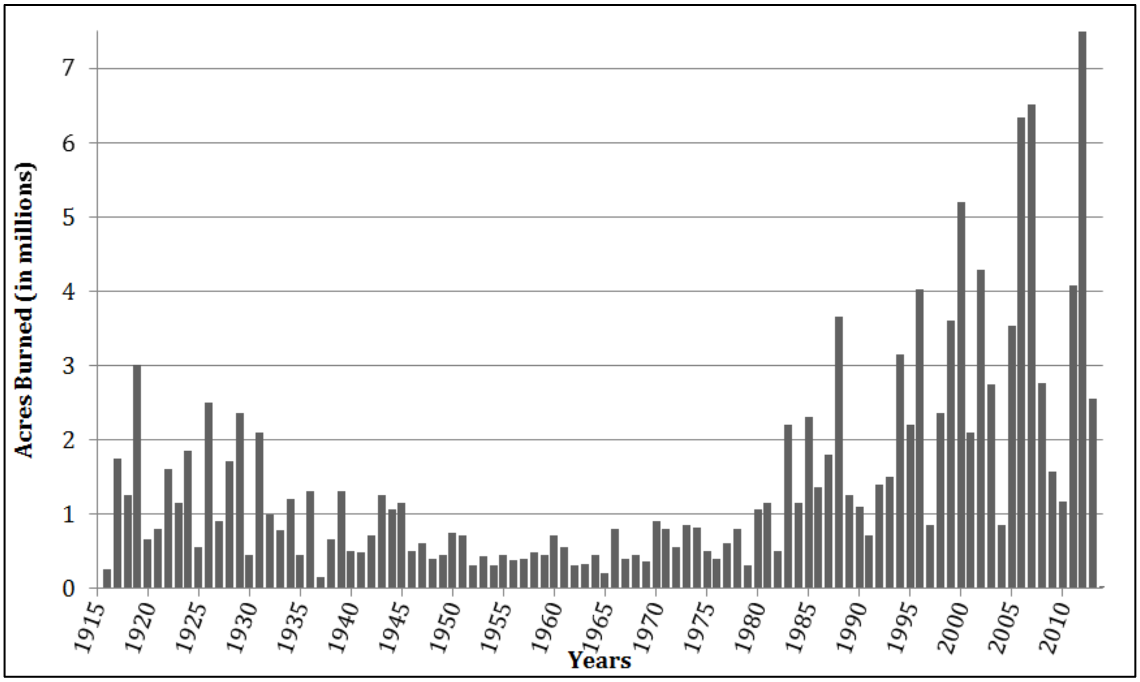

Figure 1.3.5. Annual burned acres for western United States from 1916–2013 (Image courtesy of Professor Jay O'Laughlin, University of Idaho Department of Conservation Social Sciences).

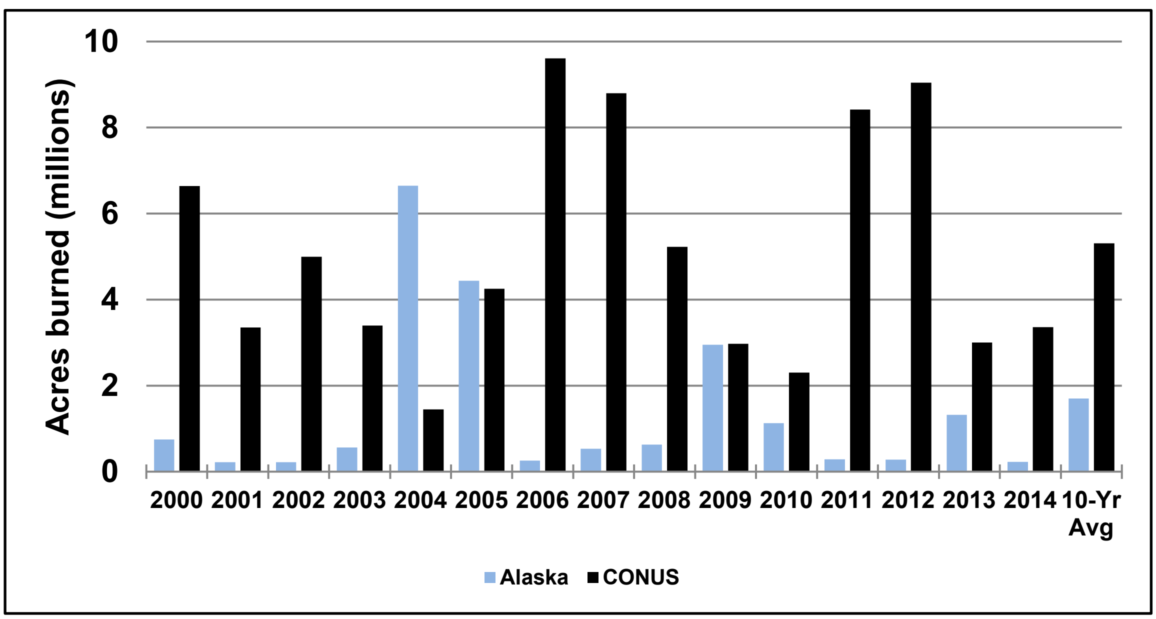

Figure 1.3.6. Annual burned acres for Alaska and contiguous United States (CONUS) for 2000–2014 (source: National Interagency Fire Center).

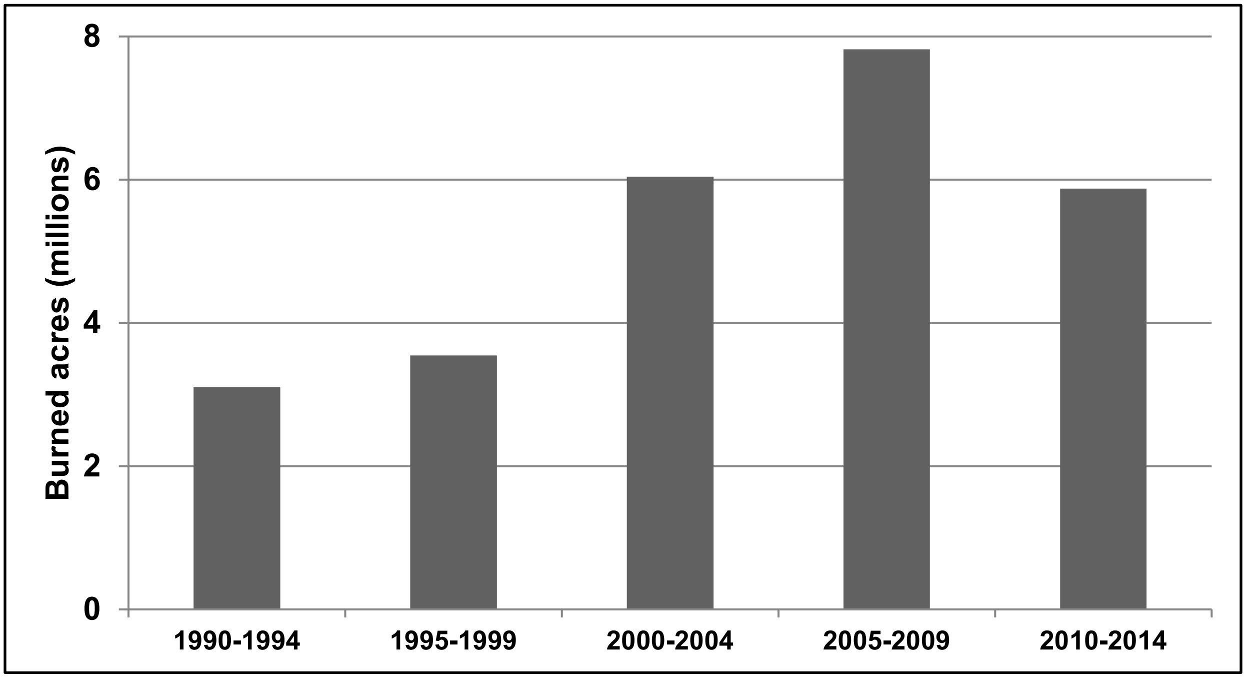

Figure 1.3.7. Five-year running average of wildfire burned acres from 1990–2014 (NIFC 2014). Data represent information from different sources compiled over time under varying reporting requirements and procedures that present differences in data presentations.

potential for escalating effects on societal values but is also alarming from an ecological standpoint in that, burned areas are still not reflecting the level needed for restoration of fire's natural role.

Even though wildfire numbers and acreages affected show variable trends since 2000, individual wildfires in specific dry years have reached markedly larger sizes. Wildfires in Florida in 1998 affected larger areas than had been previously experienced and caused evacuations of entire counties for personal safety. The largest wildfire on record in Arizona occurred in 2002, but then was surpassed in 2011. The largest wildfire on record in Oregon occurred in 2012. The largest wildfire in Colorado occurred in 2002 with the second and third largest occurring in 2012. The largest wildfire on record for New Mexico occurred in 2011 and was surpassed in 2012. Large wildfires burned in Georgia in 2002, 2007, and 2010. The Rocky Mountains of Idaho and Montana experienced large and widespread wildfires in 2000, 2003, and 2007. California experienced large and sometimes devastating wildfires in 2003, 2007, 2008, and 2013. The largest wildfire in Washington history occurred in 2014. Texas has seen a previously unparalleled scale of burning in 2006 and 2010-2011. Individual wildfire sizes have expanded by a factor ranging from 10 to 100 in specific areas.

Population growth and house construction continue to expand the wildland urban interface (WUI). This trend is significant in that housing construction rates inside the WUI have nearly tripled those outside the WUI (NWCG 2009). For the next decade, a slower rate of growth in the WUI is expected; however, growth will still occur and be focused on the southern and western portions of the United States, locations where wildland fire situations are worsening (NWCG 2009).

Changes in species diversity, increases in non-native species, widespread wildfire suppression, changing fuel complexes, expanding WUI, and shifts in fire frequency, fire numbers, area burned, and severity are directly altering natural fire regimes. Altered fire regimes are the principal force affecting vegetation structure, composition, and biological diversity of plant communities covering over 350 million acres in the United States (Ferry *et al.* 1995). For nearly 1.25 billion acres of federal and non-federal lands in the contiguous United States, 48 percent are within the historical fire frequency range (condition class 1), 38 percent are moderately altered from the historical range (condition class 2), and 15 percent are significantly altered (condition class 3) (Schmidt *et al.* 2002). The moderately and significantly affected areas comprise over 650 million acres (Schmidt *et al.* 2002), now considerably higher than was projected by Ferry *et al.* (1995). Figure 1.3.8 shows Schmidt *et al.* (2002) relative areas in each fire regime condition class by fire regime group.

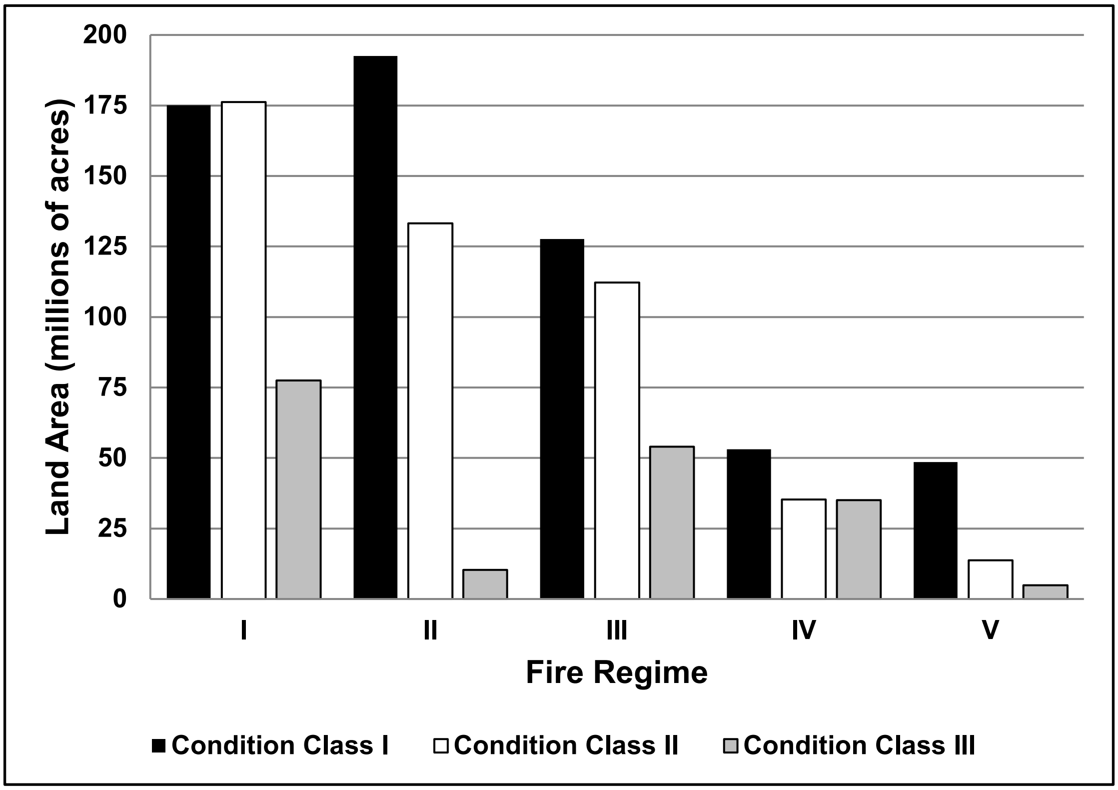

Figure 1.3.8. Breakdown of fire regime condition class areas by fire regime groups (from Schmidt *et al.* 2002).

Wildfires are becoming more numerous and occurring closer to developed areas resulting in increased ecological impacts and smoke production. The general public largely believes that wildfire is a threat that should not be tolerated on the landscape. As a result, society tends to react strongly to large and severe wildfire events. When these fires destroy personal property, threaten public health, and affect societal infrastructure, swift reactions are likely warranted. However, applying this perspective to all wildfires does not serve land management objectives and clearly results in some undesirable effects.

Land managers need to engage in better, more credible, stronger, and more rapid communication with the public. The public demands information. Internet communications, social media, and other modern information dissemination methods facilitate rapid and widespread communication. Information dissemination methods now exist that represent significant opportunities for land managers to manage communication and message content faster and reach more audiences. Also, the public, as a stakeholder, needs to be engaged (USDI-USDA 2014) in planning, zoning, and personal property management.

Development of a National Cohesive Wildland Fire Management Strategy is an attempt to recognize the cultural, responsibility, mission, funding, and perception differences across the country (USDI-USDA 2014). This effort seeks to address wildfire not only as an individual fire management, fire operations or wildland urban interface issue, but also as a larger, more comprehensive land management and societal issue. Awareness of the lack of past active management; the need for a better understanding of the natural role of fire in landscapes; health, social, and regulatory challenges to active landscape management; and the impacts of fire on air quality, water resources, and commodity and community values are the basis for this effort. It represents leading-edge efforts as it has a primary goal of ensuring equal consideration of the human dimension and physical and ecological science of fire (USDI-USDA 2014).

Summary

This chapter describes how our view on wildland fire has progressed from its historic role as an important and consistent ecological factor to a social factor often seen as a nuisance and threat. Currently, wildland fire is viewed as good and as bad; important to natural ecosystems but also a highly-scrutinized threat to human values. No longer is fire management based on a fire-vegetation dynamic only; it is now affected by occasionally conflicting social, political, and ecological influences.

Wildland fire management has progressed over time to a flexible and multi-faceted system with a range of options available for accomplishing management objectives. The important role of fire in ecosystems has not changed but management of fire, especially efforts to exclude fire from wildlands, has resulted in changes in fire frequency and severity, alterations of vegetation and fuel complexes, and shifts in ecological processes. In many instances, the lack of fire is drastically affecting ecosystem function and health. And now, when wildfires occur, they are often larger and more severe than in the past. Societal understanding and requirements around wildland fire, although progressing, is still struggling with variable acceptance levels strongly influenced by conflicts with other objectives.

To effectively shape an efficient, mature, and proactive wildland fire management program for the future, social, political, and ecological concerns must be addressed and future programs must be dynamic and responsive. Fire management at the landscape level will become more important and partners including federal land management and regulatory agencies, tribes, states, counties, local governments, the private sector, and the public must be involved. Smoke management must be considered in planning processes as challenges of protecting social values, actively integrating wildland fire into resource management, and minimizing negative effects are evaluated and acted upon.

Wildland urban interface development poses a major ecological disadvantage (Stanionis and Glick 2006). People living in fire-prone areas and the expansion of community values into wildlands will continue to be the overriding value. As wildland fire management becomes more oriented to population-based issues, factors such as proximity to wildland urban interface areas, critical social infrastructure; visibility from communities, highways, and recreation areas; and readily accessible real-time information from commercial and social media sources are placing greater importance and attention on nearly all fires and management response activities. If not aligned, perspectives can become conflicting—from the singular view of a social perspective, less fire presence is desirable, but from a singular view of an ecological perspective, more fire presence is desirable. To become a more viable program in the future, fire management must have a solid foundation that ensures the equal inclusion and alignment of the human dimension with the physical and ecological science dimensions of fire.

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CHAPTER 2 – SMOKE IMPACTS

2.1 Public Health and Exposure to Smoke

Susan Lyon Stone, Martha Sue Carraway, Wayne E. Cascio, Scott Damon, and Paul Garbe

Introduction

The quality of the air we breathe is important for health and well-being. Gaseous and particle pollutants in the air can adversely affect human health. These gases and particles originate from many sources, including smoke from wildland fires (prescribed fire and wildfire).

Wildland fire smoke is an important source of air pollution that can be harmful to public health. This chapter discusses adverse effects of air pollution from wildland fires on human health, using fine particles as a specific example.

What is Particle Pollution?

In general, particle pollution (also known as particulate matter or PM) is a mixture of microscopic solids and liquid droplets suspended in air. It is made up of many components, including acids (such as nitrates and sulfates), organic chemicals, metals, smoke, soil or dust particles, and allergens (such as fragments of pollen or mold spores).

The size of particles is directly linked to their potential for causing health problems. Small particles less than 2.5 micrometers in diameter ($PM_{2.5}$) pose the greatest risk to human health because they can get deep into human lungs, and some may even get into the bloodstream. Exposure to these particles can affect the lungs, heart and blood vessels. Larger particles (larger than 10 micrometers in diameter) are of less concern, although they can irritate eyes, nose, and throat.

Small particles of concern include "fine particles" (such as those found in smoke and haze), which are 2.5 micrometers in diameter or less, and "coarse particles" (such as those found in wind-blown dust), which have diameters between 2.5 and 10 micrometers.

> The terms *micron* and *micrometer* are both abbreviated as *µm* and are interchangeable.
> They are units of measure equaling one-millionth of a meter.

Particle Pollution and Wildland Fires

Characteristics of particle emissions from wildland fires depend on the type and amount of material being burned, fuel and soil conditions, and the temperature of the combustion phase (flaming, smoldering, or glowing). Atmospheric conditions, fuel source and composition, and the size distribution of the fine particles all affect the capacity of the smoke to harm–or technically speaking, to oxidize–the tissues of the human airways (Leonard *et al.* 2007). There are substantial differences in the composition of smoke from wildfire and prescribed fire in different fuel types, and it is not yet fully understood how these characteristics determine the toxicity of the smoke. For example, smoke generated from smoldering peat bog fires contains different components than that from hot-burning canopy wildfires (Robinson *et al.* 2011, See *et al.* 2007). Health effects associated with these two types of fires may be different (Rappold *et al.* 2011); this could relate not only to differences in components, but also to the relative quantity of the smoke, or the tendency of smoke from smoldering peat fires to stay closer to the ground.

Particle Pollution and Human Health

An extensive body of scientific evidence shows that particle exposure can lead to a variety of health effects. For example, numerous studies link particle levels to increased hospital admissions and hospital emergency department visits, and even to death from heart or lung diseases (EPA 2009). Both long- (months to years) and short-term (24-hours or longer) particle exposures have been linked to health problems.

Long-term exposures, such as those experienced by people living for many years in areas with high particle levels, have been associated with problems such as reduced lung function and the development of chronic bronchitis, and even premature death.

Short-term exposures to particles can aggravate lung disease, causing asthma attacks and acute bronchitis, and may also increase susceptibility to respiratory infections. In people with heart and vascular disease, short-term exposures have been linked to heart attacks, worsening of heart failure, stroke and arrhythmias (irregular heart rhythm). Short-term exposures have been linked to premature death. Healthy children and adults have not been reported to suffer serious effects from short-term exposures, although they may experience temporary minor irritation when particle levels are elevated.

Fine particle pollution levels in the United States have dropped dramatically in the past 20 years; yet even as recently as 2013, more than 33 million people lived in U.S. counties that did not meet the Environmental Protection Agency's (EPA) health standards for $PM_{2.5}$ (EPA 2014).

Some health effects linked to short-term (acute) PM exposure:

- Irritation of the eyes, nose, and throat
- Coughing and phlegm production
- Chest tightness and shortness of breath
- Triggering of heart attack and stroke
- Aggravation of heart diseases, such as heart failure or ischemic (coronary) heart disease
- Aggravation of lung diseases, such as asthma and chronic obstructive pulmonary disease (COPD)
- Premature death in older adults and people with heart or lung disease

Some health effects linked to long-term (chronic) PM exposure:

- Premature death in older adults and people with heart or lung disease
- Reduced lung growth in children exposed to PM over many years
- Possible development of atherosclerosis (hardening of the arteries) and chronic bronchitis in people exposed to PM over many years

Who is at risk from particle pollution?

Healthy children and adults have not been reported to suffer serious effects from short-term exposures to particle pollution, although they may experience temporary minor irritation when particle levels are elevated. However, people with heart or lung disease, older adults, children and adults of lower socioeconomic status are considered at greater risk from particles than other people, especially when they are physically active. Exercise and physical activity cause people to breathe faster and more deeply and to take more particles into their lungs.

- People with heart or lung diseases such as coronary artery disease, heart failure, and asthma or chronic obstructive pulmonary disease (COPD) are at increased risk because particles can aggravate these diseases.
- Older adults are at increased risk, possibly because they may have undiagnosed heart or lung disease or diabetes. Many studies show that when particle levels are high, older adults are more likely to be hospitalized, and some may die of aggravated heart or lung disease.
- Children are likely at increased risk for several reasons. Children's lungs are still developing, which increases their risk from prolonged exposure (months to years) to particle pollution. They also spend more time at high activity levels, and thus are often exposed to higher inhaled doses of particle pollution, increasing the likelihood of symptomatic effects. Children are more likely to have asthma or acute respiratory diseases that can be aggravated when particle levels are high. These preexisting diseases can put children at greater risk of needing medical attention during smoke events although healthy children are likely to have only symptomatic effects, such as airway irritation.
- People of lower socioeconomic status are likely at increased risk for several reasons. Generally, they have been found to have a higher prevalence of preexisting diseases, limited access to medical treatment, and increased nutritional deficiencies, which can increase their risk to PM-related health effects (EPA 2009).
- In addition, research suggests that people with diabetes, people with certain health conditions such as obesity, and pregnant women and newborns also may be at increased risk of PM-related health effects.

Human Health Effects of Wildland Fire Smoke Exposure

Fine particle pollution is the principal pollutant of concern in wildland fire smoke for the relatively short-term exposures typically experienced by the public. The individual particles in wildland fire smoke are very small; collectively, they are visible to the naked eye as smoke. Particles in wildland fire smoke are primarily $PM_{2.5}$ and can be inhaled into the lungs.

Besides PM, components of smoke with implications for human health include carbon monoxide (CO), a colorless, odorless gas produced by incomplete combustion of wood or other organic materials. At high levels, CO can cause dizziness, nausea, and impaired mental function. Carbon monoxide levels are highest during the smoldering stages of a fire, especially in close proximity to the fire.

Smoke also contains a number of toxic air pollutants such as aldehydes (including formaldehyde and acrolein) and organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and benzene (U.S. EPA 2013). Acrolein and formaldehyde are potent eye and respiratory irritants. Benzene is a known carcinogen that can cause headaches, dizziness, and breathing difficulties.

Ground level ozone (O_3) is a secondary pollutant in that it is not emitted directly from wildland fires but can form downwind when volatile organic compounds (VOC's) and nitrogen oxides (NO_x) react in the presence of sunlight. Wildland fire smoke is an important source of VOCs as well as a source of NO_x. While there are instances in which ozone levels can be affected by wildland fire emissions, typically the NO_x involved in ozone formation originates from urban and industrial sources, such as vehicles and power plants.

Some health effects linked to short-term (acute) ozone exposure:

- Respiratory symptoms, including: coughing; throat irritation; pain, burning or discomfort in the chest when taking a deep breath
- Reduced lung function, leading to shallow breathing and a feeling of shortness of breath
- Airway inflammation
- Aggravation of asthma and other chronic lung diseases
- Increased susceptibility to respiratory infection
- Premature death in people with heart and lung disease

Some health effects linked to long-term (chronic) ozone exposure:

- Aggravation of asthma and other chronic lung diseases
- New-onset asthma
- Permanent lung damage
- Premature death in people with lung disease

The acute (short-term) effects of smoke exposure range from irritation of the eyes and respiratory tract to more serious injury of the respiratory tract resulting in bronchitis, pneumonia and acute injury of the lungs. These injuries may cause symptoms of persistent cough, phlegm production, wheezing, and physical discomfort when breathing. The exposure can result in reduced lung function, even in healthy people. In addition, exposure to the PM in smoke may aggravate underlying medical conditions of the heart and lungs. Inhaled particles can also alter immune function by diminishing the ability of immune cells to remove foreign materials like pollen and bacteria from the lung, predisposing a person to lung infections. Respiratory complications of smoke exposure may be of particular concern in the very young, and in older individuals (Delfino *et al.* 2009).

In recent years, evidence showing negative health effects from exposure to wildland fire smoke has increased. Some studies have examined the link between health effects and monitored increases in PM, while others have tied these effects to overall smoke coverage (e.g. from satellite images). Scientists at EPA recently found an increase in emergency department visits for cardiac and respiratory complaints associated with the smoke plume from a large pocosin (wetland) wildfire in rural Eastern North Carolina (Rappold *et al.* 2011). Further analysis of this incident indicates that socioeconomic factors, specifically lower socioeconomic status, were the most significant predictor of county residents' risk for asthma attacks and heart failure, respectively, due to the fire (Rappold *et al.* 2012).

Other studies have also shown increased emergency room visits for respiratory complaints linked to $PM_{2.5}$ from a wildfire in Australia (Morgan *et al.* 2010) and wildfire fires in southern California (Delfino *et al.* 2009). Some scientists have not found such clear-cut effects of wildland fire smoke affecting metropolitan centers (Vedal and Dutton 2006), and it is thought that it may be difficult to statistically separate the adverse effects of high background air pollution levels that already exist in larger cities. Work is ongoing to understand this problem, including specific medical effects, the importance of underlying medical conditions (risk factors), and how the source and characteristics of the fire play a role in the effects of smoke on humans who are exposed.

Mechanisms of Health Effects

Respiratory effects

The upper and lower respiratory tract are the initial point of contact between smoke and the internal body. Irritant gases, toxic chemicals and particles in smoke make contact with the mucosal surfaces of the respiratory tract. The level of contact (upper respiratory vs. lower respiratory) is determined by the dose and reactivity of the chemicals and gases, as well as the size of the particles contained in the smoke (figures 2.1.1 and 2.1.2).

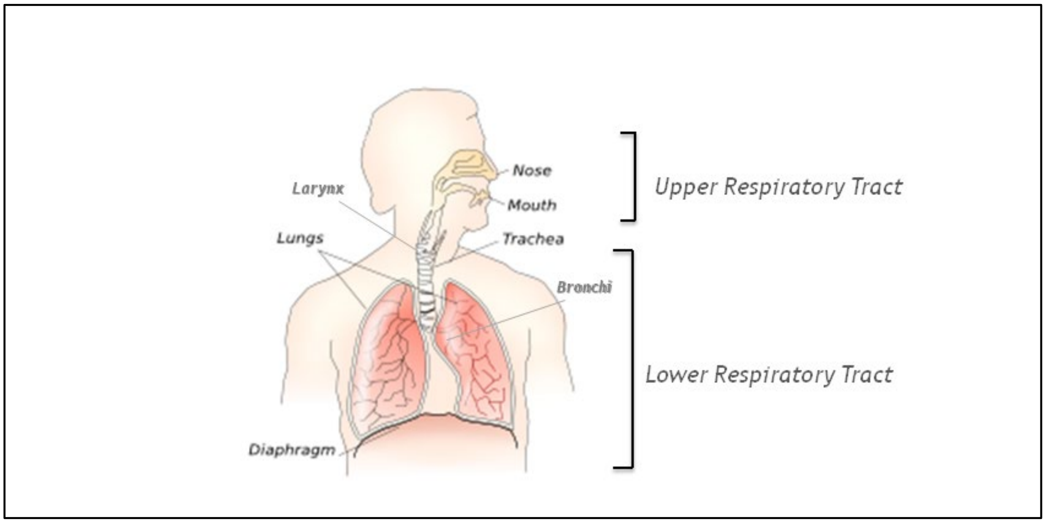

Figure 2.1.1 Respiratory tract anatomy. The upper respiratory tract includes the nose, mouth, and larynx. The lower respiratory tract begins below the larynx, and includes the trachea, bronchial tubes, and lungs.

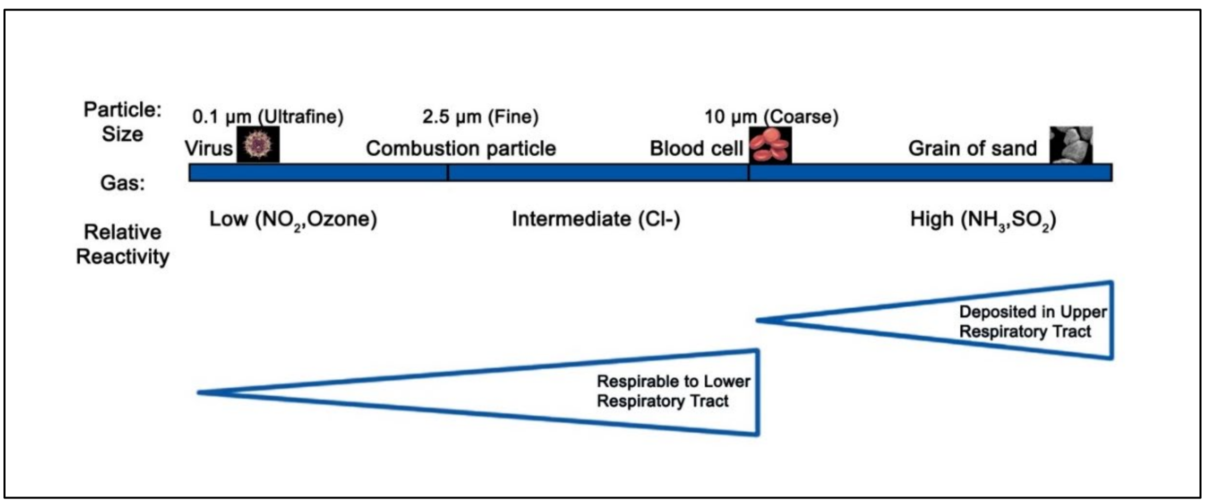

Figure 2.1.2. Anatomical deposition of inhaled particles and gases. The site of deposition of smoke components within the respiratory tract is determined by the particle size, and by the solubility and concentration of gases. Sizes of recognizable objects are shown for perspective.

Particles and gases that primarily contact the upper airway tend to cause nasal congestion, tearing of the eyes and coughing. Those that make it to the lower airways cause irritation or damage by direct toxicity to the respiratory epithelial cells that line the airway passages, leading to symptoms of coughing and wheezing. Those smallest particles and gases that are inhaled to the extreme lower respiratory tract can damage the immune cells of the lung (alveolar macrophages) as well as the cells of the air sacs, which control oxygen uptake. These interactions lead to direct mechanical damage, and begin a cascade of inflammation that amplifies the injury, resulting in further recruitment of inflammatory cells and leakage of fluid from the blood into the lung. If mild, the injury may be reversible and self-limited, but can initiate wide-ranging systemic effects in the body due to the inflammatory effects. Also, even mild effects within the lung can augment respiratory problems or lead to lung infections in "susceptible groups" such as patients who have underlying respiratory diseases, older adults and children, including teenagers. If the injury is moderate or severe, it can result in overt symptoms, even in healthy people, and lead to respiratory impairment and long-term respiratory damage.

Cardiovascular effects

Particulate matter exposure can affect organs and systems other than the lungs. Inhalation of PM initiates a number of neurological and inflammatory pathways that can increase the risk of clinical vascular events (such as heart attacks and strokes) in the short-term, and promote the development of atherosclerosis (hardening of the arteries) in the long-term (Brook *et al.* 2010).

Such effects may occur either through neurological signaling and systemic responses starting in the lung, oxidative stress, inflammation, and/or through the transport of PM or its constituents to the circulatory system. The effects of particles originating from biomass combustion have not been studied with the same detail as that of urban ambient PM; however, the mechanisms are likely to be similar (Brook *et al.* 2010).

Short-term cardiovascular health effects are most likely caused by activation of autonomic nervous system reflexes, as indicated by changes in heart rate variability. This leads to the predominance of sympathetic activity (fight or flight response) with its associated physiological and biochemical responses. These include but are not limited to an increase in: vasoconstriction, heart rate, blood pressure, platelet aggregation, arrhythmia, neurally-mediated reactive oxygen species, and endothelial (inner lining of blood vessels) dysfunction (Brook *et al.* 2010).

Short-term effects probably begin within the lung from PM-induced oxidative stress and inflammation with a cascade of effects into the circulatory system that lead to many other biochemical and physiological effects. Exposure to ambient PM has been shown to increase several cellular inflammatory responses, such as an increase in the number of white blood cells, platelets, histamine and oxidized lipids, among others, while simultaneously decreasing antioxidant defenses. These responses also affect endothelial cell function and cause vasoconstriction. Associated increases in blood clot formation (thrombus formation) and decreases in blood clot destruction (fibrinolysis) increases the risk of thrombosis (blockage of a blood vessel) -- the root cause of most heart attacks and strokes.

Other effects include increasing insulin resistance, dyslipidemia (abnormal fat levels in the blood) and impaired HDL (good blood fat) function. In the long-term, these changes in biochemistry and vasomotor regulation are considered risk factors for the development of atherosclerosis. Another potential pathway for effects is through the translocation of ultrafine PM, soluble metals and organic compounds directly into the circulatory system (Brook *et al.* 2010).

Communicating With the Public About Health Impacts of Wildland Fire Smoke

A growing body of research specifically examines the effects of smoke from wildland fires on public health. Although questions remain, respiratory and cardiovascular health effects are likely, and it is clear that some populations are potentially at greater risk from smoke exposure.

EPA has developed the Air Quality Index, or AQI, to provide nationally uniform and easy-to-understand health advisories for several common air pollutants, including $PM_{2.5}$. The AQI provides cautions to people about the health risks associated with daily air quality, if any. Table 2.1.1 provides the AQI categories and their meaning for $PM_{2.5}$. The breakpoints listed in table 2.1.1 are based on 24-hour averages, reflecting the substantial body of evidence linking 24-hour exposures to adverse health outcomes.

The multi-agency Wildfire Guide for Public Health Officials – May 2016 (Stone *et al.* 2016), is a good reference for recommended actions that can be taken for protection of human health during wildfire smoke episodes. The basic recommendations from that document are integrated into table 2.1.1.

Table 2.1.1. The national Air Quality Index (AQI) for $PM_{2.5}$ links air quality conditions to health concern categories and includes recommended actions people can take to protect themselves (EPA 2014).

Levels of Health Concern	**AQI Values**	$PM_{2.5}$ **24-hr ave. (µg/m³)**	**Recommended Action**
Good	0-50	0-12	Air quality is considered satisfactory, and air pollution poses little or no risk.
Moderate	51-100	12.1-35.4	Air quality is acceptable however there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101-150	35.5-55.4	Members of sensitive groups may experience health effects and should take steps to reduce their exposure. The general public is not likely to be affected.
Unhealthy	151-200	55.5-150.4	Everyone may begin to experience health effects and should take steps to reduce exposure by cutting back on outdoor exertion, by changing either time or intensity of exertion, or both. Members of sensitive groups may experience more serious health effects.
Very Unhealthy	201-300	150.5-250.4	Health warnings of emergency conditions. The entire population is more likely to be affected. Everyone should stay indoors and avoid prolonged or heavy outdoor exertion.
Hazardous	301-500	>250.5	Health alert: everyone may experience more serious health effects. Everyone should avoid all outdoor activity. People at greater risk may want to evacuate to a clean air shelter, if one is available–or leave the area, if it is safe to do so. This is especially important if they are having symptoms or smoke levels are expected to remain high. Symptoms such as chest pain or tightness, palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. People with these symptoms should contact their health care provider.

Wildland fire smoke can cause dramatic, short-term, eg. two hours, changes in $PM_{2.5}$ concentration however, the AQI for particle pollution is a 24-hour average to reflect EPA's National Ambient Air Quality Standards and the science on PM exposures and health.

Scientific evidence does not support health advisories based on averages of less than 24 hours (Brook *et al.* 2010, EPA 2009). The majority of studies on $PM_{2.5}$ and health have examined health effects when a person is exposed for 24 hours or longer. Controlled human exposure and epidemiologic studies available at this time indicate that exposures of less than 24 hours do not result in health effects unless PM concentrations are extremely high (e.g., > 500 $\mu g/m^3$). However, very high short-term exposures will increase a person's 24-hour exposure, thereby increasing the likelihood that s/he will experience effects. To give the public the most up-to-date information on particle pollution possible, EPA uses a "NowCast" to estimate current air quality in the 24-hour AQI form, and uses the NowCast to generate the "current AQI" maps available at https://www.airnow.gov. In August 2013, EPA updated the NowCast so it is more responsive to rapidly changing air quality conditions, such as those that can occur during wildland fires. This change will give people information they can use to protect their health when air quality is poor, and help them get outdoors and get exercise when air quality is good.

The new method uses a weighted average of the previous 12 hours of monitored $PM_{2.5}$ concentrations to estimate the current AQI. When air quality is more stable, the hours are weighted more evenly; when air quality is more variable, the most recent hours are weighted more heavily.

The public will understandably have many questions and concerns during a wildland fire smoke event. A list of frequently asked questions and answers is included at the end of this chapter. Ideally, if a smoke event is serious and prolonged a local public health official will be available for direct communications and more detailed answers to public questions and concerns.

Conclusions

The health effects of wildland fire smoke are of real concern to fire managers, public health officials, air quality regulators and the public. Fire managers need to understand the potential health impacts of fine particulate matter and minimize public exposure to smoke.

Days or weeks of smoke exposure may result in serious health impacts. In part, this may be because the lung's ability to clear these particles out of the respiratory passages may be suppressed over time. Prolonged exposure may occur as the result of topographic or meteorological conditions that trap smoke in an area. Familiarity with the location and seasonal weather patterns can be invaluable in anticipating smoke impacts. Fire managers should be aware of at risk populations and sites that may be affected by wildland fires, such as medical facilities, schools or nursing homes.

Frequent Questions from the Public About Smoke (With Answers from EPA)

The text that follows these common questions can be used for outreach materials or for answering direct questions about smoke and public health.

What's in smoke from a wildland fire?

Wildland fire smoke is a complex mixture of water vapor, particulate matter (also called particle pollution), carbon monoxide, carbon dioxide, hydrocarbons and other organic chemicals, nitrogen oxides, and trace minerals. The individual compounds present in smoke number in the thousands. Smoke composition depends on many factors, including the fuel type and moisture content, the fire temperature, wind conditions and other weather-related influences, whether the smoke is fresh or "aged," and other variables.

Particulate matter is the principal pollutant of concern from wildland fire smoke for the relatively short-term exposures typically experienced by the public. Another pollutant of concern during smoke events is carbon monoxide, which is a colorless, odorless gas produced by incomplete combustion of wood or other organic materials. Carbon monoxide levels are likely to be highest in very close proximity to a smoldering fire. Smoke episodes can be, but are not always, associated with higher levels of ozone. Because fires do not generate ozone directly, but rather generate precursor emissions which can mix with emissions from other sources and lead to downwind increases in ozone, ozone production associated with smoke events can vary widely depending upon the characteristics of the source fire, the meteorological conditions associated with the smoke plume and any interactions with emissions from other sources.

Other air pollutants, such as the potent respiratory irritants acrolein and formaldehyde, as well as the carcinogen benzene, are present in smoke, but at much lower concentrations than particulate matter and carbon monoxide.

Is smoke bad for me?

Yes. Avoid breathing smoke if you can. If you are healthy, you usually are not at great risk from wildland fire smoke. But people with heart or lung diseases, such as congestive heart disease, chronic obstructive pulmonary disease (COPD), emphysema or asthma, and older adults and children are at greater risk. More specifically, people at greater risk of heart disease or stroke (and therefore at greater risk from particle pollution) include: men 45 years or older, and women 55 years or older; people with a family history of stroke or early heart disease (father or brother diagnosed before age 55; mother or sister diagnosed before age 65); people with high blood pressure or high blood cholesterol; people who are overweight or not physically active; and people who smoke cigarettes (EPA 2016).

How can I protect myself?

- Pay attention to your local air quality reports. Most areas report EPA's Air Quality Index (AQI) for fine particle pollution. Fine particle pollution is one of the biggest dangers from smoke. As smoke and air quality get worse, the AQI changes—and so do guidelines for protecting yourself.
- Use common sense. If it looks smoky outside, it's probably not a good time to go for a run and it probably is a good time for your children to remain indoors.
- Reducing physical activity is an effective strategy to lower your dose of inhaled air pollutants and thereby reduce health risks during a smoke event.
    - Here's why: During exercise, you can increase your air intake as much as 20 times over your resting level, bringing more pollution deep into the lungs. Also, when you breathe through your mouth during exercise you bypass the natural filtering ability of the nasal passages–again delivering more pollution to your lungs.
- If you're told to stay indoors, keep your windows and doors closed. Run your air conditioner if you have one. Keep the fresh air intake closed and the filter clean.
    - Be cautious when the weather is hot. If your home does not have air conditioning, and you depend on open windows and doors for ventilation, remaining inside with everything closed can be dangerous. Older individuals, or others in frail health run the risk of heat exhaustion or heat stroke. If outdoor temperatures are very high and you do not have air conditioning, it would be prudent to stay with friends or family members who do, to go to a cleaner air shelter in your community, or to leave the area.

- Keep indoor particle levels lower by not using anything that burns, such as wood stoves and gas stoves, or even candles.
- Don't smoke. That puts more pollution in your lungs–and those of the people around you.
- If you have asthma, be sure to take your medicines as prescribed. If your asthma action plan calls for you to measure your peak flows, make sure you do so. Call your doctor if your symptoms worsen.
- If you have heart disease, or another cardiovascular disease, limit your exposure to smoke and check with your doctor or health care provider about other ways to protect yourself.

How can I tell when smoke levels are dangerous? I don't live near a monitor.

Generally, the harder it is to see, the worse the smoke. Some states, especially in the western U.S., use a visibility guide to help you know when smoke levels may pose a concern for you. This technique is not particularly accurate and entirely invalid in areas of high humidity, especially in the southern U.S. Always stay alert for symptoms (see next question).

How do I know if I'm being affected?

You may have a scratchy throat, cough, sore sinuses, headache, a runny nose and stinging eyes. Children, older adults and people with lung diseases may find it hard to breathe as deeply as usual, and they may cough or feel short of breath. People with lung diseases such as asthma or chronic bronchitis, or heart diseases such as congestive heart failure, may find their symptoms worsening.

Should I leave my home because of smoke?

Maybe. The particles in smoke do get inside your home. If smoke levels are high for long enough (such as several days), these particles can build up to unsafe levels indoors.

- If you have symptoms (scratchy throat, cough, sore sinuses, headache, a runny nose, stinging eyes, or worsening of heart or lung disease symptoms), call your doctor. This is particularly important for people with heart or lung diseases, the elderly, and children. If you live in an area affected by wildland fire smoke, and the outside air clears, consider opening windows to clear the air inside your home. This also is a good time to do outdoor activities.

Are the effects of smoke permanent?

Not usually. Healthy adults and children generally find that their symptoms go away after the smoke is gone.

Do air filters help?

Indoor air filtration devices with HEPA filters can reduce the levels of particles indoors. Make sure to change your HEPA filter regularly. Don't use an air cleaner that works by generating ozone, which will put more pollution in your home.

Do dust masks help?

No. Paper "comfort" or "nuisance" masks trap large dust particles — not the tiny particles found in smoke. These masks generally will not protect your lungs from wildland fire smoke.

You may be able to buy disposable respirators, known as "N95" or "P100" masks at a hardware or home repair store or at a pharmacy. These respirators give some protection when used the right way. Check with your doctor before using a mask: they can make breathing more difficult for people with existing heart or lung conditions. Guidelines for mask-fitting and respirator use can be found in the Wildfire Guide for Public Health Officials (Stone *et al.* 2016).

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2.2 Fire Personnel Smoke Exposure and Safety

Timothy E. Reinhardt and Roger D. Ottmar

Introduction

This chapter summarizes the inhalation health hazards and management implications to wildland firefighters and fire camp personnel from exposure to air pollutants at both wildfires and prescribed fires (wildland fires). It includes smoke from natural fuels (with mention of soil dust) but does not consider smoke from the burning of man-made products encountered by structural firefighters at wildland urban interface fires, or airborne hazards resulting from fires burning across polluted soils.

Smoke is both an acute and a chronic health hazard. An acute hazard can be as short as an instant effect (e.g., eye irritation from smoke at a campfire) while a chronic health hazard only appears after repeated exposure over a long time (e.g., lung cancer or emphysema from cigarette smoking). Management response to smoke exposure has historically aimed at preventing acute effects.

In the past, firefighters believed smoke was only an inconvenience, irritating the eyes and nose, causing coughing, and occasionally causing nausea and headaches. However, there is evidence there may be serious chronic health effects, and potentially even a reduced life span from long-term exposure to wildland fire smoke. There is also some evidence that acute effects could be serious for persons with preexisting cardiovascular disease. Preliminary studies find that Type 1 crews (e.g., hotshot, helitack) have better-than-average health and cardiovascular fitness, while Type 2 crews and fire camp personnel health and cardiovascular fitness are no better than the average U.S. population (Sharkey 2008, Domitrovich 2013). The long-term health consequences of a career of smoke exposure will take many years to evaluate. Furthermore, we do not have enough evidence to know if the increase in the number of wildfires, longer fire seasons, larger fire sizes, and more severe fires that has been documented in recent years has exacerbated acute and chronic exposure to wildfire smoke.

Hazards in Smoke

Wildland fuels are composed of living and dead vegetation, and the burning of this fuel produces smoke. In a complete combustion environment, fuels are consumed by fire and converted mostly to carbon dioxide (CO_2) and water vapor (H_2O) with the release of heat. However, the combustion process in wildland fires is never complete, and incomplete combustion produces dozens of significant chemicals and hundreds of trace chemicals (Sandberg and Dost 1990, Reinhardt and Ottmar 2000, Reinhardt *et al.* 2000, Sharkey 1997, Sharkey 1998, Naeher *et al.* 2007). Some of the combustion products may present acute hazards, others may present chronic hazards, and some can be both. Many combustion products are gases such as CO_2 and carbon monoxide (CO). Other combustion products (often called particulate matter) are a visible mix of liquids and solids that are mainly composed of organic and inorganic carbon. For comparison against standards to protect the occupational health of firefighters, gases are usually measured in parts per million (ppm), while particulate matter is commonly measured as a weight-per-volume of air (micrograms per cubic meter of air, $\mu g/m^3$). The main inhalation hazards for firefighters and other personnel at fire camp are CO and respiratory irritants such as particulate matter and several key gases: acrolein, formaldehyde, nitrogen dioxide and sulfur dioxide. But smoke includes other components such as polycyclic aromatic hydrocarbons (PAH), some of which are carcinogenic or thought to be, and airborne soil dust which can contain respirable crystalline silica. A brief summary of the health effects of these follows:

Carbon monoxide

Inhalation of carbon monoxide causes acute health effects ranging from diminished work capacity and a loss of visual perception, manual dexterity, driving performance, and attention level, up to headache and nausea, with more serious effects at very high levels (Raub and Benignus, 2002). For people with preexisting heart disease, it can trigger an angina attack, increase abnormal heartbeats, and potentially lead to sudden heart failure. It causes these effects by displacing oxygen from hemoglobin in the blood to form carboxyhemoglobin (COHb), which affects body organs like the brain and heart that require large amounts of oxygen. When people are exposed to CO, the time until they reach a toxic level of COHb can be predicted as a function of CO concentration, breathing rate, altitude, and other factors (Coburn *et al.* 1965). The harder the work and the higher the altitude, the more rapidly COHb forms at a given concentration of CO. In heavy smoke where there is a high level of CO, symptoms of overexposure to CO can occur during hard physical labor after 15 minutes. Fortunately, most of these acute effects are reversible and CO is rapidly removed from the body once in clean air (after 4 hours in fresh air, the COHb levels in the blood are cut in half). Some studies have linked chronic CO exposure to heart disease, but more research is needed. Symptoms related to CO exposure are presented in table 2.2.1.

Table 2.2.1. Adverse health effects corresponding to blood carboxyhemoglobin levels (COHb) and CO exposures (Winter and Miller 1976, Ellenhorn and Barceloux 1998).

CO in Atmosphere (ppm)	**COHb in Blood** (percent)	**Signs and Symptoms**
10	2	Asymptomatic (without symptoms). Typical CO exposure level of a non-smoker is 1-8 ppm.
70	10	No appreciable effect except shortness of breath during vigorous exertion; possible tightness across the forehead; dilation of cutaneous (along skin) blood vessels; increased risk of arrhythmias in coronary artery disease patients and exacerbation of asthma.
120	20	Shortness of breath during moderate exertion; occasional headache with throbbing in the temples.
220	30	Headache; irritability; easily fatigued; poor judgment; dimness of vision.
350-520	40-50	Headache, confusion; collapse; fainting during exertion; disorientation; dizziness; drowsiness; nausea; vomiting.
>600	>50	High risk of death.
800-1,220	60-70	Unconsciousness; intermittent convulsion; respiratory failure; coma; death if exposure is continued.
1,950	80	Rapidly fatal.

Commonly used units for particulate matter

Micrometers, or µm, indicate one millionth of a meter, and are used to describe particulate matter. $PM_{2.5}$, particulate matter of a diameter less than 2.5 µm, is the pollutant most often discussed in the context of wildland fire smoke and air quality regulation. PM_4, particles less than or equal to 4 µm, also appear in this chapter as they are often the unit of measurement used in the occupational health and safety studies referenced herein.

Particulate Matter

Airborne smoke particles are a mixture of sizes and generally range in diameter from over 100 micrometers (µm, one millionth of a meter), down to nearly the size of a few atoms. The potential of particulate matter to harm human health depends on its chemical composition and whether it is (1) of a size that can remain airborne long enough to reach us, (2) small enough to be inhaled, and (3) small enough to be deposited deep in the respiratory system, but not so small it is exhaled without being deposited in the lungs (See figure 2.1.1 in the Public Health and Exposure to Smoke chapter). Current National Ambient Air Quality Standards for the general public are established for $PM_{2.5}$ and PM_{10}. However, the respirable particulate matter standard used for the general workforce which includes firefighters, considers all particulate matter that can penetrate to the lower airways, which includes all particles less than or equal to 4 µm (PM_4). If we measured smoke particles using a $PM_{2.5}$ sampler, we'd measure slightly lower mass than if we measured the same smoke with a PM_4 sampler, but the levels would be very similar because most of the individual particles in smoke are less than 0.6 µm in diameter (Chakrabarty *et al*. 2006). In the last decade, air pollution and public health research has confirmed an inflammatory effect in the lungs from small particulate matter less than PM_4 in diameter. While this may not pose a hazard to healthy individuals who are intermittently exposed to smoke, there is evidence that chronic exposure can lead to hardening of the arteries, and an acute exposure may increase the risk of cardiac events in people with preexisting cardiovascular disease.

The human body has several ways to protect itself from particulate matter associated with wildland fire smoke (U.S. EPA 2013). The larger particles (>2.5 µm in diameter) and a portion of the fine (≤2.5 µm in diameter) and ultra-fine (≤ 1 µm in diameter) particles will be captured in the mucous that covers nasal hairs and cilia (microscopic hairs lining the respiratory tract which help to remove dust and bacteria) within the body's airways. The mucous and captured particles will eventually leave the airway through coughing or swallowing. The portion of fine and ultra-fine particles not captured by the mucous will continue to travel deeper into the body and will eventually be deposited on the lining of the lung where they can become trapped. If the person is in a clean atmosphere, the body will eventually cleanse itself by incorporating the particles in mucous where they will leave the body through coughing or swallowing. The ultra-fine particles can travel through the lining of the lung and enter the blood stream. White blood cells eventually will remove the foreign material from the blood stream.

Aldehydes

Smoke includes a small percentage of various aldehydes, which are volatile organic compounds that are either gases or liquids that quickly evaporate into gases (Dost 1991). Most are easily detected by people from their distinctive odor. Formaldehyde and acrolein are the two most potent aldehydes found in wildland fire smoke that cause adverse health effects. Acute health effects include eye, nose and throat irritation, depression of breathing rates, and temporary paralysis of cilia. Acrolein is especially irritating to the eyes and mucous membranes at very low concentrations (Kane and Alarie 1977). Chronic exposure to formaldehyde is associated with nasal cancer (U.S. Department of Labor, Occupational Safety and Health Administration 1987).

Oxides of Nitrogen and Sulfur

Oxides of nitrogen (NOx) and sulfur (SOx) strongly irritate the eyes, mucous membranes and respiratory tract. They can trigger breathing difficulties among asthma sufferers, but fortunately they do not reach high levels in smoke. However, they are likely to add to the respiratory irritant burden that firefighters face and likely contribute to respiratory problems during brief periods of high smoke exposure.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are mainly found as solids and tarry liquids within smoke particles. They are not believed to pose a cancer hazard to wildland fire personnel because the combustion conditions at wildland fires are usually not oxygen-starved, like the conditions in damped-down wood stoves that create proportionately more PAHs. Measurements among firefighters have not found significant levels of exposure (Robinson *et al*. 2008, Materna *et al*. 1992).

Other smoke components

Although hundreds of other chemicals are found in smoke, most are not believed to create an inhalation hazard. Some potential hazards have been evaluated and found not to be significant in the western U.S., but were of concern in other regions. For example, exposure measurements for benzene and other volatile organic compounds (VOCs) have been made among wildland firefighters. Benzene is a well-known carcinogen implicated in leukemia, but there is conflicting evidence on how much firefighters are exposed to it. It was not found to be a hazard in the western U.S., with the highest levels occurring while working with gasoline-powered equipment (Reinhardt and Ottmar 2004), but other countries have noted higher levels during wildland fire emissions and exposure measurements (Reisen and Brown 2009, Barboni *et al*. 2010). More research in different fuel types would help to resolve the discrepancies.

A perennial topic is whether urushiol-bearing plants (e.g., poison oak and poison ivy) create special inhalation hazards, which may be a serious issue among firefighters that are allergic to these compounds. No measurements have been reported yet, but it is a likely hazard that should be evaluated in areas where the vegetation includes these plants.

Research on fire emissions and ambient air pollution has identified ozone in smoke, but it is believed to be rapidly consumed by reactions with other smoke components close to the fire. No exposure data can be found that documents exposure among firefighters. However, ozone can form in a plume as a secondary reaction of sunlight, VOCS, and nitrogen oxide, and may reach unhealthy levels downwind in populated areas (Jaffe and Wigder, 2012).

Isocyanic acid is another potential hazard which has recently been found in plant biomass smoke and is reported to contribute to cardiovascular inflammation-related diseases at low concentrations (Roberts *et al.* 2011).

In an ideal occupational health evaluation, the exposure to all respiratory irritants affecting the respiratory system would be evaluated. Practically, there may be too many different irritants in smoke to effectively measure them all at once. Given the toxicity of respirable particles implied from public health studies for other sources of $PM_{2.5}$ and PM_4, simply controlling exposure to PM_4 may give adequate protection against all other components in smoke.

Smoke Inhalation Hazards from Burning of Artificial Fuels

Potential inhalation hazards in smoke generated from the burning of vegetation has been the focus in this chapter. However, there are other inhalation hazards firefighters may be exposed to that are generated from fuels such as plastics and other artificial substances. Although discussion of the inhalation hazards generated from the burning of artificial fuels, which may be encountered by structural and wildland firefighters, is beyond the scope of this guide, a few generalities can be stated:

1) If a structure is only wood, the emissions will be similar to wildland fuels unless the wood has been painted or chemically treated; however, concentrations within a structure can be much higher than outdoors,
2) Plastics have a variety of compositions and are associated with various hazards. For example, chlorinated plastics (polyvinyl chloride) and those treated with flame retardants would be expected to create a wider array of chlorinated and other toxic compounds that are unhealthy if breathed, and

3) The wide variety of artificial materials and chemicals that may be present in structures or vehicles could cause a number of health hazards.

As mentioned, chlorinated plastics can produce toxic compounds when combusted. However, the low-density polyethylene plastic used to keep woody piles dry in many regions burns relatively cleanly. The amount of this plastic used to cover piles does not produce a significant amount of airborne toxins compared to the woody biomass consumed when the pile is burned, and has been shown to be safe to use (Hosseini *et al.* 2009, Hosseini *et al.* 2014).

Non-Smoke Inhalation Hazards at Wildland Fires

A few other notable inhalation hazards do occur during wildland fire operations that are not related to the smoke generated from burning live or dead biomass. Exhaust from vehicles and other engines and combustion sources (diesel and gasoline-powered generators, pumps, and space heating equipment) pose an inhalation hazard if personnel are nearby (chiefly from CO and particulate matter from combustion of diesel fuel). Wildland fires burning in areas with mines or other sources of heavy metals (such as arsenic, cadmium and lead) are unlikely to pose a special hazard unless levels of these metals in the soil are high enough that breathing airborne soil dust could be hazardous, or if plant material concentrates metals from the soils and becomes incorporated into the smoke. As for the airborne soil dust, calculations show that it will usually take high levels of visible dust over a work shift to reach a hazardous level when the soils are not so laden with toxic metals that they cannot support plant life. Two other important hazards that may occur during wildland fire operations are exposure to dust that contains respirable crystalline silica and asbestos.

<u>Respirable Crystalline Silica</u>

Figure 2.2.1. Firefighter conducting dry-mop-up operations in volcanic soils on the eastside of the Cascades.

Crystalline silica is widely-distributed in soils across the United States. Typically found as quartz, when this crystalline silica is made airborne by walking, digging, mop-up, or vehicle operations, the respirable dust that contains crystalline silica can contribute to the risk of silicosis (fibrous scarring of the lungs decreasing breathing ability), should exposure at high levels go on for multiple years (figure 2.2.1). Current measurements find that a small percentage of firefighters could be overexposed to levels of respirable crystalline silica and should have exposure controls (Broyles 2012). There are no acute effects that can be relied on to tell the difference between respirable crystalline silica exposure and exposure to less hazardous dusts. If significant levels of visible dust are present in a fire operation where soils are known to contain granitic rocks and other sources of crystalline quartz, then steps should be taken to evaluate the silica hazard and control the dust exposure. These steps could include reducing dry mop-up activities, leaving space between each individual when hiking on dry, dusty trails, and providing enclosed vehicles such as buses or vans for transporting wildland firefighters.

Asbestos

Asbestos-bearing rocks occur in certain parts of the country, with portions of northern California identified as naturally-occurring asbestos areas. Geologic maps of area soils should be consulted prior to operations in such areas, and qualified industrial hygienists (such as state-certified asbestos consultants in California) should be involved in developing plans for exposure monitoring and effective controls. As with respirable crystalline silica, there are no obvious acute effects or warning signs of asbestos exposure. Adverse health effects (especially a type of cancer called mesothelioma) are typically associated with chronic exposure over many years.

Acute Effects

The acute or immediate irritation of smoke exposure is obvious. Stand downwind of a smoky campfire, and eye, nose and respiratory irritation will soon encourage you to move. These irritant effects are caused by the products of incomplete combustion that are classified as respiratory irritants. Respiratory irritants for fire personnel include PM_4, aldehydes like formaldehyde and acrolein, and likely organic acids like formic acid and isocyanic acid, NO_2, SO_2 and many other trace components in smoke. Acute effects of smoke exposure also include headaches, nausea, and possibly a dulling of awareness, all effects believed to be caused by CO exposure (Sharkey 1998, Reinhardt and Ottmar 1997, Sharkey 1997).

Several researchers have found small but measurable declines in wildland firefighter lung function across a work shift (Betchley *et al.* 1997, Slaughter *et al.* 2004, Gaughan *et al.* 2008). However, others have not found significant changes, despite slight cumulative effects across a wildfire season (Adetona *et al.* 2011a). Where studies have continued from season to season, lung function was found to return to normal by the next fire season (Sharkey *et al.* 1995, Harrison *et al.* 1995).

Although firefighters show a rapid increase in biochemical markers that indicate inflammation in the lungs along with an increase in upper and lower respiratory symptoms such as coughing and a runny nose (Gaughan *et al.* 2008), these are not known to pose a hazard in otherwise healthy people. However, the systemic inflammation response that has subsequently been found to occur in the bloodstream (an increase in white blood cells and band cells, and certain biological messenger cells called cytokines) has been linked to cardiovascular disease (Swiston *et al.* 2008, Hejl *et al.* 2013). There is some evidence that this may be associated with an acute morbidity and mortality hazard from cardiopulmonary symptoms and heart failure that lags the smoke exposure by several days (Rappold *et al.* 2011). Given that older members of incident teams and support personnel in fire camps appear to have a similar incidence of preexisting cardiovascular disease as the general public, there may be an acute hazard among those with serious preexisting conditions when they are exposed to high levels of smoke.

Chronic Effects

A human health risk assessment found that there could be adverse health effects from career exposure to smoke among wildland firefighters (Booze *et al.* 2004). Using average and reasonable maximum career assumptions of Type 1 crews (e.g., career duration of between 8 and 25 years; 97 days on wildfires and 17 days on prescribed fires per year) acrolein and PM_4 posed a potential risk of non-cancer health effects. Although the risk assessment indicated acrolein effects were acute and not long term, the PM_4 risks were found to be chronic. Cancer risks were also evaluated. Using the levels of PAHs measured by other researchers during wildfire smoke exposure in California and linking these to the particulate levels measured among firefighters across the western U.S., the levels of PAHs that the wildland firefighters were exposed to in smoke were not found to be the major contributors to their overall cancer risk. Of all the carcinogens identified in smoke as being at potentially significant levels, only benzene and formaldehyde exposure posed a potential cancer risk above one in one million (Booze *et al.* 2004). Benzene was found in small amounts in smoke from wildland fuels, but the highest exposure levels were found from the combustion of gasoline products, including drip torch fuel and exhaust from internal-combustion engines.

Lung function losses from smoke exposure have been measurable as a slightly diminished capacity to breathe, constriction of the respiratory tract, and hypersensitivity of the small airways (Adetona *et al.* 2011a, Letts *et al.* 1991, Reh *et al.* 1994). Small but measurable lung function declines that last for days to months have been identified among fireline workers. For example, engine-based firefighters of the California Department of Forestry and Fire Protection underwent lung function testing before and after the fire season. Small (0.3 to 2%) losses in lung function were observed among the firefighters. These losses were associated with the amount of firefighting activity during the study period. The firefighters also reported increased eye and nose irritation and wheezing during the fire season. Whether the lung function losses are permanent or recoverable with absence of exposure remains to be seen. A study among Portuguese wildland firefighters with an average age of 38 years, with 15 years of firefighting experience found that the prevalence of airway obstruction (chronic obstructive pulmonary disease, or COPD) in the firefighters was higher than the prevalence in the general population (Almeida *et al.*, 2007).

Many recent studies of epidemiology (who is getting ill) and toxicity mechanisms (how does it happen) have researched the adverse health effects of inhaling fine/respirable particles. These studies concentrated on particulate matter from urban or regional air pollution sources. Whether measured as $PM_{2.5}$ or PM_4, particulate matter has been associated with:

- Increasing the mortality of the human immune system scavenger cells that attack and normally rid the lungs of bacteria, viruses and other inhaled particles (Wegesser *et al.*, 2009),
- Causing the body to react by releasing peroxides and organic free radicals in the lungs (termed oxidative stress) that damages lung tissues and DNA and causes lung inflammation (Leonard *et al.* 2007, Swiston *et al.* 2008, Barregard *et al.* 2008, Myatt *et al.*, 2011), and
- Subsequently triggering a systemic (body-wide) inflammation response of the immune system, which induces release to the bloodstream of a number of biochemical messenger molecules (Barregard *et al.* 2006, Swiston *et al.* 2008), and these in turn cause changes that are strongly linked to cardiovascular disease and early mortality, typically via ischemia and a variety of ischemic diseases such as atherosclerosis (hardening of the arteries) and a worsening of underlying cardiovascular disease (Pope *et al.* 2004, Lippman and Chen 2009, Pope *et al.* 2009).

Among healthy workers, an increased risk of cardiovascular disease does not at this time seem to be an immediate hazard, however, the risk of cumulative damage over a career needs better definition because chronic adverse health effects are linked to chronic exposure to fine particles, and wildland firefighters are exposed to fine particles in smoke. The Missoula Technology Development Center (MTDC), one of four detached engineering units of the U.S. Forest Service, started a prospective epidemiology project in 2014 to track the long-term health of wildland firefighters, in order to compare it with other workers to see if fireline personnel have more or fewer health problems during and after their careers.

Occupational Exposure Criteria

To decide if a firefighter's smoke exposure is safe or not, air quality samples are collected right by a worker's face (the breathing zone) while they are working, to represent the air pollutants they might inhale (figures 2.2.2. 2.2.3, and 2.2.5).

Figure 2.2.3. Backpack sampler and pumps worn by firefighters to capture smoke exposure samples.

Figure 2.2.2. Backpack sampler capturing particulate matter, acrolein, formaldehyde, and other smoke exposure compounds within several inches of a workers face. Note the electronic dosimeter for testing.

The personal exposure sample results are then compared to Occupational Exposure Limits (OELs) established to protect worker health. The OELs are standards set to protect most workers most of the time. The OELs are often set at much higher levels than the ambient air quality standards established for the public which include sensitive populations such as the very young or old, and those with serious health conditions, because: 1) workers are healthier than the general public; and 2) workers are not normally exposed 24 hours a day and have time to recover and eliminate absorbed pollutants from the body.

Acronyms to know

EF – emission factor

IH – industrial hygienist

OEL – occupational exposure limit

OSHA – Occupational Safety and Health Administration

PELS – permissible exposure limit

VOC – volatile organic compound

The Permissible Exposure Limits established by the Occupational Safety and Health Administration (OSHA, the main federal agency charged with enforcing safety and health legislation) are the set of mandatory OELs applicable to federal workers (including U.S. Forest Service employees) and to many state employees. When a state has an OSHA-equivalent agency, like the West Coast states and many others, state and private industry employees must adhere to the state OELs. Where there is an OEL, there is guidance on a safe exposure. However, there are no OELs established for most chemicals in smoke. OSHA and the state occupational safety and health agencies conclude that the employer must provide a workplace free of recognized hazards. So we have to study the toxicology of the chemicals and establish an OEL that will allow safe exposure over a working career. This is the situation for PM_4 in wildland fire smoke, because the PM_4 Permissible Exposure Limit (PEL) established by OSHA is only for nuisance dusts (also known as particulate not otherwise regulated) and only applies where there are no unique toxicities associated with the particulate. Because the PM_4 PEL is not appropriate for wildland fire smoke, we no longer recommend comparing PM_4 exposures against the nuisance dust standards—this is an important change from earlier guidance, when the specific toxicity of wildfire smoke particulate was not well-established. As an interim exposure limit for a 12-14 hour work shift, the ad hoc committee directed by MTDC recommends a respirable particulate exposure for wildland fire smoke of approximately 1,000 $\mu g/m^3$. This level may increase or decrease as future studies answer important questions about the specific hazards of PM_4 from wildland fires.

Smoke Exposure at U.S. Prescribed Fires and Wildfires

A number of relatively small studies have evaluated smoke exposure during prescribed fires and wildfires. Their results are summarized in table 2.2.2. A general observation is that smoke exposure does not exceed OELs most of the time. As OELs are tailored to be more specific to wildland firefighting working conditions, the percentage of exposures that are considered unacceptable may change, but the general conclusions here are likely to remain applicable.

Table 2.2.2. Summary of inhalation hazards to wildland firefighters.

Chemical Class, Pollutant	Hazard Index[a]	Shift OEL (µg/m³) OSHA PEL[b]	Shift OEL (µg/m³) Lowest OEL[c]	TWA Exposures at Wildland Fires (µg/m³) Maximum	TWA Exposures at Wildland Fires (µg/m³) Mean	n[d]	Data Source and Reference[e]
Particulate Matter							
Total particulate	3.74	10,000	10,000	37,400	9,460	22	IH (Materna & others, 1992)
Respirable particulate	10.5	5,000	1,000	10,500	1,000	200	IH (Reinhardt & Ottmar, 2004)
Crystalline silica (PM_4)	14	100	25	280	40	79	IH (Broyles 2012)
VOCs – Aldehydes							
Formaldehyde	37.50	1000	20	737	160	30	IH (Materna & others 1992, Reinhardt & Ottmar 2004)
Acrolein	0.98	250	230	225	34	200	IH (Reinhardt & Ottmar 2004)
Aromatics							
Benzene	3.83	3,000	320	1,226	89	200	IH (Reinhardt & Ottmar 2004)
Gases							
Carbon monoxide	2.32	57,000	29,000	66,000	8,000	45	IH (Reinhardt & Ottmar 2004)
Sulfur dioxide	0.22	13,000	5,000	1,100	700	13	EF (CO_2) (Battye and Battye 2002)
Nitrogen dioxide	0.50	9,000	1,800	900	500	34	EF (CO_2) (Battye and Battye 2002)

[a] A "Hazard Index" is an easy indication of which pollutants matter. If the index is 1 or greater, the exposure is known to exceed the OEL. If it is much less, then the pollutant is likely to be a hazard only by additive or synergistic effects with other chemicals. The hazard index is the ratio of the estimated concentration divided by the occupational exposure limit (the lowest U.S. limit was selected)
[b] U.S. Occupational Safety & Health Administration Permissible Exposure Limit
[c] Lowest authoritative Occupational Exposure Limit
[d] Number of samples in Time Weighted Average (TWA) Mean
[e] Source of data--either a direct industrial hygiene measurement (IH) or an estimate based on source emission factors or plume measurements of concentration (EF), with reference to the measure of complete or incomplete combustion that was correlated to the pollutant.

A number of key OELs are listed in table 2.2.2, along with the range of exposures measured among workers by industrial hygienists (IH) or estimated by emission factor (EF) ratios to other measured smoke components (typically CO or CO_2). These are the most likely constituents to reach levels in the breathing zone of wildland firefighters that are at least 1% of an OEL. A "Hazard Index" (table 2.2.2) is an easy guide to identify which pollutants matter most. If the index is 1 or greater, the exposure is known to exceed the OEL. If it is much less, then the pollutant is likely to be a hazard only by additive or synergistic effects with other chemicals.

The hazard index can be much lower when using a higher OEL, or uses a mean exposure rather than the maximum reported. Taking these adjustments into account, CO, PM_4, formaldehyde and acrolein are the main documented inhalation hazards in smoke for wildland firefighting. Other respiratory irritants like NO_x and SO_x will add to the respiratory irritant burden. Some points that are apparent from occupational exposure measurements are summarized below.

- **Measured exposure at prescribed fires was more likely to exceed OELs than at wildfires.** Two reasons seem apparent: 1) at wildfires, most measurements have been obtained during the latter phases of fire, when mop-up operations predominate and exposure is likely to be in the mid- to low range of the measurement spectrum. At prescribed fires, the data include the entire operation, including periods when fire management becomes challenging and smoke exposures are relatively high; 2) when a decision is made to ignite a prescribed fire there is every incentive to expend all efforts to maintain the fire within the designated boundaries, which are not always at ideally-defended locations and may have high smoke exposure. Wildfire suppression can often fall back to ridgelines and other natural boundaries should a fire make a run at firelines.

- **Smoke exposure is often a short-term problem.** This does not mean that brief overexposures are acceptable, because the CO, aldehyde and nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) Short Term Exposure Limits (STELs) are applicable and many brief exposures can drive the shift average exposure to unhealthy levels. Shift-average CO exposures seldom exceed exposure limits because there is usually a lot of unexposed time in a work shift. But, it is not uncommon to exceed short-term exposure limits for CO and aldehydes because of peak exposures during short-term activities (such as holding fireline during adverse wind shifts at prescribed fires, or while performing direct attack of slop-overs or initial attack of wildfires). Finally, it has to be emphasized that multiple brief but intense exposures to respirable particulate are likely to add up to an unacceptable PM_4 exposure.
- **Direct attack and holding line have the highest smoke exposures.** These two tasks are associated with keeping the fire within the fire lines, and these efforts can lead to high smoke exposures. Sawyers appear to have the next highest potential for smoke and exhaust exposure followed by mop-up, with lighting usually having the lowest exposures.
- **Uphill and downwind smoke exposure is worse.** When a fire management task requires the firefighter to be either uphill or downwind of the fire, increasing ambient wind speed is associated with increasing smoke exposure. This is because the ambient wind can overcome the buoyancy of the plume and push the smoke towards the firefighters. When ambient winds are light and the fire is burning well, the plume actually pulls air away from the firelines and the firefighters often work in clean ambient air.
- **CO appears to be a reasonably good surrogate for other pollutants close to the active fire.** Near the active combustion zone of both prescribed fires and wildfires, strong correlations between CO and formaldehyde, acrolein, and PM_4 have been found from exposure studies in mixed conifer and chaparral fuels in the western United States. This means that inexpensive and simple to operate CO dosimeter monitors could be used for firefighters close to the combustion zone to measure daily workshift exposures (McMahon and Bush 1992, Reinhardt and Ottmar 2004, Adetona *et al.* 2011b).

Carbon Monoxide

Carbon monoxide exposure can exceed OELs at both prescribed fires and wildfires. Ever since it was first measured in the mid-1970s, it is not uncommon to find that firefighters receive too much CO exposure 5 to 10 percent of the time over the course of an average work shift (Jackson and Tietz 1979). Exposure measurements among firefighters in subsequent years support similar conclusions (e.g., Materna *et al.* 1992, McMahon and Bush 1992, Reh *et al.* 1994, McCammon and McKenzie 2000, Reinhardt and Ottmar 2004, Dunn *et al.* 2009).

<u>CO overexposures are usually short-duration</u>

Several studies (e.g., Reinhardt and Ottmar 2004) have shown that the exposure problem for CO is mainly driven by brief exceedences of STELs. At large, long duration wildfires (417 samples) the preliminary shift-duration time weighted average (TWA) CO exposure averages about 3.5 ppm, with a

95th percentile value (only 5% are worse) of 36 ppm. Their preliminary results for 60 firefighters working initial attack found an average shift-duration TWA CO exposure of 2.2 ppm, with a 95th percentile value of 10 ppm. However, short-term exposures during initial attack (the 5-minute maximum CO exposure during each shift) average 34 ppm, with a 95th percentile of 127 ppm. Clearly, initial attack shifts have enough time in cleaner air that the shift-average CO exposure is within acceptable levels. During wildfire suppression, the maximum 5-minute CO levels averaged 55 ppm, with a 95th percentile of 58 ppm. At prescribed fires, the maximum 5-minute CO levels averaged 72 ppm, with a 95th percentile of 234 ppm. In our view, the higher peak exposures during prescribed fires reflect the incentives among firefighters to maintain prescribed fires within designated unit boundaries.

<u>CO exposures in fire camp can be a problem especially if the camp is affected by inversion and if the smoke source is nearby</u>

Some past studies from the 1980s and 90s documented inversion conditions affecting incident command posts for days or even weeks, but in recent years improved attention to locations of fire camps, and use of spike camps has reduced the number of incidents. The National Institute for Occupational Safety and Health (NIOSH) measured occupational exposures to CO among 19 fire staff and logistical support contractors in the base camp at the Siskiyou/Ukonom fires on the Klamath National Forest in northern California on two days in August 2008 (McCleery *et al*. 2011). They found that shift-average CO exposures were low (below 6 ppm), although peak CO levels very briefly exceeded recommended OELs. The San Dimas Technology and Development Center, one of four detached engineering units of the U.S. Forest Service, measured smoke exposure during 64 days in incident command posts and at spike camps, and did not find a single 24-hour CO exposure above 1 ppm. The Idaho Cascade Complex fire of 2007 was a notable exception, where CO levels were estimated at 30-40 ppm for over 24 hours. The CO levels were high because the camp was situated in a valley near the active fire and a burnout operation was conducted to protect the camp while leaving the camp personnel in place.

Respirable Particulate Matter

Exposure to PM_4 can significantly exceed currently-recommended OELs at both prescribed fires and wildfires. Sampling from 2009-2011 by San Dimas Technology and Development Center found that the average shift-TWA exposure for PM_4 was about 600 $\mu g/m^3$, and it exceeds the MTDC ad hoc committee recommendations of 1000 $\mu g/m^3$ roughly 17% of the time (Broyles 2012).

Respirable Crystalline Silica

Wildland firefighting is a very dusty business, and soil dust exposure is expected to be a general hazard at all times. NIOSH found that 15% of respirable dust collected near the firefighters breathing zone at wildfires in Montana contained significant amounts of crystalline silica. Of the significant amounts they found exposures at 50% and 430% of the OSHA PEL (Kelly 1992). Sampling at California wildfires found that 24% of respirable dust samples had detectable levels of respirable crystalline silica that ranged up to 90% of the Cal/OSHA PEL (Materna *et al.* 1992). Preliminary data from 2010-2011 show that respirable crystalline silica exposure averages about 40% of the PEL at wildfires, and exceeds the PEL about 9% of the time (Broyles 2012).

Other Pollutants at Wildland Fires

- **Polycyclic aromatic hydrocarbons have not been found at unacceptable levels—**Exposure to PAHs was measured during pile burns in Arizona in 2006 (Robinson *et al.* 2008), in the New River Gorge of West Virginia in 1991 (Kelly, 1992), and in northern California in 1987-89 (Materna *et al.* 1992). In all cases, exposures to PAHs were relatively low. However, there have not been PAH measurements taken in extremely smoky conditions. Risk assessment assuming worst-case conditions over a career did not find a major cancer risk from PAHs among firefighters (Booze *et al.* 2004).

- **Acrolein and formaldehyde contribute to respiratory irritant exposures from smoke—** Occupational exposures of wildland firefighters to formaldehyde and acrolein were measured by the Forest Service at wildfires and prescribed fires in the western U.S. during the 1990s (Reinhardt and Ottmar 2004). They were considered the most likely to pose an inhalation hazard, based on the relatively low OELs and wildland fire emission factor data; most of time, the exposures at wildfires and prescribed fires were within levels considered safe for healthy workers working 40 hour a week for a lifetime. However, it was found that exposure to a combination of the respiratory irritants (formaldehyde, acrolein, PM_4) was of concern up to 30 % of the time. Because this conclusion was made while PM_4 was thought to be only an irritant and without appreciable toxicity, the percentage of overexposures would now be considered higher.
- **Herbicides have not been detected in prescribed fires occurring within months of their application—** Respirable particulate exposure measured at 14 “brown and burn” herbicide-treated units undergoing prescribed fires in Georgia during 1988 (McMahon and Bush 1992) did not detect exposure to herbicide residues, despite a median PM3.5 (now called PM_4) exposure of 1,300 µg/m3.
- **SO_2 and NO_2 have been detected in smoke, but further work is needed—**Two studies by NIOSH have found these respiratory irritants to be a potential issue among firefighters (Kelly 1992, and Reh 1992). One study found the SO_2 average level equaled the NIOSH recommended exposure limit (REL) of 2 ppm, with 23 samples at or above this (ranging up to 9 ppm in one sawyer). At a 1990 fire in Yosemite National Park, Reh *et al.* (1994) reported average exposures among one Type 1 crew of 1.4 ppm SO_2, with one SO_2 sample above the NIOSH REL of 2 ppm (Reh *et al.* 1994). A second Type 1 crew monitored averaged 1.4 ppm SO_2, again having one sample over the REL. The problem with these measurements is they seem high considering the relatively low levels of other smoke components, and the relative amounts of SO_2 that would be expected from emissions research. Because the measurements were made with a direct-reading device that is prone to positive bias from other pollutants we would expect in smoke, measurements using more robust methods should be done to evaluate this issue. Exposure to NO_2 was measured in Portugal during prescribed fires in 2008 and 2009 using electronic dosimeter technology (Miranda *et al.* 2010). The vegetation was similar to chaparral in the Southwestern United States. Peak NO_2 exposures briefly exceeded the 5-ppm OSHA ceiling exposure limit for 14 of 20 firefighters.

In summary, several studies examining smoke exposure among firefighters have identified inhalation hazards that should be of concern to occupational health professionals and supervisors responsible for employee safety and health. Carbon monoxide can be a problem, but respiratory irritants are a more common problem. Because of the evidence of cellular toxicity, oxidative stress, and systemic inflammation response that has been linked to wildfire PM_4, a lower shift-duration OEL for PM_4 of 1,000 µg/m^3 or less is being considered by OSHA. This is less than or equal to 20% of the current PEL for nuisance dust particulates not otherwise regulated—5,000 µg/m^3 which, in the past, was assumed to be appropriate for wildland firefighting. Meeting this lower criterion should prevent adverse health effects from the other known and suspected contaminants in smoke.

Monitoring Smoke Exposure of Fireline Workers

Sampling for most key potential contaminants in smoke requires expensive equipment, substantial expertise, and coordination. However, several studies have found that exposure to PM_4 and other respiratory irritants are reasonably well-predicted from easy-to-measure carbon monoxide (CO) if firefighters are close the active combustion zone of the fire (McMahon and Bush 1992, Reinhardt and Ottmar 2004, Adetona *et al.* 2011b). Consequently, fire managers and safety officers concerned with smoke exposure among fire crews on the fireline can easily use electronic CO monitors to track and prevent overexposure to smoke (figures 2.2.4 and 2.2.5). Commonly referred to as dosimeters, these

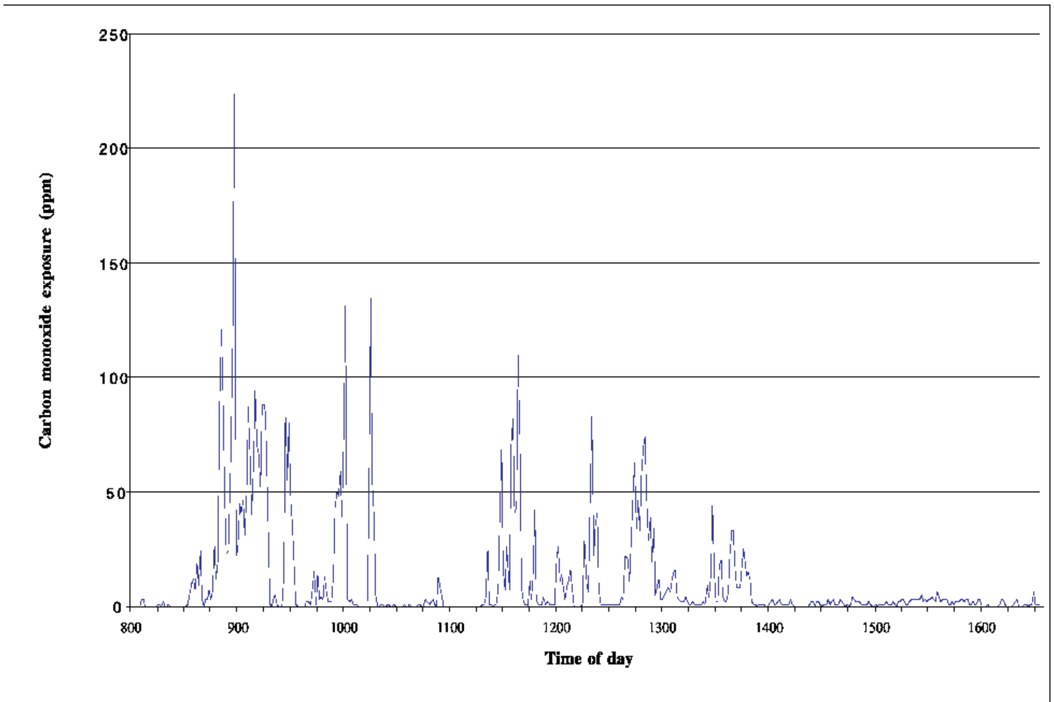

Figure 2.2.4 Carbon monoxide exposure data from electronic CO data recorder for a firefighter during a work shift on a prescribed fire (Reinhardt *et al.* 2000).

lightweight battery-powered instruments are small, weigh only a few ounces, and measure the concentration of CO in the air that fireline personnel breathe. Protocols have been developed for sampling smoke exposure among fireline workers equipped with CO dosimeters. These protocols and a basic template were outlined by Reinhardt *et al.* (1999) for managers and safety officers interested in establishing their own smoke-exposure monitoring program. In the last few years, the USDA Forest Service San Dimas Technology and Development Center has used these dosimeters extensively and gained substantial experience in the advantages and disadvantages of various models available (Broyles 2012) (figure 2.2.4). With simple steps to ensure the dosimeters are not affected by wide temperature fluctuations or fireline radiofrequency emissions, these units are generally rugged and reliable enough for routine use among fire crews. Published correlations can be used to estimate exposure to other components in smoke based on the CO measurements (McMahon and Bush 1992, Reinhardt and Ottmar 2004, Adetona *et al.* 2011b). However, correlation estimates do not include respirable crystalline silica from soil dust. That hazard will have to be evaluated and managed some other way.

Respiratory Protection

There are respirators designed to remove inhalation hazards for a wide range of industrial uses. Air-supplying respirators such as those on an airline from a clean air source, or self-contained breathing apparatus used in structural firefighting and are not designed for mobile crews such as wildland firefighters. Quality air-purifying respirators that can serve a mobile workforce have removable cartridges for specific air contaminants. However, they are complicated devices and are not as easily used as a one-piece nuisance dust mask. A dust mask gives limited protection because air can easily bypass the material. It is only slightly better than a bandanna, and neither protects against the very small particles and gases in smoke.

It is tempting to think that a respirator should be the first choice to prevent exposure to smoke. But it is long known among safety professionals that respiratory protection, like any personal protective equipment, should be the last resort to protect against a hazard. There are several reasons they should be used only as a last resort:

- Employee may not know the respirator equipment limitations;
- Employee may use the wrong filter elements in air-purifying respirators;
- Employee may not recognize when they are not being protected due to inadequate sealing or fit of their respirators;
- Employees may find the breathing restriction, heat stress or claustrophobia intolerable;
- Employee's life may be in danger if respirator malfunctions;
- Employee may have a false sense of security and move into an area that is too dangerous; and
- Respirator could reduce the ability to communicate.

Although respirators reduce work capacity, the correct respirator may minimize hazardous exposures under certain circumstances. Field evaluations by MTDC found that existing models of disposable respirators could be acceptable for short-term use but they deteriorated in the heat during several hours of use (Sharkey 1997). Maintenance-free half-mask respirators could be satisfactory except for the heat stress found with all facemasks. Full-face respirators had the added benefit of protecting the eyes from irritant gases and particulate matter, but they also remove eye irritation as an important early warning of exposure to smoke. Full-face masks were preferred for long-term use on prescribed fires because of the eye protection they provided, but workers complained of headaches, a sign of excess CO exposure since existing respirators did nothing to stop exposure to CO (Sharkey 1997). Likewise, though the recent focus on PM_4 shows it is more than a nuisance, we must realize that using respiratory protection designed only to prevent exposure to PM_4 could cause firefighters to endure higher exposures to the other contaminants if they were not also removed by the respiratory protection. For all these reasons, a respirator designed specifically for wildland firefighting is needed.

Figure 2.2.5. Firefighters equipped with breather zone samplers and CO dosimeters.

Since the last version of this guide, the National Fire Protection Association (NFPA) established the NFPA 1984, "Standard on Respirators for Wildland Fire Fighting Operations" (NFPA 2011). Developed with contributions from specialists in wildland firefighting, respiratory protection equipment, and occupational health, NFPA 1984 is a comprehensive standard for a respirator that is to be used in wildland fire conditions that are above OELs, but not immediately dangerous to life and health (called non-IDLH conditions).

Finally, recognize that any use of respirators among fireline workers must be in accordance with a written respiratory protection program that ensures fireline workers are medically fit to work in a respirator, defines the respirators to be used and conditions of use, provides for testing to make sure the respirator fits properly, and is effective at training staff in the proper use and limitations of the respirators issued to them.

Exposure at Fire Camps

Studies of firefighters and their exposure to smoke have mainly targeted personnel on the fireline. Few studies have monitored personnel in fire camp. Fire camps are located in areas of convenience, often in valleys where smoke can concentrate under inversion conditions (figure 2.2.6). Incident command team members and camp support personnel stationed at camp can be exposed to very high levels of CO, PM_4, and other hazardous compounds for hours, days, and—in certain cases—weeks (National Interagency Fire Center 2007). When firefighters are exposed to smoke both on the active fireline and in camp, they may develop respiratory ailments.

Anecdotally, when overexposed to CO, personnel have reported decreases in mental acuity and decision making capacity (cognitive skills) and disorientation (USDA-Forest Service, Intermountain Region, November 9, 2007). In response to this concern, the National Wildland Fire Coordinating Group (NWCG) issued a memorandum providing guidance for monitoring and mitigating exposure to CO and particulates at incident base camps (NWCG 2012). Considering the long periods of time personnel can spend in smoke, NWCG used suggested exposure limits from OSHA and recommended an interim exposure guideline of 8 ppm CO over 24 hours, and 16 ppm for any 13-hour work shift. NWCG also recommended a $PM_{2.5}$ exposure limit of 84 µg/m^3 over 24 hours. Electronic monitors for CO and $PM_{2.5}$ or PM_4 could be positioned in fire camp to monitor exposure at camp that trigger management actions if levels exceed these recommendations. Management actions to reduce exposure at fire camp include the following:

- Camp evacuation/relocation
- Clean air tents with filters
- Rotating personnel
- Wetting the area reducing road dust

Management Implications

Evidence confirms that wildland firefighters are exposed to a variety of pollutants at levels that can exceed recommended exposure limits. It is common for short-term or ceiling exposure limits to be exceeded during brief but intense exposures. The resulting acute adverse health effects require management intervention to reduce the exposure. Although shift-average exposures to CO and respiratory irritants other than PM_4 generally are unlikely to exceed recommended exposure limits, they occasionally are. These shift average exceedances and longer-duration exposures will require management action. Recent NWCG guidance on a PM_4 OEL for smoke exposure during wildland firefighting recommended a reduction in the acceptable exposure limit on a shift-average basis, and this may be

Figure 2.2.6. Fire camp at Cascade Complex, 2007.

adjusted further as ongoing research is completed. This means that proportionately more exposures will be judged unacceptable for long-term health of firefighters. The existing respirable crystalline silica PEL is also exceeded during dusty operations across the United States, and fire managers need to evaluate and control this hazard on a routine basis.

Both short-term and shift-average smoke exposure can be managed through a variety of engineering and administrative controls, and effective personal protective equipment will be available in the near future when the first two steps are not adequate or feasible.

The use of respirators will: (1) require a concerted coordination effort among agencies, and (2) add significantly to logistic and operational workloads. Respirator use also poses a risk of unrecognized contaminant exposure if the wrong type of respirators are used or they are not properly fit to the users, and a bacterial or chemical contact hazard if they are inadequately cleaned between uses. Most concerning is the possibility of increases in heat-related illness, and injury or deaths from communication breakdowns and erosion of situational awareness. For these reasons, electronic CO dosimetry may be a much simpler way to manage the smoke exposure problem and minimize the human burden and risk of injury or death that could occur with respirators.

The concept that few fireline personnel spend a working lifetime in the fire profession is not a reason to exempt them from occupational exposure standards. It is irrelevant for irritants and fast-acting hazards such as CO. Many of the exposure limits that are exceeded are established to prevent acute health effects, such as eye and respiratory irritation, headache, nausea and angina. Where OELs are in place to prevent chronic health effects from exposure to smoke, the smoke exposure standard needs to be established based on a risk assessment that considers career-long exposure patterns. The NWCG is addressing this issue.

Smoke exposure is both a health and safety issue and should be addressed at each wildland fire briefing, at each safety tailgate briefing, in each burn plan, and in the job hazard analysis (JHA). It is the responsibility of management, crew bosses, and individuals to know the potential acute and chronic effects that may result from exceeding smoke exposure limits, and how best to manage and limit exposure. Early in their careers, employees and supervisors of those employees who could be exposed to wildland fire smoke should be offered training in the health effects of smoke inhalation and how to mitigate exposure. For additional information see the 2014 WFSTAR video – Smoke: Knowing the Risks (WFSTAR 2014) and the Wildland Fire Personnel Smoke Exposure Guidebook (SmoC 2016).

Finally, a long-term program to manage smoke exposure at wildland fires is needed (Sharkey 1997). The program should include:

- Training on the hazards of wildfire smoke inhalation;
- Training on human senses and how they can be used to provide an indication of smoke exposure and when mitigation measures should be considered;
- Implementation of practices to reduce smoke exposure from wildfire, including rotating individuals and crews, reducing mop-up where appropriate, and locating fire camps where smoke is less likely to concentrate;
- Implementation of practices to reduce smoke exposure from prescribed fires including rotating individuals and crews, reducing mop-up where appropriate, burning under higher fuel moistures, using sprinklers and foam to reduce holding activity, and using specific patterns of igniting fuels to pull fire away from the fireline;

- Implementation of practices to reduce crystalline silica exposure by rotating individuals and crews, reducing dry mop-up, separating when hiking on dusty paths, keeping trucks separated that are transporting crews in open vehicles on dirt roads, reducing travel on dusty roads in open vehicles, and wetting down fire camp area to reduce dust;
- Routine CO monitoring using electronic dosimeters on the fireline and in fire camp where potential smoke accumulation could occur, and for respirable dust using portable electronic instruments, especially where crystalline silica is present in soils;
- Improve record keeping to include separation of smoke-related illness among fireline workers and fire camp personnel;
- Long-term health and epidemiological surveillance to detect chronic health problems and evaluate mortality patterns;
- Considering implementation of an OSHA-compliant respirator program to protect fireline personnel from PM_4 and other respiratory irritants, and CO when they must work in smoky conditions; and
- Continue research on exposure and monitoring of firefighters and other personnel on the fireline and at fire camps, and consult with OSHA on regulatory standards.

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2.3 Smoke and Transportation Safety

Anthony Matthews

Introduction

Particulate matter and water vapor produced from wildland fires (both wildfires and prescribed fires) can be a transportation safety hazard to both the public and fire personnel. Some highway fatalities have occurred in which smoke and reduced visibility were factors in the accident. In fact, of all issues related to prescribed fire, the presence of smoke on roadways has the greatest potential to result in a fatality or serious injury to the public. Because of this, transportation safety should always be a critical planning and operational consideration. Most transportation safety accidents related to smoke have occurred on highways. However, there have also been instances where smoke has affected airport traffic up to 70 miles downwind. Conditions were described as being similar to poor weather conditions where pilots had to make adjustments and land via instrument (figure 2.3.1).

Figure 2.3.1. Wildland fire smoke can be a serious problem when it affects airports.

Although smoke from most prescribed fires does not affect visibility enough to be dangerous, it can become a problem on highways anywhere in the country. Examples of smoke induced loss of visibility are not unique to any region; reduced visibility because of smoke has been a factor in highway collisions from Florida to Wisconsin to Oregon. As recently as March 2013, smoke from a prescribed fire contributed to the death of a crew person who was hit by a vehicle in New Jersey. However, it is in the Southeast where smoke on highways is an important safety issue due to the meteorology and topography, combined with population density, road density, and fire frequency. When planning to address such dangerous conditions, it is crucial for fire personnel to understand the smoke situations that reduce visibility and compromise transportation safety.

Smoke and Visibility Reduction

Smoke impacts on roads may happen any time during the course of a wildland fire, but they frequently occur in valley bottoms and drainages during the night and early morning hours. About 30 minutes before sunset, air cools rapidly near the ground and wind speeds decrease as the cooled stable airmass "disconnects" from faster moving air just above it.

High concentrations of smoke accumulate near the ground, particularly smoke from smoldering fuels that don't generate much heat and is not lofted high into the atmosphere. Smoke then tends to flow down drainages with little dispersion or dilution (figure 2.3.2). If the drainages are humid, particles in smoke can act as nucleating agents and can actually assist in the formation of local fog—a particular

Figure 2.3.2. Nighttime smoke moving down drainage.

problem in the Southeast. The worst condition is known as "superfog." Typically, the heaviest fog occurs where smoke accumulates in a drainage. Here it can reduce highway visibility and create hazardous conditions where drainages intersect roads or bridges.

Visibility along highways also may be reduced as direct impact of the smoke plume. Fine particles (less than 2.5 microns in diameter) of smoke are usually transported to the upper reaches of the atmospheric mixing height, where they are dispersed. However, smoke can drift across highways near the burn (figure 2.3.3) or travel miles downwind and settle on highways. In either case, visibility may be reduced to the point that vehicular travel may become dangerous, requiring actions to mitigate the hazard. Not only does this create a problem for the public, but also for fire personnel who may be operating vehicles or trying to manage traffic in hazardous conditions.

Figure 2.3.3. Wildland fire smoke can decrease visibility on highways, day or night. Managing vehicle traffic to maintain safe driving conditions both for operational and public safety is very important.

Smoke in the wildland urban interface, or WUI, is of particular concern (figure 2.3.4). Compared to the other regions in the United States, southern forests have the most frequent use of prescribed fire and the greatest number of acres (more than 10 million in 2011) subjected annually to prescribed fire (Melvin 2012). With direct connections of human habitation and activity through an enormous WUI, the potential exists for significant smoke problems. In 2007, the

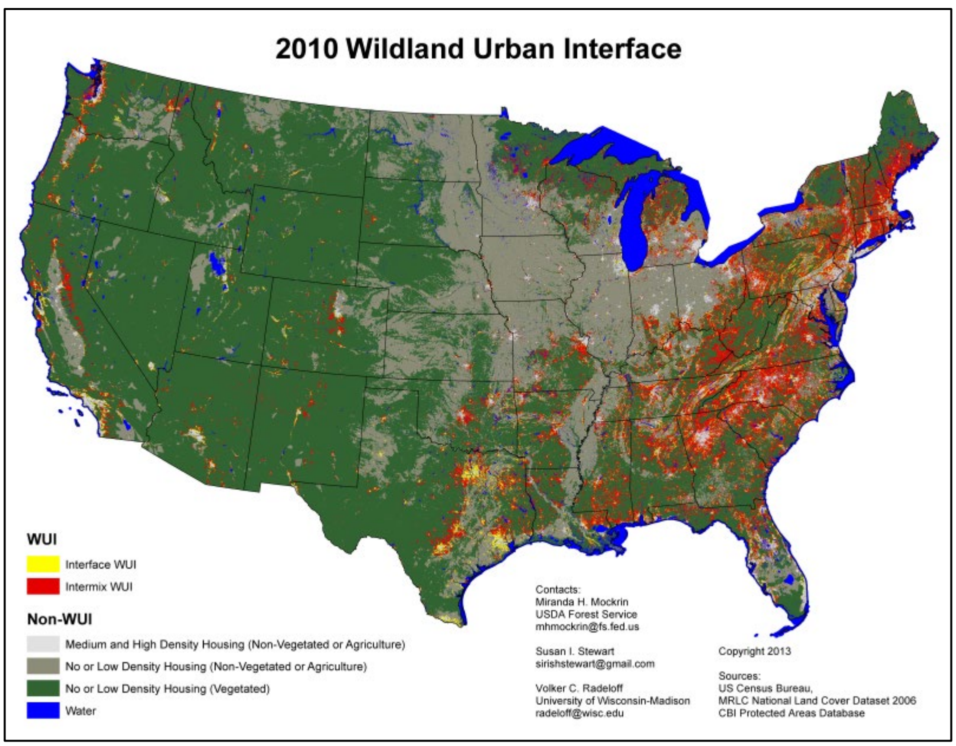

Figure 2.3.4. Population density and wildland/urban interface as of 2010. The Southeast has a large amount of wildland urban interface which is shown by the predominance of red and yellow in the figure and which corresponds with forest types where prescribed fire is frequently used (Stein *et al.* 2013).

Southern Research Station published a report (Wade and Mobley, 2007) that offers information and guidance on managing smoke within the WUI.

Smoke on the Highways

Over 20 million acres of forest and agricultural lands in the United States are treated with prescribed fire each year, most without incident (Melvin 2012). However, smoke, and combinations of smoke and fog, can obstruct visibility on highways, sometimes contributing to accidents with loss of life and personal injuries.

Smoke is most often trapped by either a surface inversion or an upper-level inversion. These are conditions in which temperature increases with height through a layer of the atmosphere. Vertical motion is restricted in this very stable air mass. Although most inversions dissipate with daytime heating, upper-level inversions caused by large scale subsidence may persist for several days, resulting in a prolonged smoke management problem (Chapter 5.1).

Most smoke-related highway accidents occur just before sunrise when temperatures are coldest and smoke entrapment has maximized under a surface-level inversion. The high sun angle during the burning season contributes to warm daytime temperatures. Near sunset, under clear skies and near-calm winds, temperatures in shallow stream basins can drop up to 20 °F in one hour (Achtemeier 1993). Smoke from smoldering heavy fuels (large diameter woody fuels) and organic layers can be entrapped near the ground and carried by local drainage winds into these shallow basins where temperatures are colder and relative humidity is higher.

Hygroscopic particles within smoke, as well as water from the combustion process, can assist in development of locally dense fog. Drainage winds as low as about 1 mile per hour (0.5 m/sec) can carry smoke over 10 miles during the night—far enough in many areas to carry the smoke or fog over a roadway.

Several attempts to compile records of smoke-implicated highway accidents have been made. For the 10-year period from 1979 to 1988, Mobley (1989) reported 28 fatalities, more than 60 serious injuries, numerous minor injuries, and millions of dollars in lawsuits. In 2000, smoke from wildfires drifting across Interstate 10 caused at least 10 fatalities: five in Florida and five in Mississippi. In the winter of 2008, a small prescribed fire escaped and became a wildfire. Smoke from this wildfire combined with heavy fog and contributed to a 70-vehicle pileup. The result included heavy damage to vehicles, 5 fatalities, and numerous injuries.

In their study of the relationship between fog and highway accidents in Florida, Lavdas and Achtemeier (1995) compared three years of accident reports that mentioned smoke, with data about fog from nearby National Weather Service stations. Highway accidents were more likely to be associated with local ground radiation fog than with widespread advection fog. Accidents tended to happen when fog created conditions of sudden and unexpected changes in visibility.

Radiation and Advection Fog

Robert Fovell*, Prof. University of California, Los Angeles

Radiation Fog: The infamous California Central Valley wintertime fogs are a classic example of radiation fog. Particularly over low heat capacity surfaces (such as soil and asphalt), the air can be cooled by radiation and conduction to its dew point over a relatively deep layer. This often forms on clear, calm nights, when (other things being equal) maximum cooling occurs to the air very near the ground. The longer the night, the more cooling can occur, so radiation fogs are most common over land in the winter. This represents the dew point approach to saturation.

Some points regarding radiation fog are:

- induced by radiative/conductive cooling of air near the surface, especially at night
- most common in winter: longer nights and colder air which is easier to saturate
- calm conditions favor this fog, windy conditions destroy it
- clear conditions favor this fog, since the atmospheric window isn't closed
- these fogs like to form in valleys, owing to cold air drainage
- particularly dense examples can persist for days

Advection Fog: San Francisco's famous summertime fogs are an example of advection fog. Advection implies air movement (especially in the horizontal), so this fog forms somewhere else and then "rolls in" (i.e., it is advected).

Warm moist air originating over the warm central Pacific is carried by the winds over colder waters off the California coast. There, the air is chilled from below down to its dew point, and a fog is produced. Then, the winds blow the fog inland over San Francisco. This is also the dew point approach to saturation.

Advection fogs also form over land in the winter. In the southern states, warm moist air originating from over the Gulf of Mexico gets blown over cold land and chilled from below. Since this is a combination of horizontal air movement (advection) and radiative cooling (that's how the land got cold), this example is often referred to as "advection-radiation fog". This is not to be confused with pure radiation fogs, which tend to dissipate when the winds increase.

*From posted presentations available at Fovell 2008.

Planning to Avoid Visibility Impacts

All prescribed fires should be designed to avoid impacting roads with smoke. This means understanding smoke movement during the fire as well as movement of residual smoke at night, and understanding high risk meteorological conditions. There are several factors that fire managers should consider when planning to meet this goal. Where conditions increase the chance of impacting a road with smoke (e.g., high road densities and/or weather), mitigation measures should be developed and implemented.

Know the region

Fire managers should develop a clear understanding of the topography in and around the burn area. This includes identifying drainages, bogs, lakes/ponds, streams, other areas of moisture, and open areas such as meadows and fields, that can provide means for smoke to move toward highways. Use local knowledge and expertise to assess the risks and to map highway locations that could be impacted by smoke, realizing that any residual smoke will tend to move down-drainage throughout the night.

Be proactive and be aware

Mitigation plans may need to be made, especially if roads are nearby or at a distance down-drainage that could be impacted by smoke and fog. The posting of signs to make motorists aware of potential smoke and fog conditions should be coordinated with appropriate state and local authorities (i.e., Highway Patrol or Dept. of Transportation). Patrolling roads during the night and early morning hours may be necessary. Remember, any personnel involved in nighttime patrols of low visibility areas will be working with an increased risk of accident. They may not be able to see other vehicles, and other drivers may not be able to see them. Thoughtful planning is required to assure the safety of those personnel.

The following is a list of situations or conditions that agency administrators and fire managers should pay attention to when planning and implementing prescribed fires. This information is offered as a tool for fire managers to use in designing and implementing an effective and efficient smoke management strategy on prescribed burns. Answering the following questions "yes" may indicate a need to strengthen or modify mitigation measures.

Planning the Prescribed Burn (Burn Plan Preparation)

Prescribed burn planning begins with the goal of protecting public and firefighter health and safety. A key is to avoid putting smoke on a highway, day or night.

- Are ignition activities, active burning, or smoldering planned during the period "2 hours before sunset to 2 hours after sunrise"?
- Are smoke-sensitive receptors, especially highways, "down-drainage" from the prescribed burn and within a distance that smoke can "flow" to during the night (up to 10+ miles)? Remember, the steeper the topography, the farther smoke can travel.
- Is the prescribed burn planned to occur when the potential for fog is high?
    - Highest potential for fog typically occurs from late fall to late spring.
    - Ground and water temperatures can remain warmer than the cooling air temperature, creating conditions conducive for fog.
- Does the prescribed burn unit contain pockets of heavy fuels (hurricane damage, fallen beetle-killed timber) that could burn and smolder for long periods?
- Is there a heavy duff layer or organic soils which could smolder for long periods if ignited?
- Is there open water within or adjacent to the prescribed burn (streams, rivers, lakes, ponds or canals)?
- Are there openings (fields or power lines) next to the prescribed burn that could funnel smoke toward a highway or other smoke sensitive area?
- Are there roadways nearby that have experienced fog- or smoke-related visibility problems in the past?
- Is the prescribed burn unit large with few options to effectively stop the fire if things don't go as planned?
- What is the potential for local weather phenomenon to affect the prescribed burn?
    - Sea breezes
    - Sea fog or advection fog

    - "Atmospheric walls" that can form over water and cause smoke to concentrate over the coastline
    - Mountain inversions
- Does the prescribed burn plan contain appropriate contact information and contingencies for situations where smoke crosses highways, day or night?
- Is smoke monitoring planned during and after the prescribed burn? How often will weather updates be needed?
- Is a road visibility problem anticipated? If so, assess the necessity of the prescribed burn on that day and consider delaying the fire until conditions improve. If the burn is to be conducted, then ask for assistance of appropriate jurisdictional authorities (Department of Transportation (DOT), Sheriff, State Highway Patrol) several days before planned burn day.
- Is the prescribed burn window long enough to complete the burn? Is it long enough for flaming fronts and residual smoldering to cease and the smoke to adequately disperse?

<u>Implementing the Prescribed Burn</u>

Successfully implementing a prescribed burn plan includes keeping roadways safe, thereby protecting public and firefighter health and safety. Implementation questions to consider include:

- Does the spot weather forecast warn of potential fog (usually part of the narrative)?
- Do forecast indices indicate potential problems with nighttime smoke?
    - Low Visibility Occurrence Risk Index (LVORI) ≥ 7
    - Nighttime atmospheric dispersion index of < 5
- Are dew point and temperature predicted to move to within a few degrees of each other during the evening hours (i.e., high relative humidity)?
- Is the plan to rely on predicted nighttime winds to continue dispersing smoke?
    - Nighttime smoke typically has no buoyancy to gain vertical lift and be influenced by upper winds
    - Regardless of forecasts, diurnal, surface winds tend to be calm to light and variable, resulting in down-drainage movement of smoke
- Do National Fire Danger Rating System (NFDRS) indices indicate that heavy fuels may ignite? Are snags and heavy fuels igniting unexpectedly?
    - 100-hr fuel moistures less than 14%
    - 1000-hr fuel moistures less than 19%
    - Keetch-Byram Dispersion Index (KBDI) > 400
    - Days since rain (figure 2.3.5)
- Do equipment breakdowns occur or firing patterns change, causing ignition delays and increasing the risk of active burning and smoldering into nighttime hours?
- Are other prescribed burns occurring in the same airshed, potentially increasing Nighttime Smoke Dispersion issues?

- Is the smoke from the prescribed burn not dispersing as forecasted?
- Has a "new" event/gathering resulted in an area unexpectedly becoming a smoke sensitive receptor and increasing area traffic (e.g. large public gatherings or national events like the Daytona 500, tournaments, balloon events, etc.)?
- Is the smoke contingency planning prior to ignition adequate and verified that it anticipates the day's specific conditions?

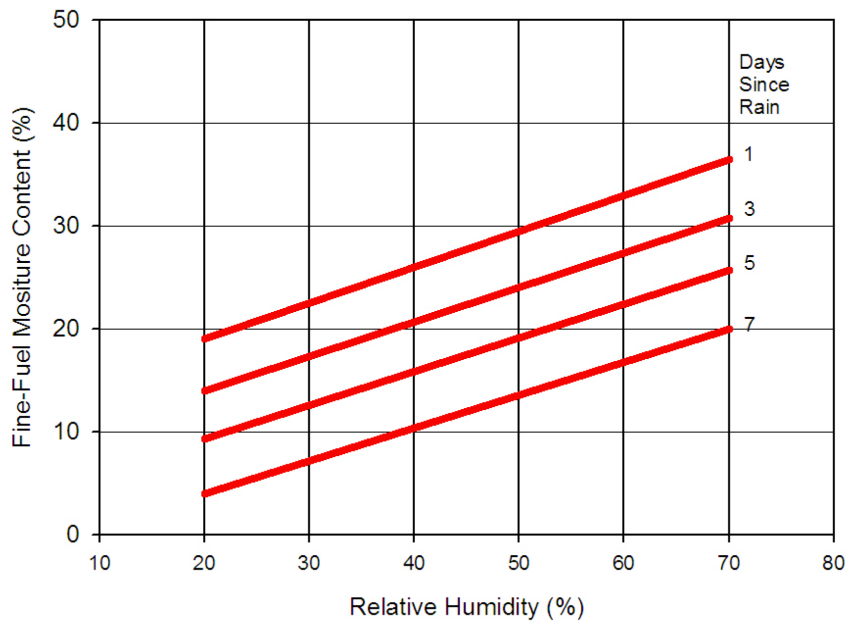

Figure 2.3.5. As days since rain increase, fine fuel moisture content decreases. From Waldrop and Goodrick 2012.

NFDRS (National Fire Danger Rating System)

NFDRS is a complex set of equations that use measured variables and user-defined constants to calculate daily indices and components used for decision support in wildland fire. The system takes into account current and antecedent weather, fuel types, and both live and dead fuel moisture.

One of the key indices in the NFDRS is the KBDI (Keetch-Byram Drought Index), created by John Keetch and George Byram (1968). KBDI is based on mathematical models for predicting the likelihood of wildfire based on soil moisture and other conditions related to drought. The KBDI is a measure of meteorological drought; it reflects water gain or loss within the soil. It does not measure fuel moisture levels in the 1- to 10-hour fuel classes; those must be measured by other means for an accurate assessment of fuel moisture, regardless of the drought index readings.

As a soil/duff drought index, KBDI ranges from 0 (no drought) to 800 (extreme drought) and reflects soil moisture depletion based on a capacity of 8 inches (200 mm) of water. The depth of soil required to hold 8 inches of moisture varies. A prolonged drought (high KBDI) influences fire intensity largely because fuels have lower moisture content.

Tools for Managing Smoke and Visibility on Highways

A few tools that may be useful in burn planning to insure safe highway travel include:

Weather Forecasts

The National Weather Service (NWS) provides dense fog advisories as well as Warnings, Alerts, Advisories, Watches and Statements which are displayed on the U.S. map at https://www.weather.gov/. Predicting fog is very difficult. If the weather forecast calls for fog or patchy fog in an area, use caution in making decisions to go ahead with a prescribed burn or to manage highway traffic when responding to wildfires.

VSMOKE

VSMOKE is a tool that estimates downwind emissions concentrations and visibility, primarily intended to represent the effects of a single prescribed fire (Lavdas 1996). It generates an estimate of emissions, plume rise, and dispersion based on a Gaussian plume dispersion model which indicates smoke concentrations at distances directly downwind from the fire. Visibility is estimated at the same downwind distances as emissions. Atmospheric dispersion index values and LVORI index (described below) values are also generated. The VSMOKE tool is used extensively by managers in the Southeastern United States VSMOKE can be downloaded from the Forest Service Region 8 & 9 Air Resource Management website (U.S. Forest Service, Air Resource Management 2015).

Planned Burn-Piedmont (PBP)

PBP (Achtemeier 2001) is a land surface model designed to simulate smoke movement/dispersion near the ground under entrapment conditions at night. The smoke plume is simulated as an ensemble of particles that are transported by local winds over complex terrain characteristic of the shallow (30-50 m) interlocking ridge/valley systems typical of the Piedmont of the South. PBP does not predict smoke concentrations because emissions from smoldering combustion are usually unknown. PBP is designed to work in the southern Piedmont but has applicability elsewhere where shorter range surface smoke flow estimation is needed, displaying the simulated smoke plume on a map of the area. This web based tool can be found at the following URL; https://cefa-new.dri.edu/PB_Piedmont/ . For further details about PBP refer to Chapter 5.2.

Atmospheric Dispersion Index (ADI)

The ADI is a numerical index estimating the ability of the lower atmosphere to disperse wildland smoke (Lavdas 1986). Based on physics assumptions and mathematics, the index is expressed as a positive number. The higher the number, the more effectively the atmosphere can disperse pollutants. A doubling of ADI implies the effective doubling of the ability of the atmosphere to disperse twice as much smoke. The ADI was originally developed to help assess the "diluting power" of the lower atmosphere for prescribed fires. However, it is just as relevant for wildfires. At sunrise, ADI is normally low. As the sun gets higher and induces more heating, the ADI will climb. At first, the increase will be minimal. On average, the best dispersion will occur early to mid-afternoon. After this period, dispersion will start to degrade and towards sunset, it rapidly drops where vertical lifting is practically nonexistent. This index is often used in fire planning, not just for transportation issues. For further details about ADI refer to Chapter 5.2.

Automated Surface Observing Systems (ASOS)

This program is a joint effort of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DoD) (NWS 2015a). The ASOS systems serve as the nation's primary surface weather observing network. ASOS is designed to support weather forecast activities and aviation operations and, at the same time, support the needs of the meteorological, hydrological, and climatological research communities.

The primary concern of the aviation community is safety, and weather conditions often threaten that safety. A basic strength of ASOS is that critical aviation weather parameters are measured where they are needed most: airport runway touchdown zone(s).

ASOS detects significant changes, disseminating hourly and special observations via the networks. Additionally, ASOS routinely and automatically provides computer-generated voice observations directly to aircraft near airports by using FAA ground-to-air radio. These messages are also available via a telephone dial-in port. ASOS observes, formats, archives and transmits observations automatically. ASOS transmits a special report when conditions exceed preselected weather element thresholds, e.g., the visibility decreases to less than 3 miles.

ASOS reports basic weather elements:

- Sky condition: cloud height and amount (clear, scattered, broken, overcast) up to 12,000 feet,
- Visibility (to at least 10 statute miles),
- Basic present weather information: type and intensity for rain, snow, and freezing rain,
- Obstructions to vision: fog, haze, smoke,
- Pressure: sea-level pressure, altimeter setting,
- Ambient temperature, dew point temperature,
- Wind: direction, speed and character (gusts, squalls),
- Precipitation accumulation,
- Selected significant remarks including- variable cloud height, variable visibility, precipitation beginning/ending times, rapid pressure changes, pressure change tendency, wind shift, peak wind.

Superfog Potential Table (SFP)

SFP table 2.3.1 provides a probability for the formation of superfog. It combines an atmospheric mixing model (Achtemeier 2008) with observations of smoldering fire air masses to measure the probability of superfog. The potential of a superfog event is the percentage of air masses with smoke from smoldering that lead to superfog conditions when mixed with ambient air at certain temperatures and relative humidity. It is very important to note that this superfog potential does not include the influence of wind/mixing. Winds need to be calm. It has been demonstrated in the laboratory (Bartolome 2013) optimum wind speeds for superfog formation were ≤ 2.2 mph and NWS Superfog Smart Tool for natural fog formation uses a wind speed ≤ 4 mph. Both these wind speed thresholds would be considered calm for a fire weather forecast. For further details about superfog potential refer to Chapter 5.2.

Table 2.3.1. Superfog Potential table for smoldering combustion on prescribed fires.

Relative Humidity (%)	Temperature (°F) 30	35	40	45	50	55	60	65	70	75	80
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0
45	10	0	0	0	0	0	0	0	0	0	0
50	20	0	0	0	0	0	0	0	0	0	0
55	30	10	0	0	0	0	0	0	0	0	0
60	40	10	0	0	0	0	0	0	0	0	0
65	50	20	10	0	0	0	0	0	0	0	0
70	60	40	10	0	0	0	0	0	0	0	0
75	80	50	30	10	0	0	0	0	0	0	0
80	80	70	40	20	10	0	0	0	0	0	0
85	90	80	70	40	10	10	0	0	0	0	0
90	100	90	80	70	40	20	10	0	0	0	0
95	100	100	90	90	70	50	40	10	0	0	0
100	100	100	100	100	100	90	70	50	40	20	10

Estimated Smoldering Potential (ESP)

ESP model is a predictive tool developed to evaluate the risk of smoldering combustion of organic soils in the pocosin/pond pine vegetation communities on the North Carolina coastal plain (Reardon *et al.* 2007). ESP uses soil properties and soil moisture to reflect the chance of continued smoldering after a successful ground ignition. Vegetation communities associated with deep duffs or organic soils occupy significant areas of the United States (Southern, Gulf and Northern Lake states and Alaska) and mountain ranges. These ground fuels present serious smoke challenges. Suppression techniques that are normally effective in controlling flaming combustion in surface fuels are often ineffective when used on smoldering combustion in ground fuels. Additionally, the long duration and poor smoke dispersion associated with smoldering combustion produces large amounts of persistent emissions which are linked to health concerns (Rappold *et al.* 2011) and an increased potential for vehicle accidents due to reduced visibility and Super-Fog events (Achtemeier 2003). For further details about ESP refer to Chapter 5.2.

National Weather Service Superfog Smart Forecast Tool

Joshua Weiss (Fire Weather Program Mgr., National. Weather Service, Wilmington, NC)

Maintaining situational awareness is extremely important especially when there is the potential for smoke to cross roadways. It is possible that there should be no driving on nearby roadways unless mitigation measures are in place to react to zero visibility if conditions indicate a high risk. Certain conditions can lead to smoke and/or fog events anywhere in the U.S. Factors such as terrain, stability, inversions, surface temperature, relative humidity and wind speed, along with cloud cover impact smoke dispersion. These factors occur differently in specific regions of the U.S. In the presence of wildland fire smoke it is very important to be aware of their interaction especially at night near roads. This is where experience and observing these interactions can increase the degree of certainty that additional mitigating steps need to be implemented.

Superfog, a combination of smoke and fog, is the most dangerous of all Southeastern United States smoke-related transportation corridor safety concerns. It can reduce visibility to just a few yards, and frequently create “white-out” events with near zero visibility (Achtemeier, 2003). Motorists cannot drive safely through these events. There are numerous instances of accidents with injuries or fatalities due to superfog on highways (Mobley, 1989), including the deadly and highly publicized Florida I-4 disaster of 2008 which killed 5 and injured 38 others (Collins *et al.*, 2009). Superfog events can be extremely hazardous for first responders as well (NIOSH 2008), and in many cases the only safe option is to close the corridor. Therefore, accurate prediction of smoke and fog movement is of critical importance.

In recent years smoke management has become forefront to land managers wanting to conduct prescribed burns (Rx-burns). Several forecast tools used operationally by National Weather Service (NWS) Weather Forecast Offices (WFOs) help determine clear Rx-burn windows to mitigate the impacts of smoke on roadways. These include:

(i) Atmospheric Dispersion Index (ADI; Lavdas, 1986)
(ii) Low Visibility Occurrence Risk Index (LVORI; Lavdas and Hauck, 1991)
(iii) Fire Weather Point Forecast Matrix (PFW)
(iv) Hourly Weather Graphic Fire Matrix

These products are created twice-daily from many Southeastern WFOs and are readily available to users. The Hourly Weather Graphic Fire Matrix and PFW provide hourly/3-hourly data (mixing heights, transport winds, ADI, etc.) within the 0-48 hour window, with less detailed data for up to 5 days beyond this period. Although most users apply these to plan safe Rx-burns, determining superfog potential takes a much greater understanding of how certain fire parameters combine to create superfog.

This forecast tool assists the fire weather forecaster in making the call for conditions which support superfog formation and the ability to warn land managers. This forecast tool highlights when all components of the smoke-dispersion matrix align concurrently to produce an environment conducive to superfog development. These components are identified by researcher Gary Achtemeier and fire environment forester Gary Curcio (Long *et al.* 2014)[1] as:

Surface Temp ≤ 70°F
Relative Humidity ≥ 90%
Wind < 7 mph
ADI < 10
LVORI ≥ 7
Sky Cover ≤ 60%
Turner Stability = ‘E’ ‘F’ or ‘G’ (a measure of atmospheric stability)

The superfog tool creates a binary forecast parameter (0 or 1) where a “1” implies that superfog is likely because all of the above elements occur simultaneously. NWS meteorologists should then alert land managers that

[1] Editor’s Note: Since 2014, scientific work regarding these thresholds continues to progress, see the *Smoke and Roadway Safety Guide*, PMS 477 for additional thresholds for use outside the scope of the NWS Superfog Smart Forecast Tool.

superfog is expected in the vicinity of a fire. Because all of these parameters coming together represent a worst-case scenario, the superfog tool can be used as a "go/no-go" forecast aid when determining whether to complete an Rx-burn that is anticipated to have smoke production through the night.

Low Visibility Occurrence Risk Index (LVORI)

Charles Maxwell, Meteorologist, USDA Forest Service

LVORI Category	Interpretation
1	Lowest proportion of accidents with smoke and/or fog reported.
2	Physical/statistical reasons for not including in category 1, not significantly higher.
3	Higher proportion of accidents than category 1, marginal significance.
4	Significantly higher than category 1, by a factor of 2.
5	Significantly higher than category 1, by a factor of 3to10.
6	Significantly higher than category 1, by a factor of 10 to 20.
7	Significantly higher than category 1, by a factor of 20 to 40.
8	Significantly higher than category 1, by a factor of 40 to 75.
9	Significantly higher than category 1, by a factor of 75 to 125.
10	Significantly higher than category 1, by a factor of 150.

The LVORI index can be a valuable tool in planning for smoke impacts. For example, all recent incidents in GA have occurred in conditions with a LVORI over 9 (Melvin 2013). The Low Visibility Occurrence Risk Index (LVORI) is a metric which combines ADI with relative humidity (RH) in relation to the proportion of traffic accidents reported due to reduced visibilities caused by smoke and/or fog. LVORI categories range from 1 to 10, with values increasing as ADI decreases and RH increases. Assuming smoke is being emitted, elevated values indicate a relatively high probability of traffic accidents due to reduced visibility caused by a combination of smoke and fog (sometimes called 'superfog'). When the forecasts indicate a LVORI of 4 or higher, then burners may want to reconsider whether specific mitigations should be included in the plan (e.g., patrols to monitor highway visibility, mop-up of all residual smoke, etc.) or whether to carry out the planned burn on a different day.

Strengths
-An easy to interpret, but fairly comprehensive, index tied statistically to an undesirable effect of wildland fire (visibility related traffic accidents)
-All the strengths associated with the ADI

Weaknesses
-All the weaknesses associated with the ADI
-Addition of relative humidity provides another source of complexity and potential error
-Does not account for variance in concentration or amount of smoke emitted

Tips for Use
-Use in the days before a planned ignition to assess nighttime conditions after the burn day(s). Consider delaying the burn or taking other mitigating actions if LVORI values are forecast to be 8 or higher.
-Consider past experience. In Georgia for example, all transportation safety incidents have occurred during conditions with a LVORI of 9 or 10.

A Cautionary Word About Indices and Models

It is important to note that the threshold values and tools throughout this chapter may need to be fine tuned depending on the region of the country as most superfog research has occurred in the Southeast. However, the indices and tools can be used to "shout watchout" when the conditions are present regardless of the location. When one or two values are close but not at their threshold value, they should be a concern to the burner as smoke dispersion can still be very poor and roadway visibility impaired.

Contingency Planning – When Smoke Crosses a Highway

Even with the best prescribed burn planning, conditions can change rapidly, requiring adjustments to operations. There may be areas where keeping smoke off roadways is difficult (areas of high road density, etc.). Predicting fog is very difficult. If the fire manager does not expect fog and fog does form, are contingency plans in place to respond to this change? If a prescribed burn ignition is delayed and smoke from active burning and heavy smoldering crosses a highway at night, are plans in place to respond? If smoke impacts roadways in areas where it was not anticipated, what resources and personnel are needed to respond adequately?

Contingency planning is critical to all wildland fire operations. There are more than enough examples of problems related to smoke from prescribed burns across the country for fire managers to understand the critical need for good contingency planning. In fact, the *Interagency Prescribed Fire Planning and Implementation Procedures Guide*, PMS484 (NWCG 2017) lists the minimum standards federal agencies must follow when planning and implementing prescribed burns. Contingency planning as it relates to smoke management objectives is one of the requirements. All fire managers, regardless of who they work for, should carefully consider and plan for contingencies to cover smoke related problems. A few considerations that may be valuable in contingency planning as it relates to transportation safety include communications and firefighter safety.

Communications

Coordinate with the appropriate agencies/personnel in advance, waiting until smoke or a smoke-fog related hazard occurs is too late. Well in advance of the prescribed burn, plan for and carry out the coordination with other federal, state, and/or local agencies to develop plans for addressing safe traffic flow through areas that can be affected by smoke from the fire. A detailed contingency plan should specify contacts, responsibilities, and the appropriate actions to take before, during, and after a low visibility smoke-related hazard occurs.

A key complication is dealing with the jurisdictional responsibilities associated with managing traffic on highways. Agencies such as State Highway Departments of Transportation must be involved in the location and wording of signs (especially electronic signs) posted to warn motorists of the hazard. State law enforcement or county/local law enforcement is necessary for closing roads or managing traffic flow on highways. Who will be responsible for moving warning signs or posting additional signs to warn motorists?

Getting notices out to news networks (TV and radio) early enough to warn motorists is helpful. Consider a public service announcement asking people to use an alternative route for a given time period. If superfog develops, the road must be closed without hesitation to address the hazard. This is only possible if a response plan has already been developed.

Everyone involved in implementing the burn should clearly understand the contingency plan and their specific responsibilities if smoke impacts a roadway. If vehicles are involved in accidents, what actions are to be taken and who has the responsibilities, especially with any communications that occur?

Firefighter Safety

The inherent dangers of personnel working in these low visibility conditions must be adequately dealt with; plans and actions must account for the safety of those trying to respond to and manage the problem.

Employees patrolling and/or setting up warning signs, especially along busy highways, must understand the hazardous working conditions and how to maintain their own safety, day and night. Remember, visibility of other drivers may be reduced; seeing each other can be difficult.

The safety plan should clearly address all hazards associated with responding to vehicle traffic where smoke or smoke/fog reduces visibility on a roadway.

Conclusion

Reduced visibility due to smoke can put fire personnel and the public at risk. Transportation safety should be a key consideration for fire personnel and land management agencies conducting prescribed fires, plan with cooperators such as law enforcement and local transportation departments. Plans can benefit greatly from local knowledge and expertise. Fire managers should check for nighttime forecast updates after the burn ends. Mitigation measures and contingency planning and response were discussed in this chapter, including key points to consider in the planning process and the use of tools for smoke management. Key in addressing transportation safety is preemptive planning to avoid potential dangers and rapid response should an incident occur.

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2.4 Visibility in Natural Areas

Scott A. Copeland

Introduction

Smoke from wildland fires can decrease visibility. This is an important and perhaps obvious statement for fire professionals. A decrease in visibility can affect transportation safety and the experience of visitors to federal lands which, in turn, can affect local economies, as well as having regulatory implications. When someone visits a natural area such as a forest, park, or wilderness area, their expectations vary but consistently include clean air and clear views. Conducting a prescribed fire in or near such areas requires planning to minimize the effects of smoke experienced by visitors. Protection of visibility in Class I areas (figure 2.4.1), which are national parks and wilderness areas that have the highest protection under the Clean Air Act (42 USC 7491), is required by regulation in many states.

In the context of smoke management, "visibility" refers to near-field visibility as might relate to motorist safety in the case of smoke plumes drifting across roadways, and to scenic or more far-field visibility that affect the ability of visitors to enjoy a pristine view. In both instances, reduced visibility is caused by small particles suspended in smoke which scatter and absorb light. These particles can accumulate in the atmosphere and are capable of being transported great distances, such that smoke can affect visibility over long time periods and across large areas, even at long distances from the original source.

This section is divided into three parts: the importance of visibility, how smoke affects visibility, and how visibility is measured.

Figure 2.4.1 Map of Class I areas in the United States.

Why is Visibility Important?

There are four principal reasons to consider visibility in smoke management: safety, regulatory requirements, visitor experience, and economic effects.

Safety

Safety considerations are fairly straightforward. Smoke in unacceptable concentrations where vehicles or aircraft are traveling can cause accidents due to reduced visibility. The ability to see can be affected just during the fire event, or can last for a long time. Therefore, monitoring the visibility effects from smoke can help track any key safety concerns. Devices for monitoring smoke effects that can be used for hazard evaluation are discussed in a later section.

Views Protected by Regulation

U.S. Environmental Protection Agency's 1999 Regional Haze Rule (40 CFR 51.308) sets a goal of eliminating "man-made" visibility impairment in mandatory Class I. Under this rule, each state is required to develop a plan to decrease visibility impairment at Class I areas, with a goal of restoring natural visibility by 2064. As part of their regional haze plan, some states now have smoke management plans which require considering visibility effects at Class I areas as part of a burn plan. There are varying degrees of regulation under different states' plans for regional haze and it is important to be familiar with any such plan in your state and any associated regulations or policies.

Visitor Experience

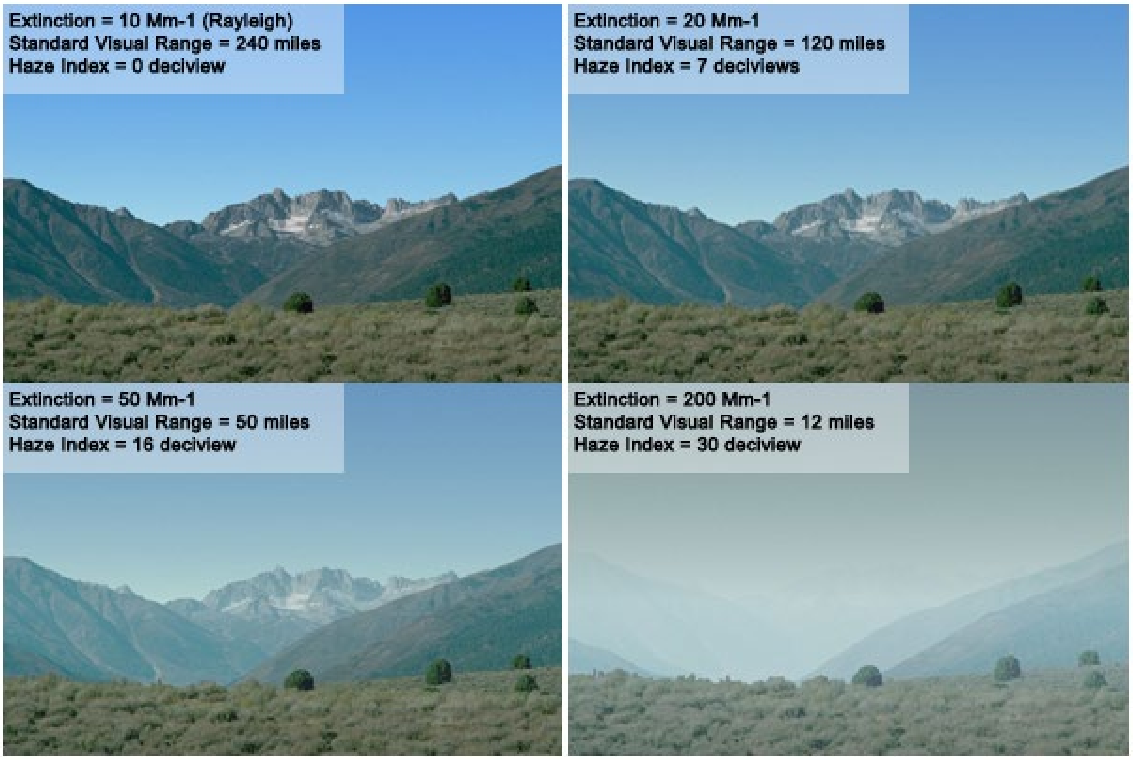
Surveys consistently show that clear air is one of the most important reasons cited for visiting national parks and wilderness areas. Visitors who come to parks and wildernesses seeking clean air are less likely to return to or stay at a destination when air quality is poor.

Economics

In practical terms, a diminished visitor experience means that local communities can suffer economic harm from poor visibility. This is often an issue when conflict arises between fire programs and their local communities. In the report by McNeill and Roberge, "The Impact of Visual Air Quality on Tourism Revenues in Greater Vancouver and the Lower Fraser Valley" (2000), tourists responded that they would be much less likely to return to a natural area with poor visibility.

How Does Smoke Affect Visibility?

There is a direct link between smoke and visibility; in fact, "smoky" is a synonym for "hazy". When first emitted, smoke is commonly a plume. Plumes characteristically have fairly defined edges and can remain plume-like for hundreds of miles. When in plume form, smoke is more readily identified as a cause of impaired visibility than when it is spread out over a broad area. Over time, plumes disperse and mix with other atmospheric pollutants to form what is called "regional haze". Regional haze is characterized by broad and fairly uniform change in the contrast and color of a scenic vista. See figure 2.4.2.



2.4.2. Computer-simulated haze at Hoover Wilderness in California. "Rayleigh scattering" is natural light scattering by the gases in the atmosphere.

On an annual average basis at Class I areas nationally, most haze is not caused by smoke but by sulfate particles that form in the atmosphere through conversion from sulfur dioxide. This is largely because of coal burning, mainly at electric generation facilities. These particles can play a disproportionate role for visibility impairment under high humidity conditions compared to their concentration in the atmosphere. Nitrogen oxide gases, which also come mainly from fossil fuel combustion, can affect visibility directly or as particles after chemical interactions in the atmosphere. Dust can significantly impair visibility, especially in the West. On an episodic basis, haze from large fires dominates visibility impairment, especially during wildfire season in the western United States. These sources are represented in figure 2.4.3. Most haze generated from smoke is caused by fine particles, also called $PM_{2.5}$ (particles with a diameter less than 2.5 micrometers). These tiny particles scatter and absorb the light between an object and an observer, resulting in less image-forming light reaching the observer and, hence, a hazy image. If more smoke is added to the atmosphere, there are more fine particles, more scattered and absorbed light, and it is hazier.

Once in the atmosphere, smoke particles can be dispersed by wind, traveling hundreds or thousands of miles; fall to the ground after days or weeks; or be washed out fairly quickly by rainfall. Smoke can also be concentrated as in the case of an atmospheric inversion where pollutants are trapped in a layer of relatively cold air near the ground. Certain meteorological conditions such as fog or snow, mixed with smoke in the atmosphere, can severely impair visibility. Figure 2.4.4 represents these processes in the atmosphere.

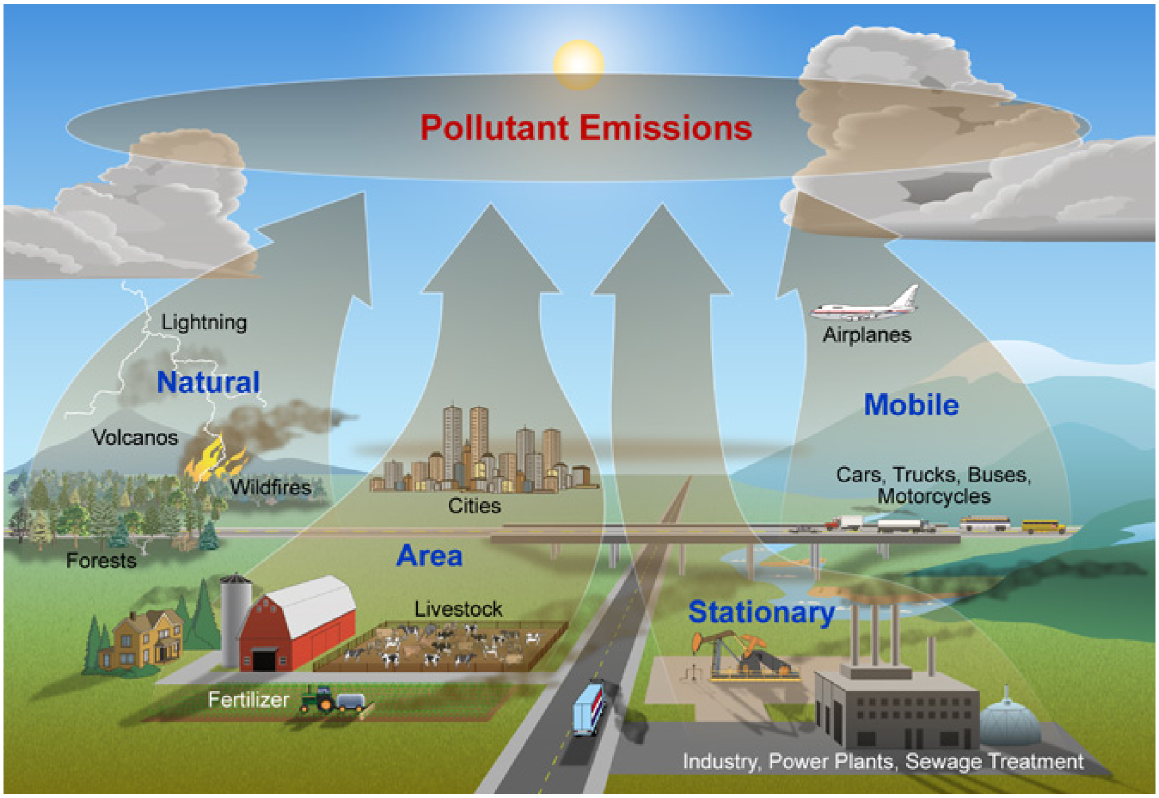


Figure 2.4.3. Air pollution sources (Courtesy of the National Park Service).

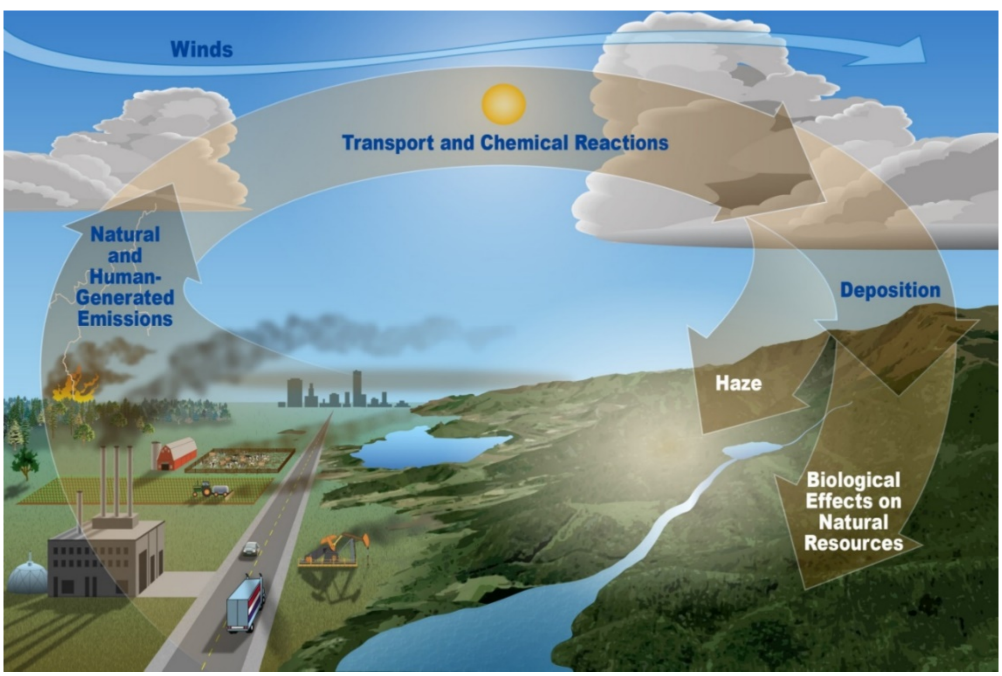


Figure 2.4.4. Transport and deposition of air pollution (Courtesy of the National Park Service).

There are three ways to minimize visibility effects from smoke: lessen the amount of smoke, control where the smoke goes, or separate the observer from the smoke. In the first case, tactics for a burn can be developed that lessen the amount of smoke produced. Second, burning can be timed to coincide with smoke dispersion and transport conditions that minimize concentrations of haze-forming particles. Finally, burning can be timed to coincide with periods when the number of visitors is minimal.

How Is Visibility Measured?

The common scales for measuring visibility are standard visual range (in kilometers or miles), atmospheric extinction (in inverse megameters [Mm^{-1}]), and haze index [in deciviews (dv)]. It is not necessary to understand how to calculate these values. However, familiarity with how the scales are used will help to understand monitoring data, regulations, burn plans, and model outputs better.

One of the more well-known early networks of haze measurements was made up of human observers in airport towers across the United States. Observers would check whether known large dark objects such as buildings or ridgelines were visible against the sky near the horizon. The most distant target that could be seen would establish the "visual range". Correcting for the effect that elevation has on atmospheric density, scientists are able to normalize the visual range to a standard atmosphere at 5,000' above sea level, yielding the "standard visual range" (SVR) measured in miles or kilometers. Standard visual range is useful for smoke management because it is easy to understand and directly relates to safety considerations.

Another long-standing visibility measurement network is Interagency Monitoring of Protected Visual Environments (IMPROVE), which started collecting data in 1988. The IMPROVE network is intended to: (1) establish current visibility conditions in 156 Class I areas; (2) measure chemical species that make up particulate matter and attribute them to sources of air pollution; (3) document long-term trends; and (4) provide monitoring to represent conditions in all Class I areas in support of implementation of the 1999 Regional Haze Rule. Data from the IMPROVE network may be represented using any of the three units summarized in table 2.4.1.

Table 2.4.1. Summary of visibility parameters.

Metric	What it means	Best use	Limitations	Units
Standard visual range (SVR)	How far an observer can see a large dark object against the horizon sky. Might hear this used during a weather forecast.	Convey visibility information to lay person, evaluate potential safety issues.	Can't be summed from individual pollutants and not proportional to perceived haziness.	Miles or kilometers
Extinction	Amount of light lost per unit length of atmosphere traversed. Might see this as output from a device that measures visibility.	Understanding causes of haze, modeling haze effects.	Non-intuitive units and name has a confounding common usage definition.	Inverse megameters (Mm^{-1})
Haziness index	Perceived haziness of a scene. Might hear this referred to by an air quality regulator.	Describing haze on a scale that relates directly to human perception.	Obscure units, calculation is based on logarithmic function.	Deciview (dv)

When scientists are trying to understand the causes of haze, it is necessary to separate the haziness by source or source category. This is the basis for using the most fundamental measurement of haze atmospheric extinction (or just "extinction"). Extinction in this context is the amount of light lost per unit of distance traveled through the atmosphere and is the sum of scattering and absorption from particles and gases. Because scattering is the dominant contributor to extinction and is easily measured, it is often used as a surrogate for total light extinction. For most smoke management applications, this approximation is reasonable. The utility of extinction as a means to describe visibility is that total extinction in the atmosphere can be calculated from the sum of extinctions from each contributor. For example, an atmosphere with 10 Mm^{-1} of scattering from smoke and 10 Mm^{-1} of scattering from sulfate particles has a total particle extinction of 20 Mm^{-1}, half of the haze can be attributed to sulfate particles. Extinction can also be estimated directly from the mass concentration of particles, so a model which estimates the mass concentration of smoke from a planned burn can easily translate that concentration into an amount of scattering. Using the same concept, the IMPROVE network relies on measurements of each constituent of extinction to estimate haze levels across the United States (figures 2.4.5 and 2.4.6.

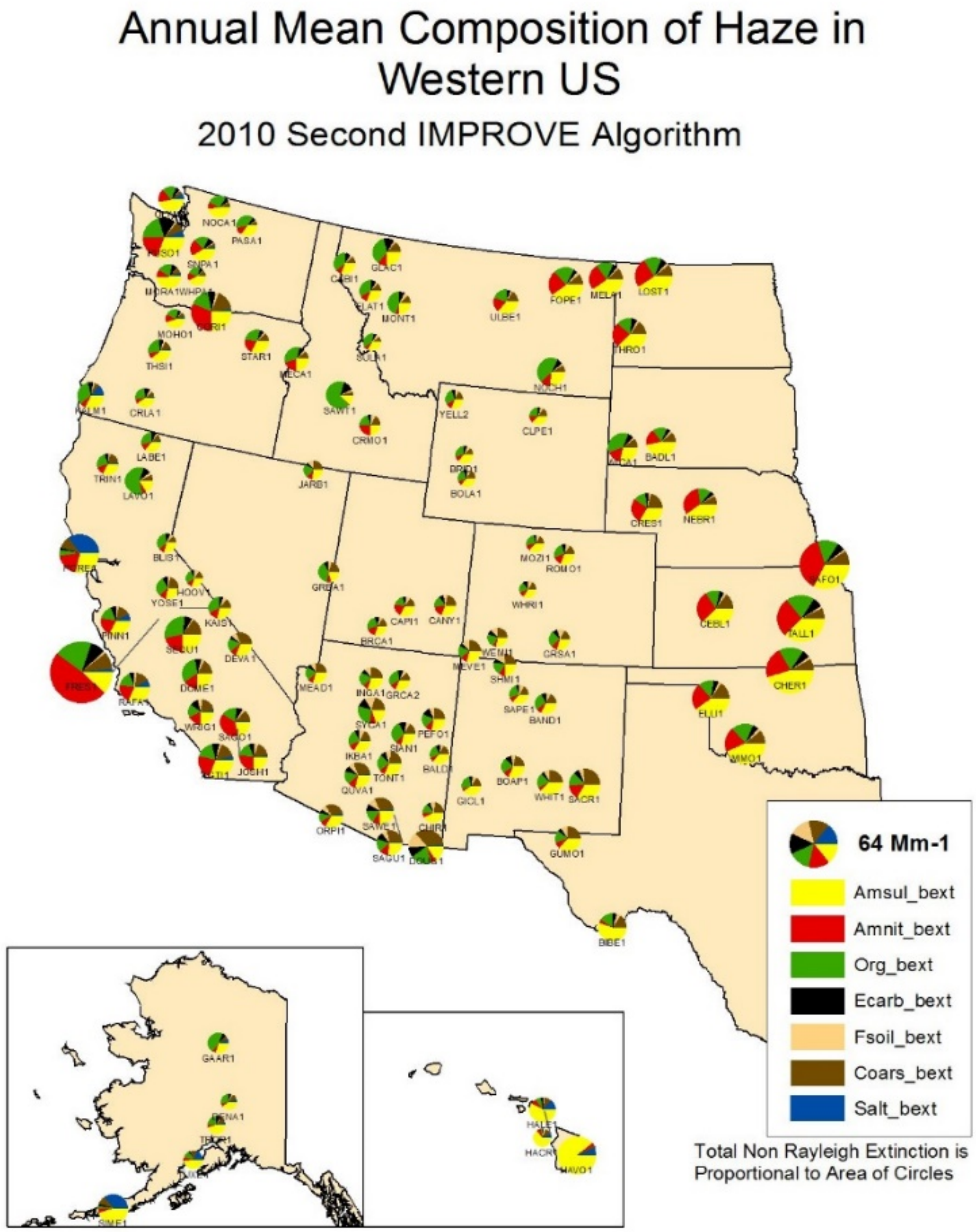


Figure 2.4.5. Annual mean composition of haze at IMPROVE sites in the Western United States. Most smoke effects would fall under the green "Org_bext" fraction which is an abbreviation for "organic extinction".

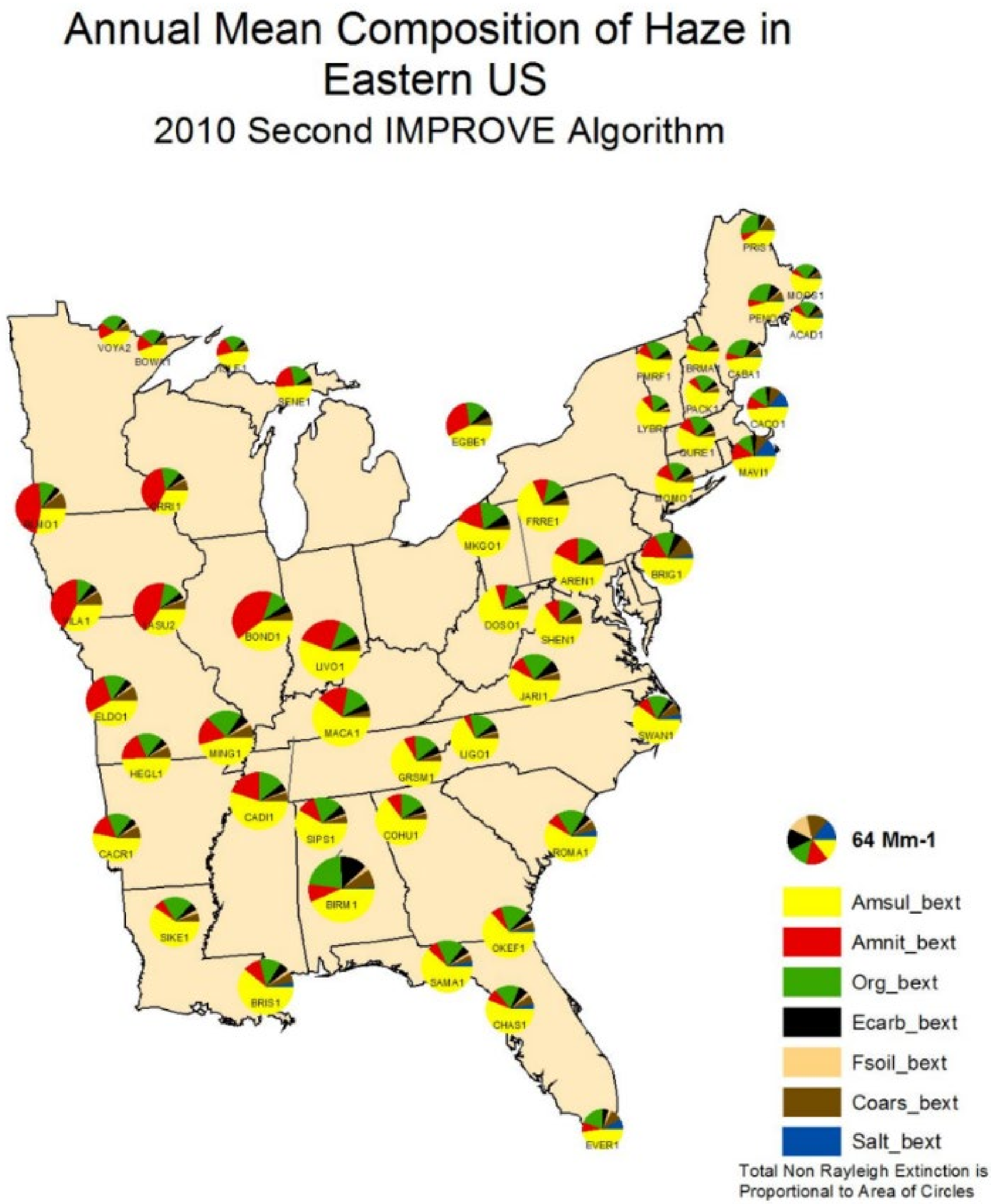


Figure 2.4.6. Annual mean composition of haze at IMPROVE sites in the Eastern United States. Most smoke effects would fall under the green "Org_bext" fraction which is an abbreviation for "organic extinction".

There are several compounds that contribute to visibility impairment. The relative importance of these varies a good deal from one part of the country to another. Ammonium sulfate (Amsul_bext in figures 2.4.5 and 2.4.6) is more significant where emissions from coal-fired power plants are higher, and ammonium nitrate (Amnit_bext) can be more of an issue in large urban areas where motor vehicles predominate, or in places with colder winters. Organic carbon (Org_bext) and elemental carbon (Ecarb_bext) can come from a variety of sources, ranging from direct emissions from vegetation to petroleum combustion to burning vegetation. Also represented in figures 2.4.5 and 2.4.6 are: soil (Fsoil_bext) which affects visibility in dry areas; coarse particles (coars_bext) which is larger than 2.5 microns and is mostly dust; and sea salt (Salt_bext), mainly from coastal areas.

The map of total visibility extinction in figure 2.4.7 suggests that visibility conditions are clearer in much of the western United States than in the eastern United States. This map is in inverse megameters where larger numbers indicate more impaired visibility.

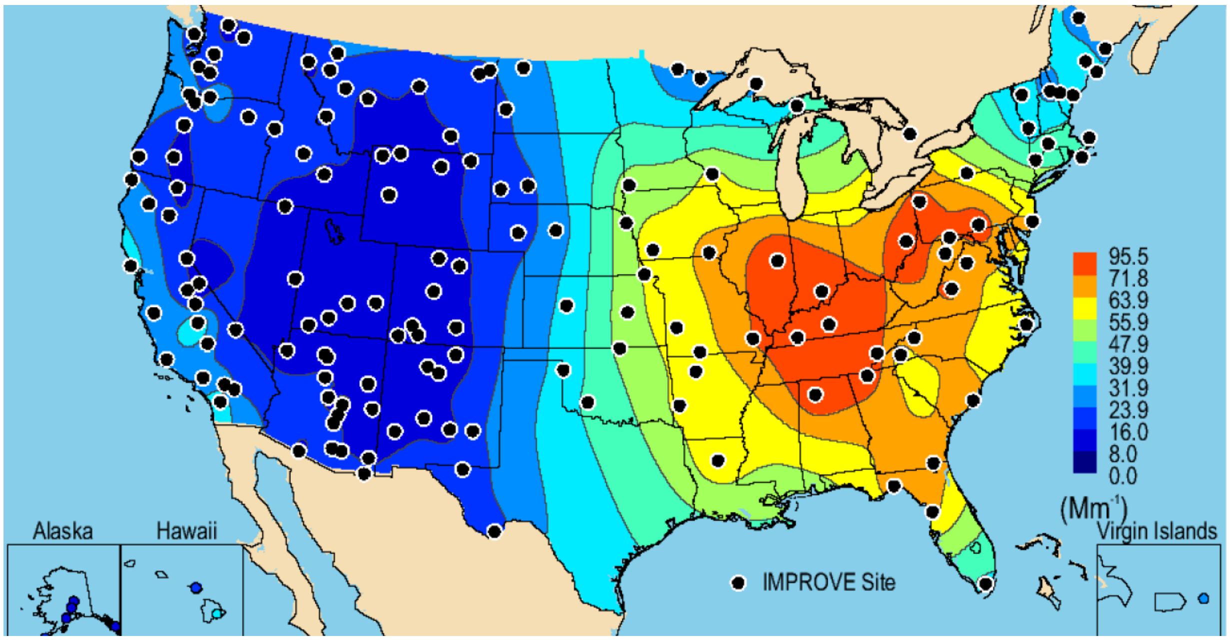


Figure 2.4.7. Annual average visibility impairment, measured in inverse megameters, from particles in the atmosphere (Hand *et al.* 2011).

A key question for smoke management is how much smoke does it take before people will notice? The physics of haze in the atmosphere are such that clear air is more sensitive to air pollutants than dirty air. Figure 2.4.2, shows how a small amount of haze added to the clearest image would be visible, while adding the same small amount to the haziest image would go unnoticed. This is the concept that led to the creation of the haze index scale, a scale that is proportional to human perception of haze. Zero deciviews on the haze index scale indicates an essentially a particle-free atmosphere, and 30 deciviews is quite hazy. Adding one deciview to a typical scene will evoke a barely-noticeable change in perceived haziness, regardless of the amount of haze originally present. Human-caused pollution is expected to decrease at Class I areas in the future, which will cause them to be increasingly sensitive to smoke effects. In 2010, at Class I areas, annual average deciview values are 15 to 20 in the Eastern United States and 5 to 10 in the western United States.

Visibility Monitoring for Smoke Management

There are several devices which measure or estimate visibility in real time and are designed to be deployed remotely. These include high-resolution cameras, beta attenuation monitors, and nephelometers. Cameras are excellent and fairly inexpensive, when compared to particulate samplers, to qualitatively monitor visual effects from smoke over a broad area. Beta attenuation monitors provide real-time estimates of atmospheric smoke concentrations. Nephelometers directly measure atmospheric scattering and can be used to estimate smoke concentrations. Both of these continuous monitoring devices can be useful where there are issues with possible health effects, citizen complaints or impacts on roadways. More information about these devices can be found in Chapter 5.4 (Smoke Monitoring) of this guide and on the web in "Smoke Particulate Monitors: 2006 Update" (Trent 2006).

Conclusion

Visibility is an important aspect of smoke management. Safety considerations, compliance with state smoke management regulations, preserving the visitor experience, and protecting communities from economic loss are all reasons to consider visibility effects. Familiarity with the various scales for describing visibility will be valuable to someone interpreting monitoring data, regulations, burn plans, or model outputs.

A good place to learn more about the science of visibility is "Introduction to Visibility" (Malm 1999), which can easily be found online. The website for the appropriate air quality regulatory agency in your area of interest should have information about smoke management requirements generally, and any related specifically to visibility. Chapter 3.2 of this guidebook on State Smoke Management Programs should also be of help.

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CHAPTER 3–REGULATIONS

3.1 Smoke Management Regulations

Janice Peterson and Rick Gillam

Introduction

In 1948 a cloud of sulfur dioxide formed over Donora, Pennsylvania, killing 20 people and sickening 6,000. In 1952, somewhere between 3,000 and 12,000 people died from what became known as London's "Killer Fog" (Bell and others 2004) (figure 3.1.1). Serious events like these led to a heightened awareness of the dangers of air pollution, and to the passage of federal and state air regulatory laws to protect public health and welfare.

Smoke from wildland fires contains pollutants that have the potential to affect human health or other societal values such as visibility. Fine particulate matter is the most concerning pollutant from wildland fire but other components of smoke can also be hazardous. Air pollution is managed and regulated through a complex web of interrelated laws and regulations. To responsibly and legally use prescribed fire as a land management tool, fire managers need to understand and follow federal, state, and local regulations designed to protect the public from possible negative effects of air pollution.

Figure 3.1.1. London smog event of 1952.

Federal Clean Air Act

The primary legal foundation of air quality regulation in the United States is the Federal Clean Air Act. The Clean Air Act (CAA) was first passed in 1963 (EPA 2007a); in 1970, 1977, and again in 1990, Congress strengthened and expanded it (Public Law 95-95) and provided the Environmental Protection Agency (EPA) with broad authority to regulate emissions from a variety of air pollution sources in the United States.

The Clean Air Act is a legal mandate designed to protect public health and welfare from air pollution. Individual states implement the Clean Air Act locally by developing specific regulations and programs for meeting the requirements through their state implementation plans (SIPs). Tribes develop tribal implementation plans (TIPs) for their lands. Fire managers must know the details of state and local air regulations and programs, and specifically how fire emissions are regulated to responsibly conduct a prescribed fire program.

Roles and Responsibilities

Although the CAA is a federal law and therefore applies to the entire country, individual states do much of the work of implementation. The Act recognizes that states, tribes and in some cases local air pollution control agencies, should have the lead in carrying out most of its provisions; this is because appropriate and effective design of pollution control programs requires an understanding of local industries, geography, transportation, meteorology, urban and industrial development patterns, and priorities. But before states take over, the EPA defines some basic national goals for air quality protection.

TERMS TO KNOW:
NAAQS: National Ambient Air Quality Standards
SIP: State Implementation Plan
TIP: Tribal Implementation Plan
Criteria Pollutants: Pollutants for which EPA has set NAAQS
Ambient Air: Anywhere the public has access
HAPs: Hazardous Air Pollutants

Clean air programs developed by EPA are designed to achieve goals described by Congress in the Clean Air Act. The first steps to regulating air quality are to identify the specific air pollutants that may harm human health and the environment, and to set limits on how much of these pollutants can be in the air where the public has access[1] (called "ambient air"). EPA has identified six common air pollutants that are found all over the United States. These six key pollutants are known as "criteria pollutants" because their regulation is based on science-based human health or environmentally-based criteria for permissible levels. The six criteria pollutants are particulate matter (regulated in 2 size categories: PM_{10} and $PM_{2.5}$), ground level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and lead (Pb). Allowable human health-based limits on the criteria pollutants are known as National Ambient Air Quality Standards (NAAQS).

The EPA develops regulations, policy and technical guidance describing how various Clean Air Act programs should function and what they should accomplish. It also plays an oversight role by reviewing state documents and programs, and ensuring that states meet CAA requirements.

States develop state implementation plans (SIPs) that define and describe customized programs that the state will implement to meet requirements of the Clean Air Act. State smoke management programs may be included as part of a state's SIP (see Chapter 3.2). Tribal lands are legally equivalent to state lands and tribes prepare tribal implementation plans (TIPs) to describe how they will implement the Clean Air Act. Individual states and tribes can set more stringent pollution standards, but cannot weaken pollution goals set by EPA. The EPA must approve each SIP/TIP, and if a proposed or active SIP/TIP is deemed inadequate, EPA can unilaterally enforce all or part of the Clean Air Act requirements for that state or tribe through implementation of a federal implementation plan or FIP (table 3.1.1).

Table 3.1.1. The roles of the U.S. Environmental Protection Agency (EPA), states, and tribes in implementing the Clean Air Act.

EPA Responsibilities	State and Tribal Responsibilities
• Establish NAAQS • Develop regulations, policy and technical guidance for states/tribes • Approve SIPs/TIPs and control measures • Backup to state enforcement • Administer air grant money • Approve Exceptional Event Demonstrations	• Develop SIPs/TIPs that meet CAA requirements and submit to EPA for approval • Implement SIP/TIP programs • Develop and maintain emission inventories • Conduct air quality monitoring • Establish and operate a permitting program for new and existing air pollution sources • Develop and submit Exceptional Event Demonstrations

[1] Note that the Occupational Safety and Health Administration (OSHA), rather than EPA, sets air quality standards for worker protection.

National Ambient Air Quality Standards

The primary purpose of the Clean Air Act is to protect humans against the negative health or welfare effects from air pollution. The NAAQS are defined in the Clean Air Act as standards for criteria pollutants (wide-spread pollutants that are considered harmful to the public and the environment). NAAQS are designed to protect the most sensitive members of the public such as children, asthmatics, and persons with cardiovascular disease. NAAQS are intended to be established regardless of possible costs associated with achieving them, although EPA is allowed to consider the costs of controlling air pollution during the implementation phase of the standard in question.

FOR FIRE MANAGERS:

$PM_{2.5}$ is the most significant of the regulated pollutants

PM_{10}, CO, and ozone also may be important in some circumstances

Every five years, EPA is required to review and reevaluate the NAAQS to ensure that they continue to protect human health and the environment. Reviewing and, when needed, updating the NAAQS is a lengthy undertaking and involves many steps including preplanning, an integrated science assessment, a risk/exposure assessment, a policy assessment, and finally rulemaking. Scientific review during each of these steps is thorough and extensive. Drafts of all documents are reviewed by the Clean Air Scientific Advisory Committee (an independent group of air quality scientists) and are available to the public for review and comment. As noted previously, NAAQS have been established for six criteria air pollutants: particulate matter (PM_{10} and $PM_{2.5}$) (figure 3.1.2), ground level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and lead (table 3.1.2). Primary NAAQS are set at levels to protect public health; secondary NAAQS are to protect public welfare (soiling, odor, visibility, etc.). The standards are established with different averaging times such as, annual, 24-hour, and 1-hour.

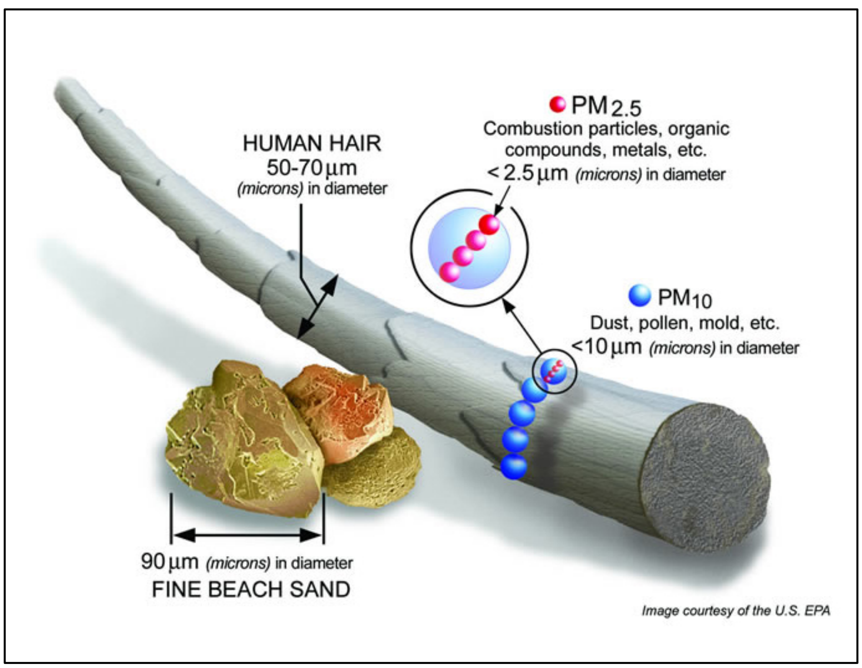

Figure 3.1.2. Relative sizes of fine particulate matter.

Table 3.1.2. National Ambient Air Quality Standards (NAAQS), 2015 revisions (U.S. EPA 2015a).

Pollutant and time-weighted period	Primary standard[a]	Secondary standard[a]
Particulate matter (PM_{10})[b]		
24-hour	150 µg/m³	150 µg/m³
Particulate matter ($PM_{2.5}$)[b]		
Annual (arithmetic average)	12 µg/m³	15 µg/m³
24-hour	35 µg/m³	35 µg/m³
Sulfur dioxide (SO_2)		
3-hour	None	0.5 ppm
1-hour	0.075 ppm	None
Carbon monoxide (CO)		
8-hour	9 ppm	None
1-hour	35 ppm	None
Ozone (O_3)		
8-hour (2015 std)	0.070 ppm	0.070 ppm
Nitrogen dioxide (NO_2)		
Annual (arithmetic average)	53 ppb	53 ppb
1-hour	100 ppb	None
Lead (Pb)		
Rolling 3-month average	0.15 µg/m³	0.15 µg/m³

[a] µg/m³ = micrograms per cubic meter; ppm = parts per million; ppb = parts per billion.
[b] Particulate matter NAAQS are established for two aerodynamic diameter classes: PM_{10} is particulate matter 10 micrometers or less in diameter, and $PM_{2.5}$ is particulate matter that is 2.5 micrometers or less in diameter.

The major pollutant of concern in smoke from wildland fire is particulate matter, especially $PM_{2.5}$. Studies indicate that about 90 percent of smoke particles emitted during wildland fires are less than 10 microns in diameter (PM_{10}) and about 90 percent of the PM_{10} is $PM_{2.5}$ (Ward and Hardy 1991). Studies on the human health effects of particulate matter indicate that $PM_{2.5}$ is largely responsible for harmful health effects such as mortality, cardiovascular and respiratory impacts, exacerbation of chronic disease, and increased hospital admissions (U.S. EPA 2009).

An area found to be in violation of a primary NAAQS is called a non-attainment area (figure 3.1.3). An area once in non-attainment but recently meeting NAAQS, and with appropriate EPA-approved planning documents in place, is a maintenance area. All other areas are attainment (if there is locally representative monitoring) or unclassifiable (due to lack of monitoring or other information needed to determine their attainment status).

$PM_{2.5}$ is the pollutant of most concern for fire managers, but other pollutants and associated non-attainment or maintenance areas must be considered also (figures 3.1.4 and 3.1.5). For the most up-to-date listings and maps of non-attainment and maintenance areas, consult EPA's "Green Book" website[1].

[1] https://www.epa.gov/green-book.

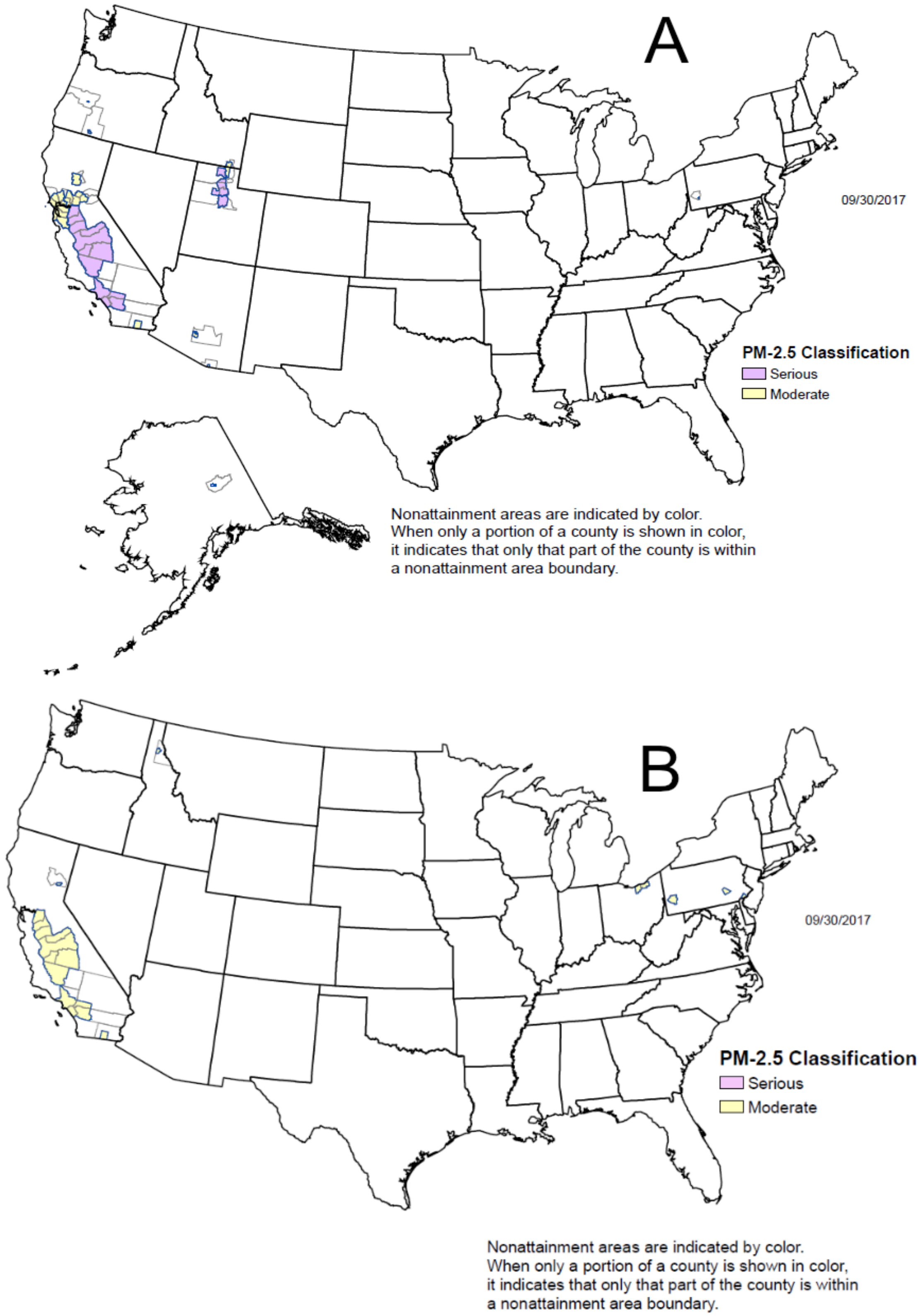

Figure 3.1.3. $PM_{2.5}$ 24-hour average attainment status (A) and $PM_{2.5}$ annual average attainment status (B) as of September 30, 2017. (See https://www.epa.gov/green-book for updates.)

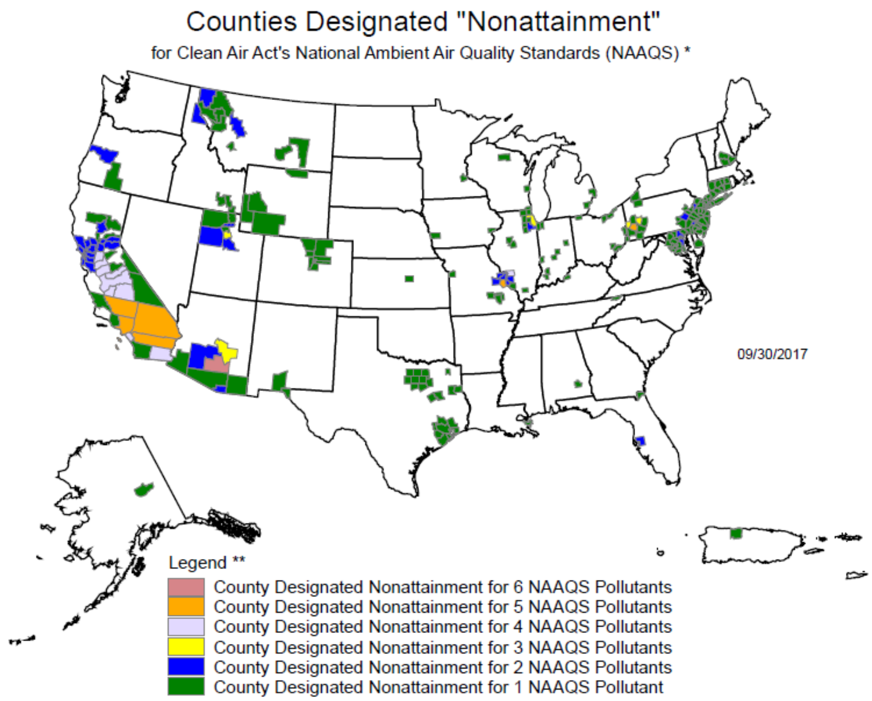

Figure 3.1.4. Counties with all or part of the county designated as non-attainment for one or more of the NAAQS pollutants. (See https://www.epa.gov/green-book for updates.)

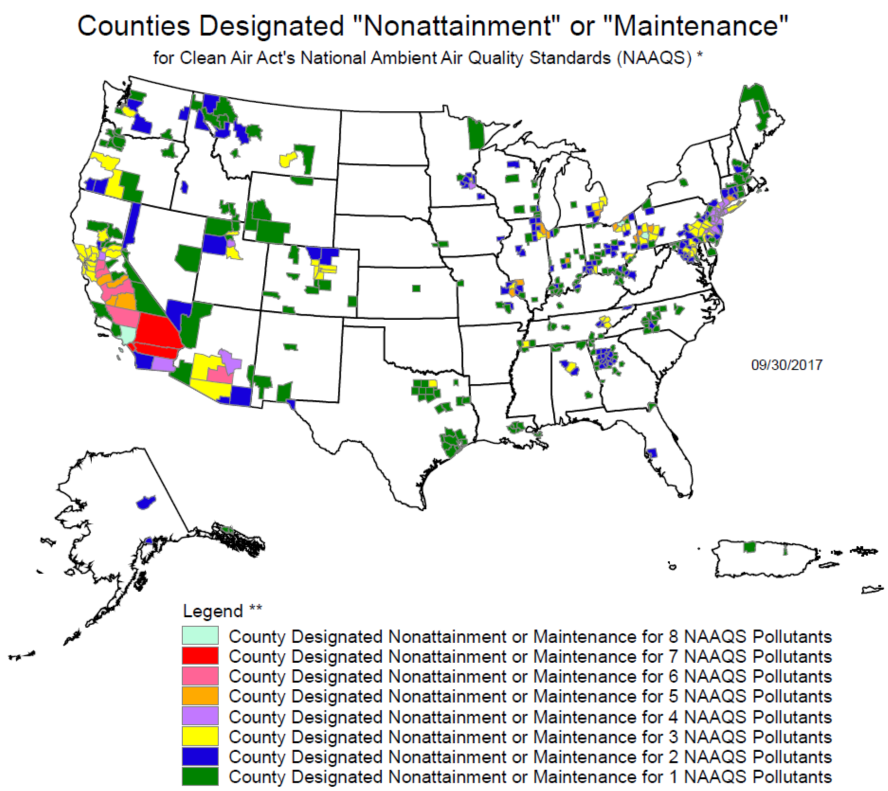

Figure 3.1.5. Counties with all or part of the county designated as non-attainment or maintenance for one or more of the NAAQS pollutants. (See https://www.epa.gov/green-book for updates.)

States are required, through their SIPs, to define programs for implementation, maintenance, and enforcement of NAAQS within their boundaries. Besides highlighting violations of a NAAQS, a non-attainment designation has many negative connotations for the area including required accounting and limiting of emissions, bad publicity, and possible sanctions from the federal government for failure to attain standards. Therefore, states generally develop aggressive programs for bringing non-attainment areas into compliance with clean air requirements.

Fire managers should know the location of any nearby non-attainment and maintenance areas, and the state or federal requirements that affect the use of prescribed fire in or near those areas. Non-attainment area boundaries change periodically and fire managers (or other air quality specialists within the organization) should engage with the state when non-attainment area boundaries are proposed for EPA approval. Typically, remote and unpopulated wildlands are not included within a non-attainment area unless there is a compelling reason to believe this will help solve the relevant air quality problem. Sometimes wildlands may end up included simply because a state relies on a convenient geo-political boundary, like a county line, to define the non-attainment area. States may include wildlands within their non-attainment areas without realizing the potential consequences to land management activities such as the use of prescribed fire. By remaining engaged in the process, land managers can ensure that non-attainment boundaries do not encroach on wildlands unnecessarily. State air regulatory agencies can provide detailed, up-to-date locations of non-attainment areas and plans for their review and modification.

Plans for prescribed fires in and near non-attainment or maintenance areas will be scrutinized to a greater degree than those in attainment areas. In addition, burning conducted on federal lands or supported by federal funds in non-attainment areas may be subject to General Conformity rules (see section below). Some states prohibit all types of outdoor burning in non-attainment areas. Extra planning, documentation, and careful scheduling of prescribed fires will likely be required in an effort to minimize smoke in the non-attainment area to the greatest extent possible. In some cases, the use of prescribed fire may not be feasible if significant impacts to a non-attainment area are likely.

There are examples, however, where fire managers have been successful at working with states to show prescribed fire is not implicated in causing or contributing to air quality issues in a non-attainment area, and they have obtained an exception or special approval conditions under which prescribed fire is allowable. Most non-attainment areas are designated as such because of air pollutant concentrations that occur during stagnant meteorological conditions. Usually the air pollutants are generated by sources that operate frequently such as power plants, vehicle traffic, woodstoves, etc. Prescribed fire is a temporary air pollution source that can be scheduled during optimum meteorological conditions or at times of the year when air pollution concentrations are less likely to exceed standards. By making a case to the air regulatory agency that burning will not cause or add to air quality standard violations, prescribed fire practitioners have been able to carry out their programs in non-attainment areas with little to no restrictions. However, this does require prescribed fire practitioners to analyze air pollutant and meteorological data for the specific area in which they want to burn.

Hazardous Air Pollutants

The Clean Air Act Amendments of 1990 identified a list of 187 hazardous air pollutants (HAPs), also known as "air toxics," that may threaten human health and the environment. Unlike the NAAQS for criteria air pollutants, there are no universal limits on HAPs. Instead, they are limited by controlling emissions from specific air emission source categories (e.g., industrial boilers, petroleum refineries, pulp and paper manufacturing, etc.). The listed HAPs are substances which are known or suspected to be carcinogenic, mutagenic, teratogenic, neurotoxic, or which cause reproductive dysfunction.

Wildland fires emit air pollutants identified on the list of 187 HAPs (for example, formaldehyde, benzo(a)pyrene, polycyclic aromatic hydrocarbons (PAHs), and benzene) (Battye and Battye 2002). However, EPA currently does not have any regulations that specifically limit HAP emissions from wildland fires.

Exceptional Events Rule

What happens to the air quality monitoring record of a state when extended periods of poor air quality are the result of an event that is largely outside of human control such as a wildfire, volcano, or windstorm (figure 3.1.6)? The Exceptional Events Rule (EER) originally issued by the EPA in 2007 (EPA 2007b), and recently revised in October 2016 (EPA 2016), establishes procedures for states to use in identifying, evaluating, interpreting, and using air quality monitoring data affected by exceptional events. The EER provides a way for air quality monitoring data to be excluded from regulatory decisions and actions such as non-attainment designations if a state can provide convincing evidence to EPA that high monitoring values are the result of an exceptional or natural event.

Figure 3.1.6. What responsibility does a state air regulatory agency have when NAAQS violations are caused by an "exceptional event" like a wildfire? (Photo credit: Lindsey Wasson, Seattle Times).

The 2016 EER recognizes that wildfires which predominately occur on wildlands are natural events. Therefore, air monitoring data showing an exceedance of a NAAQS caused by wildfire smoke can be classified as an exceptional event if the effects can be proven to be from a wildfire. In addition, the EER recognizes the ecological benefits of prescribed fire and that appropriate use of prescribed fire can reduce the risk of catastrophic wildfires. The EER clarifies that if smoke from a prescribed fire results in exceedance of a NAAQS, the prescribed fire could be considered an exceptional event if it meets all of the criteria identified in the EER.

In accordance with EPA's 2016 EER, for monitoring data to be excluded from a state's air quality record because of a specific prescribed fire, a state must document, subject to EPA's review and concurrence, the following for each exceedance event:

1. The prescribed fire caused a specific air pollution concentration in excess of one or more NAAQS at a particular air quality monitoring location.
2. The prescribed fire meets the definition of "exceptional event." Exceptional event means an event that affects air quality, is *not reasonably controllable or preventable*, is an event caused by human activity that is *unlikely to recur at a particular location* or a natural event, and is determined by the administrator in accordance with 40 CFR 50.14 to be an exceptional event.
   a. With respect to the requirement that a prescribed fire be *not reasonably controllable*, the State must either certify that it has adopted and is implementing a smoke management program or the State must demonstrate that the fire manager employed appropriate Basic Smoke Management Practices (BSMPs) identified in the EER. The BSMPs in the EER are:
      i. Evaluate smoke dispersion conditions,
      ii. monitor effects on air quality,
      iii. record-keeping/maintain a burn/smoke journal,

iv. communication-public notification,

v. consider emission reduction techniques, and

vi. share the airshed – coordination of area burning.

If a State is relying on application of BSMPs, land managers, fire managers, and air agencies must collaborate on the process for working together to select and apply appropriate BSMPs.

b. With respect to the requirement that a prescribed fire be *not reasonably preventable*, the State may rely upon and reference a multi-year land or resource management plan for a wildland area with a stated objective to establish, restore and/or maintain a sustainable and resilient wildland ecosystem and/or to preserve endangered or threatened species through a program of prescribed fire.

c. Regarding the *human activity unlikely to recur at a particular location* criterion, the State must describe the actual frequency with which a burn was conducted, but may rely upon and reference an assessment of the natural fire return interval or the prescribed fire frequency needed to establish, restore and/or maintain a sustainable and resilient wildland ecosystem contained in a multi-year land or resource management plan meeting the criteria discussed above.

In general, it is in the best interests of land managers who rely on the use of prescribed fire to assist with state efforts to document exceptional events when possible, because planning a prescribed fire in or near a non-attainment area can face greater restrictions, documentation requirements, and analysis.

Visibility and Regional Haze

The 1977 amendments to the Clean Air Act established a national goal of "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory class I federal areas which impairment results from man-made air pollution" (Public Law 95-95). States are required to develop implementation plans that make "reasonable progress" toward the national visibility goal.

Regional haze is visibility impairment produced by a multitude of sources and activities that emit fine particles and their precursors, and are located across a broad geographic area. This contrasts with visibility impairment that can be traced largely to a large plume from a single pollution source. In 1999, EPA issued regional haze regulations to manage and mitigate visibility impairment from the multitude of diverse regional haze sources (40 CFR Part 51). The regional haze regulations require states to establish long-term strategies for reducing emissions of air pollutants that cause visibility impairment in Class I areas. Wildland fire is one of the sources of regional haze covered by the Regional Haze Rule. On January 10, 2017, the EPA issued updates to the Regional Haze Rule providing amendments to requirements for state plans (EPA 2017). These rule revisions adopted the same fire-related definitions and smoke management actions as contained in the EPA's October 2016 Exception Events Rule revisions discussed above. One of the key provisions of the rule for fire managers is that 40 CFR 51.308(f)(2)(iv)(D) requires that states consider Basic Smoke Management Practices and smoke management programs when developing their long-term strategies for addressing visibility impairment. However, the rule does not require states to adopt Basic Smoke Management Practices or smoke management programs into their Regional Haze SIPs. In the preamble to the rule revisions, the EPA acknowledges that the appropriate use of prescribed fire may help reduce the occurrence of wildfires and the risk of wildfires having catastrophic impacts.

Fire managers are encouraged to engage with state air quality regulators as they develop and revise their long-term strategies for addressing visibility impacts at Class I areas (figure 3.1.7).

Figure 3.1.7. Mandatory Class I Areas within the United States.

2010 General Conformity Rule Amendments

The General Conformity Rule is meant to ensure that actions taken or funded by federal agencies in non-attainment and maintenance areas do not interfere with a state's plans to meet NAAQS. To meet general conformity requirements, federal agencies must conform to the purposes of the SIP and demonstrate that emissions from their actions will not exceed emission goals established by states for non-attainment or maintenance areas.

The rule provides two special exemptions from conformity for prescribed fires conducted by a federal agency. Fires conducted in accordance with a State Smoke Management Program that meets the requirements of the Interim Policy (EPA 1998) (or an equivalent EPA policy) are "presumed to conform" (40 CFR 93.153(i)(2)). Because the Policy does not actually contain requirements and no equivalent policy has been developed, what constitutes a qualifying SMP is quite broad. In the absence of an SMP, the other exemption for prescribed fires conducted by a federal agency is the application of Basic Smoke Management Practices (BSMPs) as long as public notice and comment is allowed for before the action is added to the list of presumed to conform actions. Currently this option is not available until the federal agencies have met all of the requirements of 40 CFR 93.153(g).

Another pathway to conformity is if the SIP attainment demonstration provides for a "budget" for emissions from prescribed fires, and has shown that attainment will be achieved even with consideration of these emissions.

Regulatory Roles and Responsibilities

As required by the CAA, State air regulatory agencies are required to design and implement programs and regulations to protect public health and welfare. As a part of these programs, many state and local air agencies require permits for a variety of air pollution sources including prescribed fires. As required by the CAA (Section 118) federal agencies are required to comply with all federal, state and local air pollution regulations to the same degree as any non-governmental entity. This includes obtaining permits, paying fees or reporting information on their activities or emissions.

When asked to name some barrier to their optimal use of prescribed fire, land managers often name air quality regulations at or near the top of the list. What can fire managers do to lessen the impact of regulations on their ability to accomplish fire program goals? Understanding exactly how air regulations work is a good start but fire managers should also look for opportunities to get involved directly with regulatory agencies as specific regulations or implementation plans are developed. Regulators can't develop effective or fair regulations unless they understand all pollution sources so fire managers need to look for ways to be involved in regulatory development. Table 3.1.3 gives some recommendations on roles fire managers and air quality regulators should play depending on the air quality protection method.

Table 3.1.3. Recommended cooperation between wildland fire managers and state or local air quality regulators, depending on air quality protection method.

	Responsible Person or Agency[a]		
Air Quality Protection Method	**Land Manager/ Fire Manager**	**Air Quality Regulators**	**EPA**
NAAQS	Aware	Review	Lead
Attainment Status	Involved	Lead	Approve
SIP Planning	Involved	Lead	Approve
General Conformity	Lead	Approve	Review
Smoke Management Programs	Partner	Lead	Aware
Visibility Protection	Partner	Lead	Approve
Land Use Planning	Lead	Aware	Aware
Environmental Impact Statements (EIS's)	Lead	Involved	Review
Prescribed Fire Plans	Lead	Involved	N/A

[a] A **lead** role indicates the responsibility to initiate, bring together participants, complete, and implement the particular air quality protection method. **Partners** fully participate with the lead toward development and implementation of the air quality protection method in a nearly equal relationship. **Involved** means responsibility to participate in certain components of development and implementation of the air quality protection method although not as a full partner. **Aware** means the responsibility to have a complete working knowledge of the air quality protection method but likely little or no involvement in its development or daily implementation. **Review** means the responsibility to assess air quality protection methods and make comments to those in the lead role.

Conclusions

Smoke from wildland fire can negatively affect public health and welfare. Air quality regulations are designed to protect the public from the adverse effects of air pollution including smoke from wildland fire. Fire managers need to understand and comply with air quality protection regulations to remain within the law and to maintain public support for their programs. Air quality regulations are frequently revised and updated, so remaining well informed requires some effort. In addition, fire managers and agency administrators should proactively look for opportunities to be involved in regulatory update processes so that regulators have a full understanding of wildland fire as a source of air pollution and regulations can be developed that achieve air quality goals without unnecessarily restricting the responsible use of prescribed fire. Cooperation and collaboration between wildland fire managers and air quality regulators is of great importance to achieve the difficult balance between protection of air quality and use of prescribed fire.

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3.2 State Smoke Management Programs

Michael George

Introduction

Smoke management is a critical part of responsible fire use, and fire managers must understand and follow state laws and regulations pertaining to fire. This is a very important section for this guide as it describes the real-world activities that you may be required to perform as a part of your state's smoke management program (SMP) responsibilities. This section will attempt to prepare fire managers for what they may encounter while participating in such a program and working with air regulatory or state forestry staff and management.

Overview of Program Approaches

State SMPs represent a broad range of procedures and requirements for managing smoke from prescribed fires. Most SMPs are designed to minimize effects on what are often called smoke sensitive receptors which can include, but are not limited to, populated areas, roadways, and federal Class I areas where protection of visibility is required by statute. As National Ambient Air Quality Standards (NAAQS) become more stringent and emissions from other sources are controlled, mitigating smoke impacts will become increasingly important in state or local efforts to protect public health and welfare.

Is a simple voluntary program adequate for managing smoke, or might it be necessary to implement a program that ensures coordination and authorization of daily burning activities? These assessments and the associated dialogue are generally undertaken by state air quality regulators in consultation with federal and state land managers, as well as private land owners. These are good opportunities to engage air quality regulators and make known any issues with the SMP, or to simply ask questions. Collaborative processes like these are generally more effective at getting buy-in from all involved and aid in ensuring fire managers achieve resource management objectives while also protecting the public from smoke impacts.

Generally speaking, the Environmental Protection Agency (EPA) does not monitor day-to-day management of smoke; rather, it has delegated that responsibility to states. Some tribes also have SMPs which often have more direct EPA participation. Occasionally, a state chooses to delegate some responsibilities to an air district or other local authority, especially if there are daily operational decisions to be made. The responsibility for managing smoke may reside with air quality agencies or may be included in the overall fire management program through state forestry agencies.

The range of programs that regulate burning is broad. Some states may not have a SMP and burning may be as simple as notifying the appropriate state or local agency or fire department that a prescribed burn is planned. Other states have complex programs that require an application or request on each individual burn for a permit; and approve, disapprove or conditionally approve those requests based on a variety of factors such as weather, other burns in the area, or proximity to smoke-sensitive receptors. Also, programs may or may not have specific enforcement authority for prescribed fire. The type of program is often the result of the local history of smoke effects, public complaints, nuisance concerns, and whether the area is in non-attainment for air quality standards. Some programs are designed solely to meet the requirements of EPA's Regional Haze Rule section 51.309(d)(6) (EPA 1999). For example, the Regional Haze Rule requires that certain Western states consider and address the effects of smoke on visibility in Class I areas in their regulatory programs. Several core elements of these Western programs are included in the discussion of state SMPs below. In addition, these states are to establish an emissions tracking system for all wildland fires and all agricultural fires; a more regional multi-state approach may also be deemed necessary. Other elements are the consideration of emissions reduction techniques and annual emissions goals for prescribed fire and agricultural burning.

As SMPs are developed and modified it is important for the fire management community to be involved. Close collaboration with air regulatory agencies will ensure that a balance is maintained between meeting land management objectives and protecting public health and welfare.

EPA's Interim Air Quality Policy on Wildland and Prescribed Fires

EPA's Interim Air Quality Policy on Wildland and Prescribed Fires (EPA 1998) provides direction for state and tribal air quality programs for smoke management. This includes, first and foremost, working closely with land managers to ensure an effective approach. The policy also describes the seven elements of a basic SMP that should be considered, most of which are described below. This 1998 interim policy has been superseded by the 2016 Exceptional Events Rule (EER) (EPA 2016). Under the EER NAAQS exceedances from fire can be removed from the record if certain requirements are met, and the state demonstrates these appropriately to EPA. For prescribed fire, demonstration must show it is burned within the natural fire return interval or at a fire frequency needed to establish, restore and/or maintain a sustainable and resilient wildland ecosystem as documented in a land/resource management plan or equivalent plan and if there is a SMP in place. If no SMP is in place, then appropriate Basic Smoke Management Practices must be utilized. The Exceptional Events Rule which is described in more detail in Chapter 3.1 on smoke management regulations. The EPA is developing a document which will summarize how wildland fire is addressed in its various rules and how these rules should be implemented for these smoke sources. That document is planned to fully supersede the 1998 Policy.

Smoke Management Programs

State Smoke Management Programs (SMPs) are intended to:

- Consider EPA's, "Interim Air Quality Policy on Wildland and Prescribed Fires" (EPA 1998)
- Consider EPA's Exceptional Events Rule (EPA 2016)
- Address nuisance smoke
- Minimize air quality impacts
- Comply with state implementation plan requirements
- Address visibility and Regional Haze Rule requirements (EPA 2017)

Some programs are aimed at more than one of these issues. State SMPs may be mandatory or voluntary. However, most attempt to manage the amount and effects of smoke. There is a broad range of how this is done around the country.

The following are examples of what might commonly be found in a state SMP:

1. **Consideration of smoke sensitive receptors:** Many states want burners to limit smoke effects on population centers. This may even include individual residences or businesses if near the prescribed burn. Class I areas for visibility protection may be included as smoke-sensitive receptors. Not impairing motorist visibility on roadways so as to become a safety hazard is also often required. Chapter 8.1 on fire management planning should be reviewed for information on how to best to manage smoke impacts. In addition, a review of the transportation-specific issues described in Chapter 2.3 might be helpful in this regard.
2. **Dispersion or ventilation criteria:** Some state SMPs have requirements or thresholds related to the meteorology forecast on the day of the burn. This consideration of the weather is most commonly related to how well the smoke is predicted to disperse. Some states provide a means

for getting this information while others expect burners to acquire it on their own. The discussion of obtaining and applying weather forecasts for prescribed fire activities is in Chapter 5.2 and should be reviewed if the smoke management plan has these kinds of requirements.

3. **Fuel or emissions limitations:** Some states have established a maximum number of acres, or tons of fuel per acre, that may be burned on a given day. The material in Chapter 4.1 on fuel consumption and smoke production should be reviewed closely if it is necessary to estimate emissions to determine the ability to burn under a state SMP.
4. **Alternatives to burning:** Many state SMPs require a documented assessment of alternative fuel treatments such as mechanical or chemical treatments. Typical criteria for such an evaluation might include cost and the degree to which each option meets land management objectives, as well as whether any ecological advantages or disadvantages are associated with the options.
5. **Consideration of emission reduction techniques:** There are many actions that can be taken when burning to reduce the amount of smoke produced, including firing techniques and ignition patterns. Several states require that the applicable options be considered and those that are feasible be implemented for the burn in question. This assessment process must also be well documented. There is a more detailed discussion of emission reduction techniques in Chapter 4.2 which should be reviewed when it is necessary to undertake such an assessment.
6. **Monitoring:** States may require monitoring of smoke movement and accumulation to ensure that smoke is going where it was forecasted and that no more smoke is being generated than was expected. There are several monitoring options, with visual observation being the most common. A state may also request that more sophisticated automated monitoring equipment be used for larger prescribed fires in or near smoke-sensitive areas both to inform the public and to inform operational decision making. For a more in-depth discussion of monitoring refer to Chapter 5.4.

State SMPs often have requirements to ensure that proper planning has been done, or to allow for coordination of multiple prescribed fires at the same time. It is also often required to notify the public of any prescribed fire activity. Some of the specific requirements might include:

7. **Burn plans:** Required burn plans by states can take several forms. For example, some required plans for smoke management are simply a part of the burn plan required by the state forestry agency. Some of these plans are more robust and require smoke-specific elements to meet state regulations or policy or guidance. Some air quality regulators even require documentation called a 'burn plan' that is separate from the overall burn plan, which might be a bit confusing. These plans can be very explicit as to what needs to be addressed in the planning process. Most often such a plan is required at the beginning of a particular project but can also be an annual requirement where multiple projects might be included.
8. **Request and approval process:** Many SMPs have a request and approval process which allows states to coordinate smoke emitted from multiple prescribed fires in a given area. These requests may be for either multiple days at a time or on a day-by-day basis. The response to the request may be an approval, an approval with certain conditions, or denial. The information required usually includes many of the elements described in numbers one through six above to assist in decision making by the regulator. Some states also require a follow-up report that details what was actually done.
9. **Public notification:** Several states require public notification before the ignition of the prescribed fire. The means by which this can be done is usually somewhat open-ended so referring Chapter 6.1 should be most helpful for this type of communication.

There are as many variations in terms of what SMPs may contain as there are SMPs. Table 3.2.1 is intended to illustrate the variety of programs that exist—from fairly simple to more involved—and is intended to be illustrative. It does not show all state SMPs. This table is current at the time of the publication of this guide but programs do change over time.

Table 3.2.1. Examples of State Smoke Management Program elements.

State Smoke Management Program Elements	PA	GA	SC	WY	OR	AZ
1) Consideration of smoke sensitive receptors	X	X	X		X	X
2) Dispersion or ventilation criteria		X	X	X	X	X
3) Fuel or emissions limitations			X			X
4) Alternatives to burning		X		X	X	
5) Consideration of emission reduction techniques				X	X	X
6) Monitoring	X			X	X	X
7) Burn plans	X		X	X		X
8) Request/approval process		X	X		X	X
9) Public notification			X		X	

Note: The elements indicated for Oregon do not apply in the entire state, check with the state for requirements for your local area.

There is a significant range in the type and number of requirements in table 3.2.1. These are due to differences in program goals. Some contrasts are based on which element of the Clean Air Act is of most concern relative to smoke: visibility, as in the case of Wyoming, or non-attainment of NAAQS, as in the case of Georgia. Some programs, like the one in Arizona, have been driven largely by the sensitivity of communities to smoke, and by incidents where high concentrations of smoke from prescribed fires have affected many people.

It is highly recommended that appropriate state agencies are contacted for clarity to ensure compliance with their requirements because there are often gaps between what is intended by smoke management regulation, policy or guidance documents and the way it is interpreted by a fire manager. A clarifying discussion with air quality regulators early on can be quite helpful in ensuring compliance.

Basic Smoke Management Practices

Regardless of the existence of an applicable state SMP, all fire practitioners should consider using some or all of the following Basic Smoke Management Practices (BSMPs) on every burn. Basic smoke management practices are a set of six universally applicable activities which help manage, track, and reduce the effect of prescribed burning on air quality. Although all six are not always appropriate, these BSMPs should always be considered for use in addition to local burn requirements such as obtaining a permit or participation in a state SMP.

These six BSMPs are cited in the EPA's "Treatment of Data Influenced by Exceptional Events Rule" [Exceptional Event Rule (EER) of 2016)] and "Revision to the General Conformity Rule" (2010). The USDA NRCS and Forest Service released a 2011 Tech Note (USDA NRCS 2011) describing BSMPs in detail, and it is summarized in table 3.2.2. Basic smoke management practices are useful for any fire manager wishing to maintain the social acceptability of using prescribed fire and managing air quality effects of smoke. Air regulatory authorities may also find greater acceptability of prescribed fires with use of BSMPs. Each BSMP has varied applicability depending on the type of burn, fuels to be burned and level of effort needed to address air quality concerns. EPA in the EER (EPA 2016) stated the list of BSMP below is not intended to be all-inclusive as all BSMP are not appropriate for all burns. It further notes that other BSMPs may become available due to technological advancement or programmatic refinement. EPA also expressed that elements of these BSMP could also be practical and beneficial to apply to wildfires for areas likely to experience recurring wildfires.

BSMP #1: Evaluate smoke dispersion conditions to minimize smoke impacts

Always evaluate smoke dispersion conditions by an appropriate combination of the following: (1) identify smoke sensitive receptors, (2) model or map dispersion to determine where smoke may go and the degree of potential impacts, (3) use the most recent meteorological forecast of conditions that influence smoke dispersion, and (4) verify the accuracy of the forecast before lighting and during the burn to insure smoke is dispersing as planned.

BSMP #2: Monitor the effects of the prescribed fire on air quality

Monitoring the effects of prescribed fire on air quality includes keeping track of where the smoke goes, how high it lofts and whether it disperses well or remains tight and dense. This can be done through visual monitoring and documented by notes, photographs, aircraft observations, satellite imagery, air quality monitoring data, and post-burn evaluations. Before igniting, assess the local and potential impact area air quality to avoid making a condition worse. Air quality forecasts are available from EPA's AirNow website (EPA 2015) or other sources like the National Weather Service. Determine the air quality conditions during and after the prescribed fire by checking all available air quality monitors.

BSMP #3: Record-keeping of BSMPs, prescribed fire activity, and smoke behavior

Keep records of the BSMPs used and include: notes on weather forecast; conditions both during and after the prescribed fire which influenced the dispersion of smoke; burn acres, location, date, time, fuel type and consumption as well as actual smoke dispersion and effects if any. Record-keeping can be as simple as keeping a personal journal and could be very important if a smoke crosses a road, affects a smoke sensitive area, or contributes to the exceeding of national or local air quality standards.

BSMP #4: Communication—public notification

Fire managers need to notify appropriate authorities and people potentially affected by the smoke. It is useful to prepare for contingency actions for during and after the prescribed fire. In addition, it's useful to prepare for contingency actions during the fire to reduce exposure of people at smoke sensitive receptors if unintended impacts were to occur.

This includes a public communication plan which could reduce exposure of people if an unintended impact were to occur.

BSMP #5: Consider use of emission reduction techniques (ERTs)

Whenever executing a prescribed fire, consider methods for reducing emissions which will reduce downwind effects. Care should be taken to ensure the ERTs are appropriate for the site and will still allow burn objectives to be met (see Chapter 4.2 Techniques to Reduce Emissions from Prescribed Fire for more details).

BSMP #6: Share the airshed to minimize exposure of the public—Coordination of area burning

Develop a communications and information-sharing network among fire managers who may be in the prescribed fire vicinity on the same day or who could cumulatively affect a smoke sensitive receptor. This enables coordination and planning of ignitions to cooperatively schedule prescribed fires to avoid overwhelming overwhelm the ability of the atmosphere to disperse smoke from multiple prescribed fires.

Table 3.2.2. Basic smoke management practices are universally applicable techniques that should be considered every time prescribed fire is used, and are also criteria for consideration under the 2016 Exceptional Event Rule.

Basic smoke management practice	Benefit	When the BSMP is applied—Before/During/After the Burn
Evaluate Smoke Dispersion Conditions	Minimize smoke impacts	Before, During, After
Monitor Effects on Air Quality	Be aware of where the smoke is going and degree it affects air quality	Before, During, After
Record-Keeping/Maintain a Burn/Smoke Journal	Retain information about the weather, burn and smoke. If air quality problems occur, documentation helps analyze and address air regulatory issues	Before, During, After
Communication – Public Notification	Notify neighbors and those potentially affected by smoke, especially sensitive receptors	Before, During, After
Consider Emission Reduction Techniques	Reducing emissions through mechanisms such as reducing fuel loading, can reduce downwind impacts	Before, During, After
Share the Airshed – Coordination of Area Burning	Coordinate multiple burns in the area to manage exposure of the public to smoke	Before, During, After

Conclusion

Complying with state smoke management regulations is an important part of any prescribed fire program. A conversation with the organization regulating smoke can improve understanding of what is required under state SMP. This understanding can be facilitated by a conversation with the organization charged with regulating smoke, as well as reviewing this section and related sections of this guide. This can ensure a balance between meeting land management objectives and mitigating air quality effects. Be aware that the details of SMPs may vary among states.

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CHAPTER 4–FUEL CONSUMPTION AND EMISSIONS REDUCTION

4.1 Fuel Consumption and Smoke Production

Roger D. Ottmar

This chapter describes the process of calculating emissions from wildland fire. Whether the concern is with carbon dioxide (CO_2), particulate matter (PM), carbon monoxide (CO), methane (CH_4), nitrogen oxide (NOx), non-methane volatile organic compounds (NMVOC), water (H_2O), or black carbon, smoke components from wildland fires are generated from combustion of live and dead plant biomass or what we often refer to as fuel. The amount of smoke produced can be derived from knowledge of: (1) the size of the area blackened, (2) length of burning period, (3) fuel loading, (4) fire behavior, (5) fuel consumption, and (6) emission factors. Multiplying an emission factor (lbs/t) by the fuel consumed(t/ac), and adding the time variable (hr) to the emission production and fuel consumption equations results in emission and heat release estimates needed to run smoke dispersion models (figure 4.1.1) (Ottmar *et al.* 2009). The chapter reviews the knowledge and predictive models currently available for deriving each of the principal inputs required to obtain emissions and heat release rate. An understanding of the variables that control the production of smoke will lead to improved prescribed fire planning to reduce the impacts of smoke on the public and smoke sensitive receptors. It will also provide more accurate emissions inventories and improved disclosure in National Environmental Policy Act (NEPA 1969) analyses.

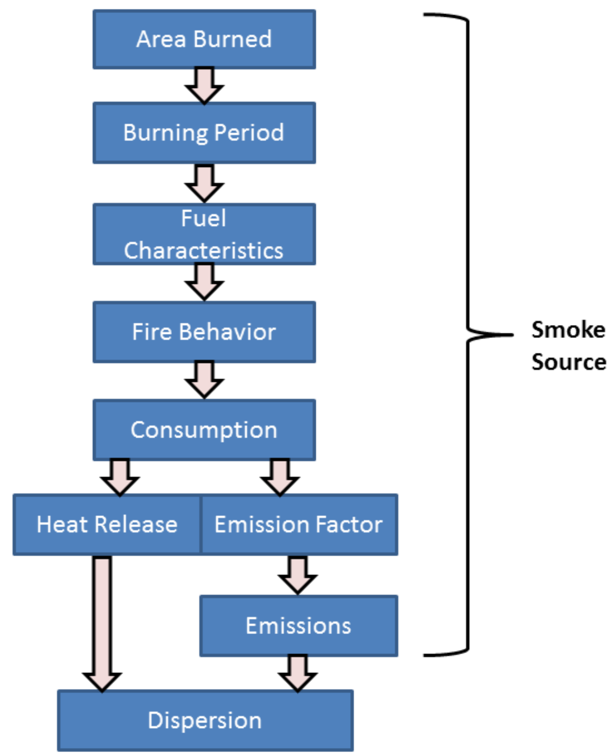

Figure 4.1.1. Inputs required to determine emissions generated from wildland fires.

Area Burned

The area (acres) of a wildland fire burned or blackened is one of the more important variables required to estimate emissions from wildland fire. It also can be one of the more difficult parameters to accurately obtain (Battye and Battye 2002). Large errors may exist in both reporting the total perimeter of a wildland fire and the area within the perimeter where fuel was consumed (Peterson 1987). Individual estimates of fire perimeter and actual area blackened can be exaggerated (Sandberg *et al.* 2002). For example, the entire landscape within a fire perimeter is often reported burned although non-uniform fuels, geographic barriers, or changes in the weather can cause a fire to burn in a mosaic pattern with unburned patches. Meddens *et al.* (2016) determined that approximately 20 percent of the area within a wildfire perimeter was unburned. In other instances, poor reporting systems may miss a large number of fires. If private burners and land management agencies are required to report the number of acres to be burned before a permit is issued, prescribed fire acreages may be more accurate. However, if there is an escape of a prescribed fire, or if the acres treated are not totally blackened and did not have a chance to burn, or if the burned area is not required to be reported, an accurate assessment of area burned will be more difficult to obtain. The best approach is to require a post fire assessment that accounts for only the area actually burned to obtain the most accurate accounting of smoke produced from wildland fire.

Measurements of the post-fire area burned can be obtained from three primary sources: wildfire reports, prescribed fire or smoke management reports, and aerial and satellite imagery (Battye and Battye 2002). All three procedures have problems associated with the information. For example, wildfire reports can be hard to locate, fire location and vegetation data associated with the fire may be incorrect, and the daily perimeter growth is rarely included. Prescribed fire and smoke management reports often provide correct project size; however, the fuel loading and actual area burned (black acres) may be incorrect. Although large scale inventories of area burned are often derived from satellite imagery (e.g. SmartFire 2 (Larkin and Raffuse 2012)), the technique can be inadequate in landscapes with variable slope and often can't detect fires under a canopy (Crutzen and Andreae 1990, French *et al.* 2004, Levine 1994, Sandberg *et al.* 2002). Lentile *et al.* (2006) provides an excellent review of remote sensing techniques and capabilities to assess active fires and fire effects. Although accurately estimating the burned or blackened acres after the fire takes more time, this additional information will provide a more accurate estimate of emissions and resulting air quality effects.

Burning Period

The burning period (hours) is the length of time fuels are burning. It can be estimated based on known ignition time and information about when fuel consumption is expected to end.

The burning period for a wildland fire event may be several hours or several months. There may be periods of high intensity fire growth associated with a large smoke plume interspersed with periods of low intensity associated with slow growth and a low buoyant smoke plume. Fuel is seldom consumed throughout the burn area all at one time, but rather is along an ever-changing perimeter that experiences successive ignitions, flaming spread, and smoldering combustion periods. Reporting of the actual burning periods required for estimating emissions produced over time (tons/hr), and the amount of heat released over time (Btu/hr). Emission production and heat release rate are used by dispersion models to estimate smoke concentrations and air quality effects (Hardy *et al.* 2001, Sandberg *et al.* 2002).

Fuel Characteristics

A fuelbed is a homogenous unit on the landscape representing a unique combustion environment composed of live and dead vegetative biomass (Ottmar *et al.* 2007, Riccardi *et al.* 2007). Often, fuelbeds are categorized into fuelbed types representing vegetation cover type such as Douglas fir forest, sagebrush shrub land, or longleaf pine plantation. The characteristics of the fuelbed include loading, chemical make-up (water, carbohydrates, fats and proteins, and minerals), geometry and compactness, and continuity. These characteristics along with weather and topography play an important role in determining how much fuel will consume and the resulting emissions (Ottmar *et al.* 2009, Ottmar 2014, Parsons *et al.* 2016).

One of the most important characteristics of the fuelbed is the loading. Loading can vary widely across fuelbed types (figure 4.1.2) (Weise and Wright 2014) and within the same fuelbed type (figure 4.1.3). The lightest fuel loadings are typically associated with an area of limited vegetation (e.g., less than1 t/ac for perennial grasses in the Midwest with no rotten material or duff) (Ottmar and Vihnanek 1999). The heaviest fuel loadings are normally associated with forested sites where woody debris has been left following logging and other human disturbances, live and dead material has accumulated through natural succession (e.g., deep duff layers and woody debris) or a natural disturbance has occurred (e.g., wind throw, wildfire, insect and disease). Over 200 t/ac of sound and rotten woody debris and deep layers of duff can be associated with wet temperate Douglas fir/western hemlock forests of the Pacific Northwest (Wright *et al.* 2012).

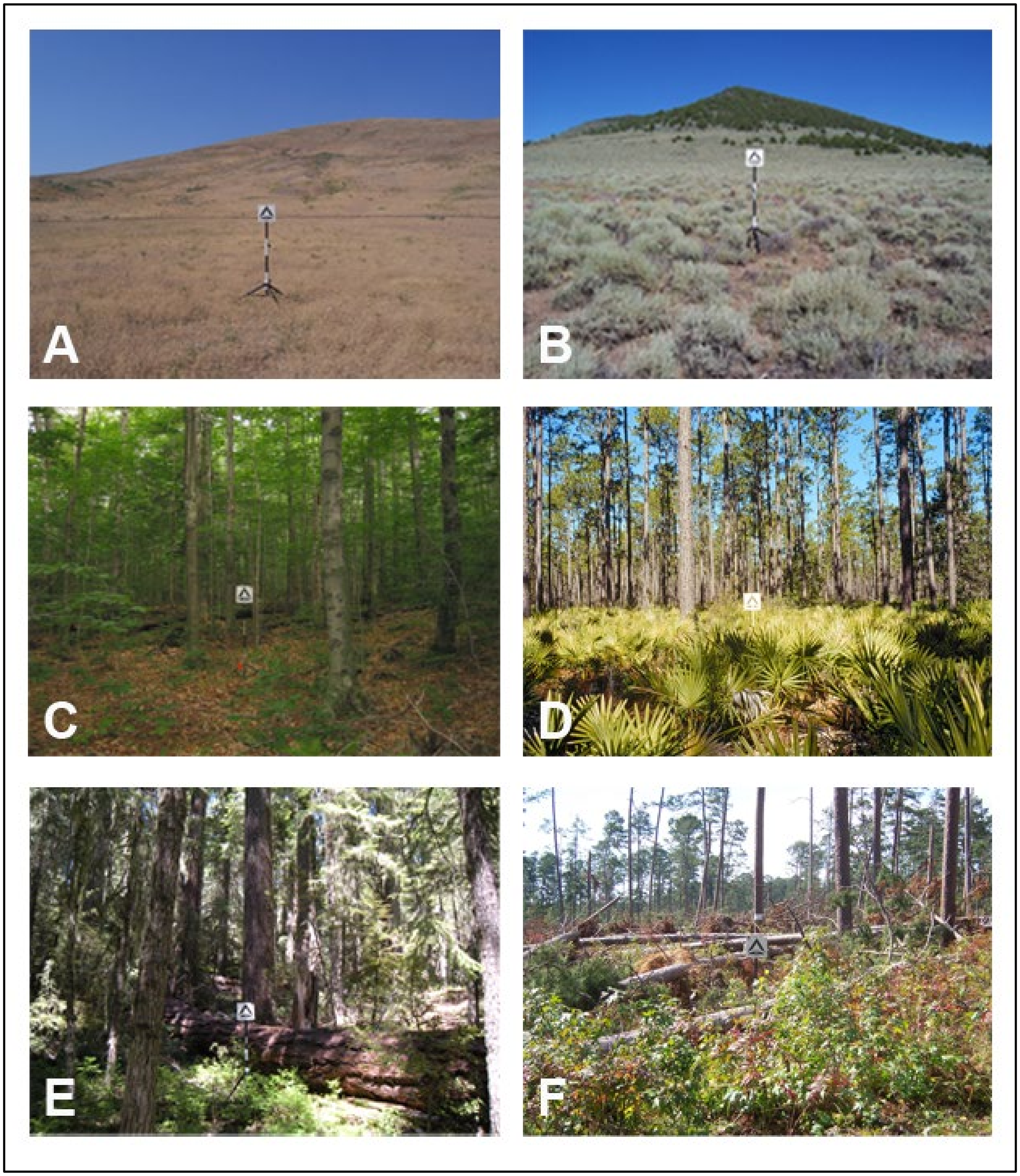

Figure 4.1.2. Preburn fuel loading (shrubs, grasses, dead woody, litter, and duff) varies among fuelbed types as shown in (A) eastern Oregon grassland, 0.25 t/ac; (B) eastern Oregon sagebrush 4.25 t/ac; (C) Northeast mixed hardwoods 11.30 t/ac; (D) Southeast longleaf 23.12 t/ac; (E) Northwest old-growth Douglas-fir and hemlock forest 103.25 t/ac; and (F) Southeast short leaf pine stand with hurricane blow-down 90.35 t/ac.

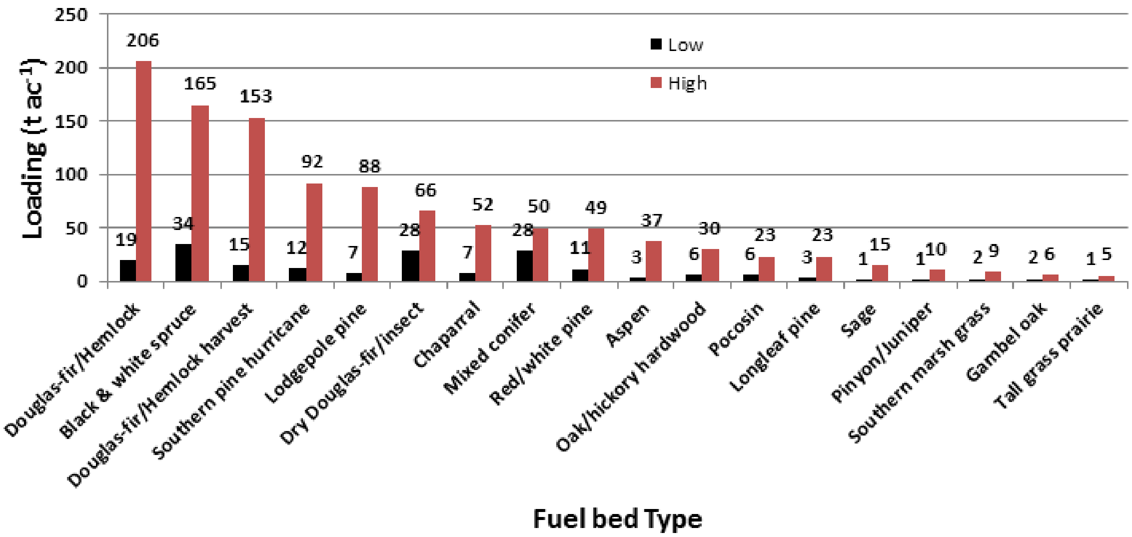

Figure 4.1.3. Variability of fuel loading across several fuelbed types. These data are from the natural fuel photo series (Ottmar *et al.* 1998a, Ottmar and Vihnanek 1999, Ottmar and Vihnanek 2000a, 2000b, Wright *et al.* 2012).

Loading

Loading of fuel is a fundamental fuel characteristic important for estimating the amount of fuel that will be consumed (Prichard *et al.* 2007, Brown *et al.* 1991). Total fuel loading is the entire amount of both live and dead vegetative material present.

Higher fuel loading generally equates to more fuel consumption and emissions if the combustion parameters remain constant. For example, a frequently burned southern or western pine stand may have a fuel loading of 12 t/ac while a recently harvested pine stand with logging slash left on the ground may have a fuel loading of 50 t/ac. Prescribed fire under a moderately dry fuel moisture situation would achieve 50 percent biomass consumption equating to 6 t/ac consumed in the unlogged pine stand and 25 t/ac consumed in the logged stand.

There are several techniques available for determining fuel loading (U.S. Department of the Interior 1992). Collecting and weighing the fuel is the most accurate method but is impractical for many fuel types. Measuring a biomass parameter and estimating the fuel loading using a pre-derived equation is less accurate but also less time consuming (Brown 1974). Other techniques that currently or will, in the future, provide managers with less time consuming and improved estimates of fuel loading and other characteristics include:

- Natural fuels photo series (Ottmar *et al.* 1998a, Ottmar and Vihnanek 2000b, Wright *et al.* 2012), and digital photo series (Wright *et al.* 2010a)
  The photo series is a sequence of single and stereo photographs with accompanying fuel characteristics. Over 30 volumes are available for logging and thinning slash and natural fuels in forested, shrub land, and grassland fuelbed types throughout the United States. Many of the natural fuel photo series are housed in a searchable electronic database called the Digital Photo Series (University of Washington 2015).

- Pile calculator (Wright *et al.* 2010 b,c)
  The Pile Calculator is a web application that uses formulas for different geometric shapes to estimate pile volume, and empirically-derived relationships between volume and biomass to estimate pile weight for different piles types (machine vs. hand) composed of different material (different types of coniferous material for machine piles, and coniferous vs. hardwood/shrub material for hand piles).

- Fuel Characteristic Classification System (FCCS) (Ottmar *et al.* 2007, Ricarrdi *et al.* 2007, Sandberg and Ottmar 2001, Prichard *et al.* 2013).
  The FCCS is a national system designed for building and classifying wildland fuelbeds according to a set of inherent properties to provide the best possible fuels estimates and probable fire parameters based on available site-specific information. The system has been used to generate fuelbeds for the United States which have been mapped in the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) (Rollins and Frame 2006) (figure 4.1.4).

- Fuel loading models (Sikkink *et al.* 2009)
  Fuel loading models (FLMs) are a new classification system for predicting fire effects from on-site fuels (Sikkink *et al.* 2009). Each FLM class represents fuel beds that have similar fuel loadings and produce similar emissions and soil surface heating when burned using computer simulations.

- Aerial and ground Light Detection and Ranging (LiDAR) (Loudermilk *et al.* 2009). The ground-based LiDAR is an upcoming technology that may precisely quantify fuel bed characteristics with the help of lasers (Loudermilk *et al.* 2009).

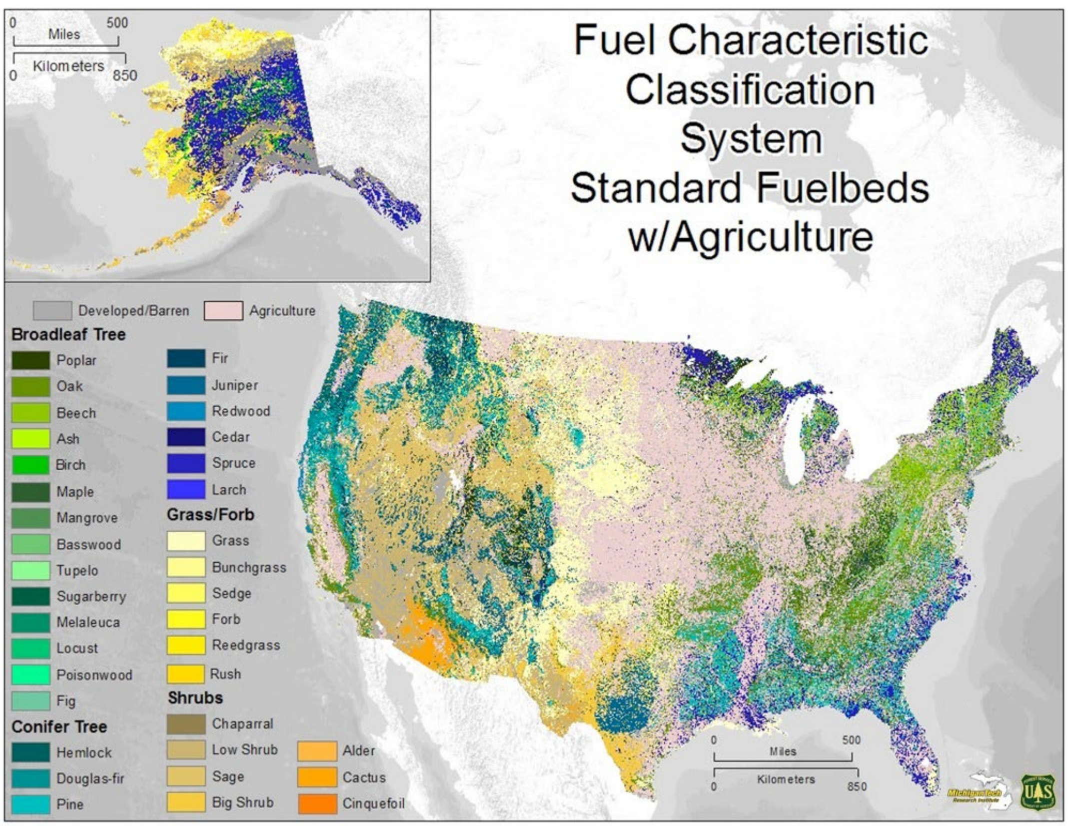

Figure 4.1.4. FCCS fuelbeds mapped by LANDFIRE vegetation classes aggregated with agriculture.

Chemistry

Fuels are composed of four broad chemical categories: (1) water, (2) carbohydrates, (3) fats and proteins, and (4) minerals (Parsons *et al.* 2016). The allocation of each chemical category varies depending on the type of fuel, whether the fuel is dead or alive, and in the case of dead material, how much decay has occurred.

The water content of a fuel is a critical factor in determining fuel consumption because a large amount of energy is required to evaporate the moisture before the fuel can begin to consume. Many studies have shown that it takes longer to ignite fuel and less fuel is consumed with higher moisture content (Sandberg and Ottmar 1983, Brown 1991). There are two types of fuel moisture, live and dead. Live fuel moisture content can vary by temperature, relative humidity, rainfall, soil moisture, seasonality and species. Dead fuel moisture content varies by temperature, relative humidity, rainfall, species, material size, and decay class.

Fuel moisture content not only influences the amount and rate of consumption; it also affects the flame temperature which in turn influences how efficient a fuel will burn. Generally, fuels with low fuel moisture content burn more efficiently and produce less particulate matter, CO, methane (CH_4) and non-methane volatile organic carbons (NMVOC) per ton of fuel consumed. But somewhat surprisingly these efficient burns actually emit more carbon dioxide (CO_2) and nitrogen oxide (NO_x) per ton of fuel consumed. More particulate matter, CO, CH_4, and NMVOC per ton of fuel burned will be produced at higher fuel moistures because the fuels combust less efficiently. However, total emissions may be less when burning moist fuels if less of the fuels burn—typically the large woody fuels and forest floor consume less under moist fuel conditions.

Carbohydrates are another chemical category that make up a large portion of wildland fuels. These carbon-based compounds provide the primary substance for the gases that contribute to flaming consumption. The fat-based compounds make up about 10 percent of the fuels' dry mass. The fats are generally composed of waxes, oils, resins, and isoprenes, are often highly flammable, and have twice the heat content of any other compound (Merrill and Watt 1973). Although proteins are contained in wildland fuels, they are not a large contributor to combustion. Finally, mineral or ash content is the measure of the amount of fuel that is composed of unburnable compounds. Ash content can vary greatly among species and small amounts of changes in the ash content can induce large changes in the combustion of wildland fuels (Broido and Nelson 1964).

The biochemical differences among species also play a role in combustion. Certain species such as hoaryleaf ceanothus (*Ceanothus crassifolius*), waxmyrtle (*Myrica cerifera*), palmetto (*Serenoa repens)* and gallberry (*Ilex glabra*) contain volatile compounds that make them more flammable than species such as Carolina azalea (*Rhododendron carolinianum*) under similar live moisture contents (figure 4.1.5).

Geometry and compactness

Because combustion generally takes place at the surface of the fuels, the amount of fuel surface area compared to the volume of the particle (surface-area-to-volume ratio) strongly influences fuel consumption, especially whether most of the fuel consumption will take place in the flaming or smoldering phase. Smaller particles (e.g., grass and small twigs) require less heat exposure to ignite and combust compared to larger fuel particles (e.g., large logs). The small particles generally burn during the flaming stage and larger fuels that often burn during the smoldering stage. Furthermore, the geometry determines moisture uptake and release from a fuel particle. For example, particles with large surface-area-to-volume ratios such as grass can gather and release moisture quickly compared to fuels with small surface-to-volume ratios.

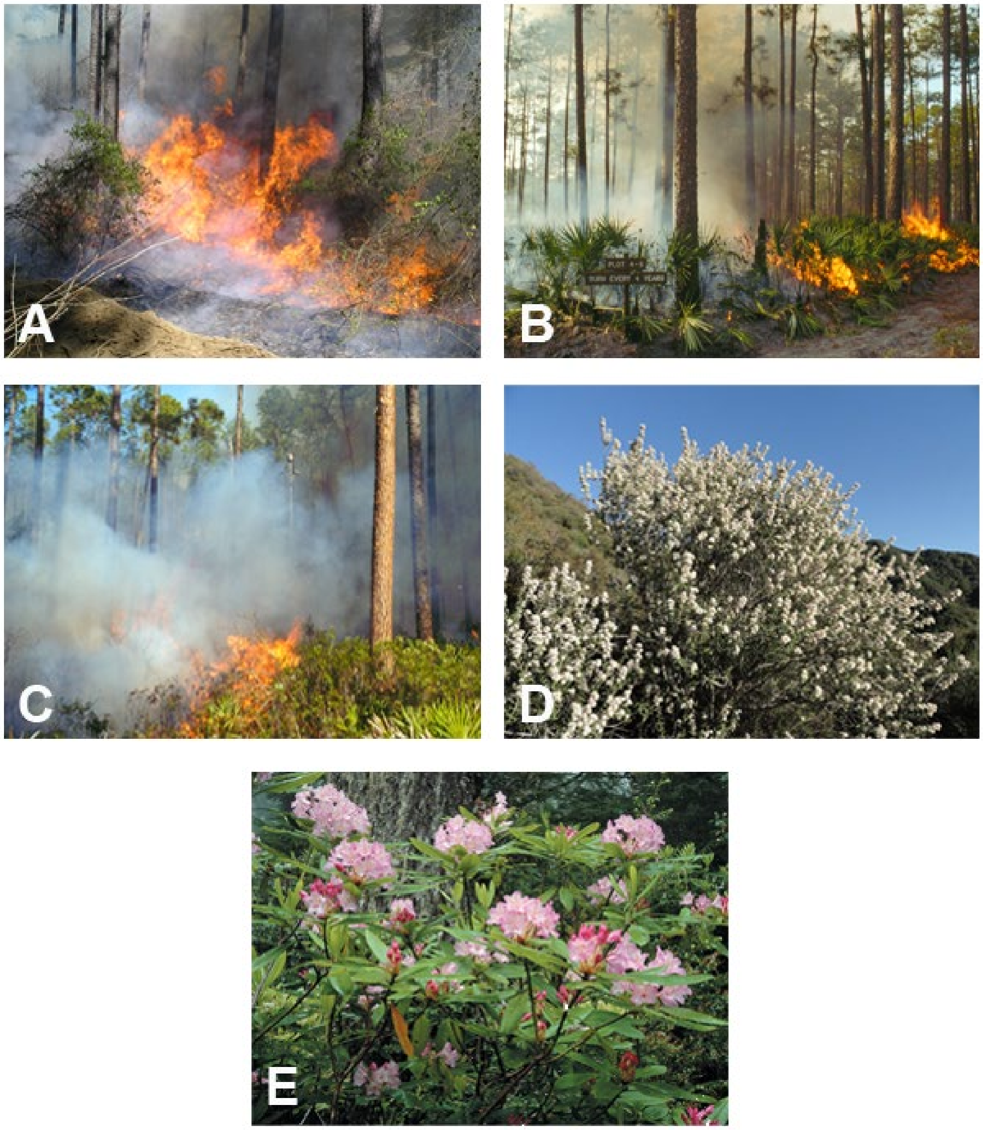

Figure 4.1.5. Biochemical differences among the waxmyrtle (A), palmetto (B), gallberry (C), and hoaryleaf ceanothus (D) make these species more flammable compared to the rhododendron (E).

The compactness of fuel particles in fuel beds can either enhance or retard fuel consumption, and affect how efficiently a fuel will consume and generate emissions. The packing ratio (the fraction of the fuel bed volume occupied by fuel) is the measure of the fuel bed compactness. A loosely packed fuel bed (low packing ratio), such as a sparse shrub field, will have plenty of oxygen to be available for combustion, but may inefficiently transfer heat between burning and adjacent unburned fuel particles. Many particles cannot be preheated to ignition temperature and are left unconsumed. On the other hand, a tightly packed fuel bed (high packing ratio) such as duff can efficiently transfer heat between the particles but access to oxygen may be limited, reducing consumption and combustion efficiency. An efficiently burning fuel bed such as a loosely packed pile will have particles close enough for adequate heat transfer with large enough spaces between particles for oxygen availability.

Continuity

Another fuel characteristic with important implications for fuel consumption is the size of gaps between fuels. Sustained ignition and combustion will continue only if fuel particles are close enough together and heat can be transferred between particles allowing combustion to occur.

Classifying and characterizing fuel beds

At a landscape scale, the variability of fuels makes them difficult to characterize and classify. One strategy for addressing this complexity is to describe fuels as a series of fuel bed categories and subcategories, each with unique properties that will determine how they will combust and consume. This is the approach taken in the Fuel Characteristic Classification System (FCCS) (Ottmar *et al.* 2007, Riccardi *et al.* 2007, Prichard *et al.* 2013) where the FCCS defines a fuel bed as a relatively homogenous composition of fuels on the landscape, representing a unique combustion environment. The fuel bed is composed of up to six strata with many categories and subcategories to represent every fuel element that has a potential to consume (figure 4.1.6).

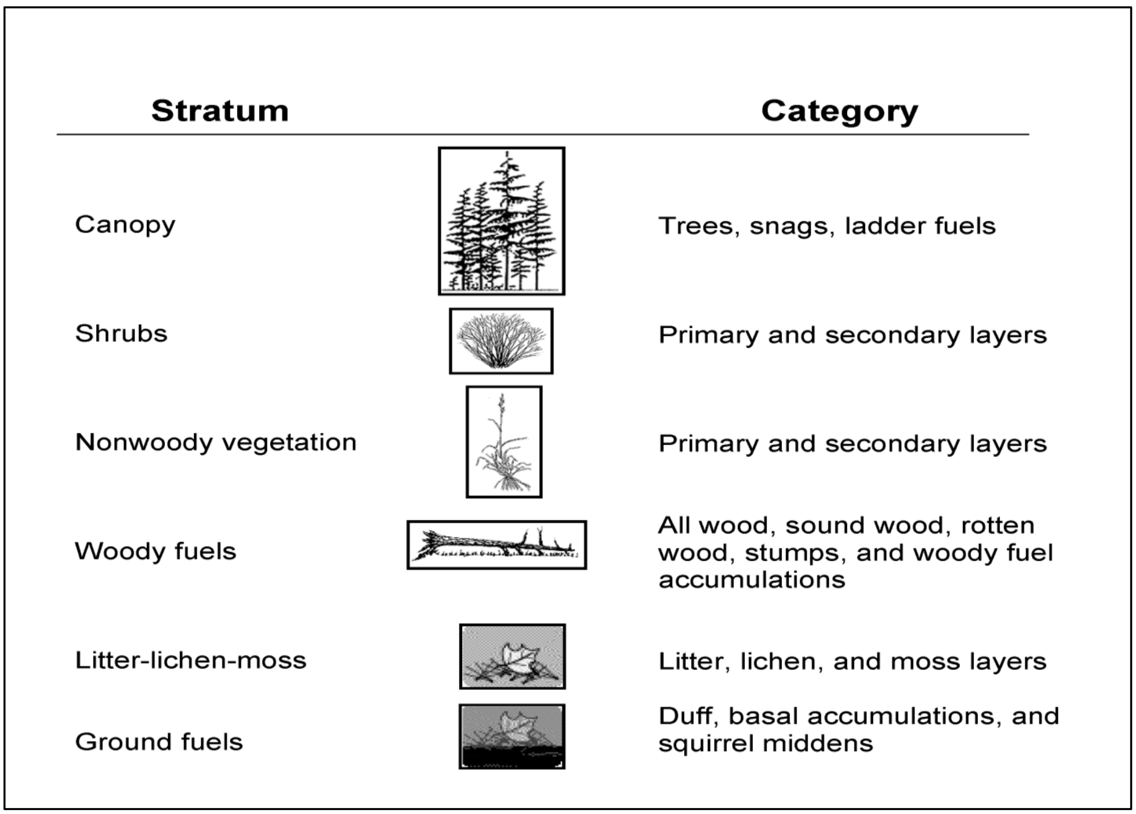

Figure 4.1.6. Stratification of a fuelbed.

Fire Behavior

Fire behavior is the manner in which fire reacts to the smaller fuels available for burning, weather, and topography (DeBano *et al.* 1998, National Wildfire Coordinating Group 2014). It is dependent upon the type, condition, and arrangement of the shrubs, grasses, woody, and litter, lichen, and moss fuel bed strata, local weather conditions, topography and in the case of prescribed fire, lighting pattern and rate of ignition. Three aspects of fire behavior are:

- Fireline or reaction intensity (the amount of heat released per unit length of fireline; Btu/ft^{-2}/min)

- Rate of spread (activity of the fire in extending its horizontal dimensions; ft/min)
- Residence time (amount of time a certain section, specific spot, or area spends in the flaming, smoldering, and residual stages of combustion; min). (Sandberg *et al.* 2002).

These aspects influence how efficiently fuels consume and the type and amount of pollutants produced from wildland fires. During fires with rapid rates of spread and high intensity but relatively short duration, most of the biomass consumed will be the smaller fuels with high surface-to-volume ratios (e.g., grass, litter, and small woody fuels) and will occur during the more efficient flaming period resulting in less total smoke. Burning dry grass and shrublands, clean and dry piles, and rapid ignition of circular or strip-head fires may produce these characteristics. In simple, uniform fuel beds such as pine and leaf litter with shallow organic material beneath, a backing fire with lower rates of spreads and intensities may consume fuels very efficiently, producing less total smoke. In more complex fuel beds, the backing flame may become more turbulent and thus combustion efficiency may lessen. During wildfires and prescribed fires with long burning durations, a large portion of the biomass consumed typically will occur during the less efficient smoldering phase, producing more smoke relative to the fuel consumed. Smoldering fires often occur during drought periods in areas with high loadings of large woody material or deep duff, moss, or organic soils.

The Fire Emissions Production Simulator (FEPS) (Fire and Environmental Research Applications Team 2006) and the Fire Area Simulator (FARSITE) (Finney 1998, 1999) are two models that take into account fire behavior and ignition period and pattern to estimate emission production rates. Both tools model the flaming and smoldering combustion and duration in down, woody fuels and duff, although FEPS is better parameterized to predict flaming versus smoldering (Sandberg *et al.* 2004).

Fuel Consumption

Fuel consumption specifies the amount of live or dead vegetative biomass that consumes during wildland fire (Ottmar 2014). Fuel consumption is expressed as mass of biomass consumed per unit area (e.g., tons per acre). In cases where the time it takes to consume a specific amount of fuel is known, consumption rate can be calculated and expressed as mass consumed over time (e.g., tons per minute).

Fuels are consumed in a complex combustion process that varies widely among wildland fires. In the simplest terms, combustion of vegetative matter (cellulose) is a thermal/chemical reaction whereby plant material is rapidly oxidized producing carbon dioxide, water, and heat. This is the reverse of plant photosynthesis where energy from the sun combines with carbon dioxide and water, producing cellulose. In the real world, the burning process is much more complicated. Burning fuels is a two-stage process of pyrolysis and combustion. Although both stages occur simultaneously, pyrolysis occurs first and is the heat-absorbing reaction that converts fuel elements such as cellulose into char, carbon dioxide, carbon monoxide, water vapor, and highly combustible vapors and gases, and particulate matter. Combustion follows as the escaping organic hydrocarbon vapors released from the surface of the fuels burn. Because combustion efficiency is rarely 100 percent during wildland fires, hundreds of chemical compounds are emitted into the atmosphere, in addition to carbon dioxide and water. Pyrolysis and combustion proceed at many different rates because wildland fuels are often very complex and non-homogeneous (DeBano *et al.* 1998).

After wildland fires, charred residues and ash remain as by-products of incomplete combustion. Carbon in these residues, often called black carbon, is basically inert, and has a prolonged residence time if it becomes incorporated into the soil. This may offset a portion of the carbon released into the atmosphere during the fire (Kuhlbusch *et al.* 1996, DeLuca and Aplet 2008, Rovira *et al.* 2009, Brewer 2012).

Furthermore, how quickly vegetation reestablishes and grows will help determine the carbon sequestration potential of the site after the fire.

Phases of combustion

Combustion phases occur both sequentially and simultaneously as a fire front moves across the landscape. Understanding the combustion process of each phase will assist managers in employing various emission reduction techniques. There are four major phases of combustion when fuel particles are pyrolized and consumed (Mobley 1976, Prescribed Fire Working Team 1985). These phases are: (1) pre-ignition heating, (2) flaming, (3) smoldering, and (4) glowing (figure 4.1.7). The efficiency of combustion in each combustion phase is not the same, resulting in a different rate of energy and chemical compounds being released into the atmosphere.

During the pre-ignition phase, fuels ahead of the fire front are heated by radiation and convection and

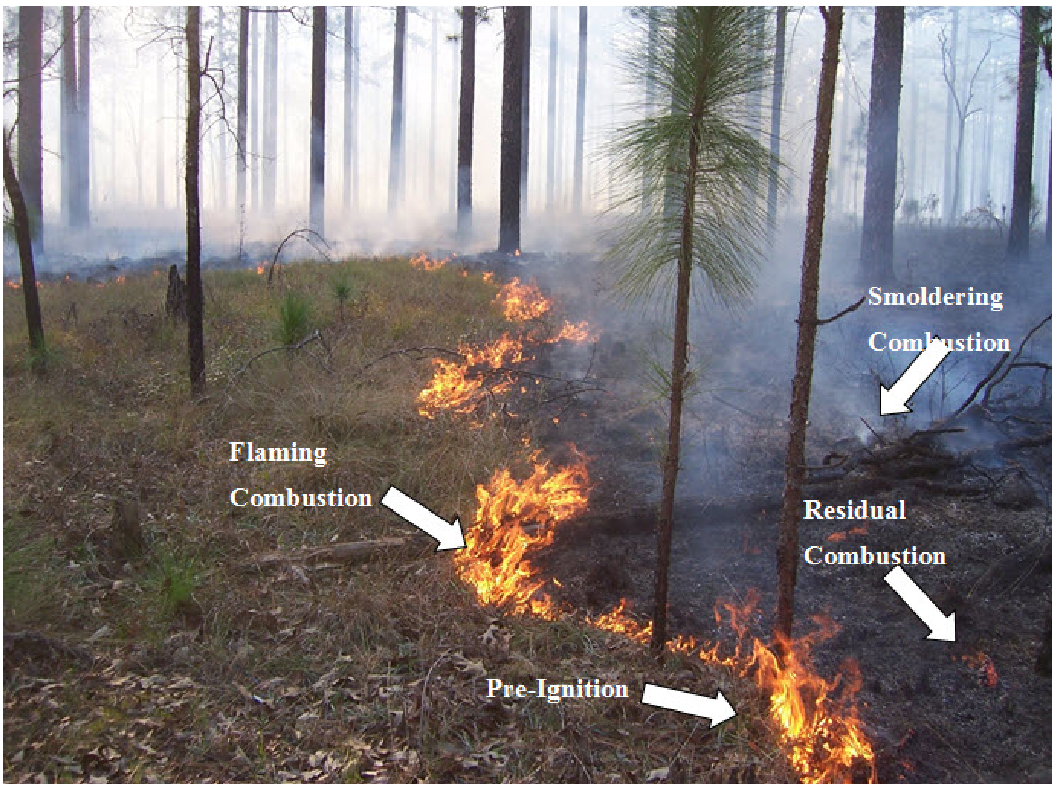

Figure 4.1.7. The four phases of combustion, pre-ignition, flaming, smoldering, and residual (glowing) combustion.

water vapor is driven to the surface of the fuels and expelled into the atmosphere. This is called distillation and occurs at temperatures of 140 °F to 392 ° F (Rowell and LeVan-Green 2005). A variety of organic compounds have been observed to be released during the pre-ignition process including terpenes, methanol, and acetic acid (Greenberg *et al.* 2006). As the fuel's internal temperature rises, pyrolysis begins and cellulose and lignin begin to decompose, releasing combustible organic gases and vapors (Ryan and McMahon 1976). Because these gases and vapors are extremely hot, they rise and mix with oxygen in the air and ignite at temperatures between 617 °F and 662 °F, leading into the flaming phase (DeBano *et al.* 1998).

Fuel type, fuel moisture content, arrangement, and the way the fuels are ignited in the case of prescribed fires, can affect the amount of biomass consumed during various combustion stages. The flaming stage has a high combustion efficiency; that is it tends to emit the least amount of $PM_{2.5}$ and CO emissions and the most CO_2 relative to the mass of fuel consumed**.** The smoldering stage has a lower combustion efficiency and produces more $PM_{2.5}$ and CO and less CO_2 relative to the mass of fuel consumed. The energy release rate is also less during the smoldering phase, producing less buoyant smoke than the flaming combustion period.

In the flaming phase, fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by flaming of the combustible gases and vapors. The combustion efficiency is usually high as long as volatile emissions remain near the flames. The predominant products are CO_2 and H_2O. Water vapor is a product of the combustion process and also originates from moisture being driven from the fuel. Temperatures range between 932 °F to 2,552 °F (Ryan and McMahon 1976). During the flaming period, the average exterior diameter reduction of round wood material occurs at a rate of 1 inch per 8 minutes (Anderson 1969). For example, a dry limb 3 inches in diameter would take about 24 minutes to completely consume if flaming combustion was sustained during the entire time.

During the smoldering phase, emission of combustible gases and vapors above the fuel is too low to support a flame. Fire spread decreases and temperatures drop significantly. Peak smoldering temperatures range from 572 °F to 1,112 °F (Agee 1993). Gases and vapors condense, appearing as visible smoke as they escape into the atmosphere. The smoke consists mostly of particles less than a micrometer in diameter. The amount of particulate emissions generated per mass of fuel consumed during the smoldering phase is more than double that of the flaming phase.

Smoldering combustion is more common in certain fuel types (e.g., duff, organic soils, decayed logs) due to the lack of oxygen necessary to support flaming combustion. Smoldering combustion is often less prevalent in fuels with high surface-area-to-volume ratios (e.g., grasses, shrubs, small diameter woody fuels) (Sandberg and Dost 1990). Because heat generated from smoldering is seldom sufficient to sustain a convection column, it often concentrates in nearby valley bottoms, compounding the effect of the fire on air quality (figure 4.1.8). Near the end of the smoldering phase, the pyrolysis process nearly ceases, leaving the fuel that did not completely consume with a layer of black char, high in carbon content.

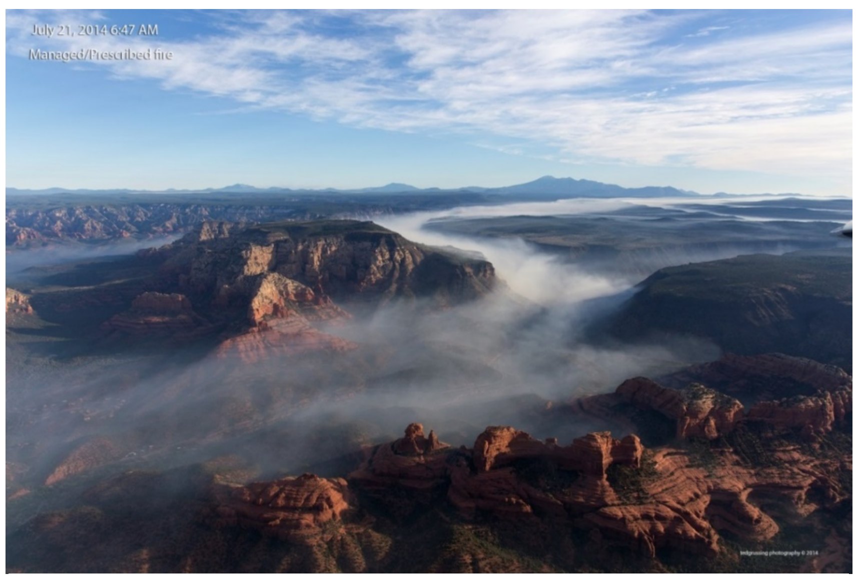

Figure 4.1.8. Smoke from the active fire phase and the less buoyant phase may settle into canyons and valley bottoms compounding air quality impacts. Photo courtesy of Theodore Grussing.

In the glowing phase, most volatile gases have already been driven off. Oxygen in the air can now reach the exposed surface of char left from the flaming and smoldering phase and the remaining fuels begin to glow with the characteristic orange color. Peak temperatures of the burning fuel during the glowing phase are similar to those found in the smoldering phase and range from 572 °F to 1,117 °F (DeBano *et al.* 1998). There is little visible smoke. Carbon dioxide and carbon monoxide are the principal products of glowing combustion. This phase continues until the temperature of the fuel drops or until only noncombustible, mineral gray ash remains.

The combustion phases occur both sequentially and simultaneously as a fire front moves across the landscape. The efficiency of combustion that takes place in each combustion phase is not the same, resulting in a different set of chemical compounds being released at different rates into the atmosphere. Understanding the combustion process of each phase will assist managers in employing various emission reduction techniques. Fuel type, fuel moisture content, arrangement, and the way the fuels are ignited in the case of prescribed fires, can affect the amount of biomass consumed during various combustion stages. The flaming stage has a high combustion efficiency; that is it tends to emit the least amount of $PM_{2.5}$ emissions relative to the mass of fuel consumed**.** The smoldering stage has a lower combustion efficiency and produces more $PM_{2.5}$ relative to the mass of fuel consumed.

Fuel consumption modeling

Consumption of herbaceous and shrub biomass, woody fuels, piled slash, and duff has become better understood over the years (Sandberg 1980, Sandberg and Dost 1990, Brown *et al.* 1991, Ottmar *et al.* 1993, Albini and Reinhardt 1997, Reinhardt *et al.* 1997, Ottmar and Sandberg 2000, Ottmar and Sandberg 2003, Ottmar *et al.* 2006, Prichard et al, 2007, Ottmar 2014). Recent work has shown that shrub consumption is best modeled as a function of fuel amount, fuel condition (e.g., dead fuel moisture content) and environment (e.g., season, wind speed, and slope) (Wright and Prichard 2006, Wright 2013a, 2013b). Fuel consumption of grass, herbaceous material, small dead woody fuels (1–3 in diameter), and litter is dependent upon total fuel load and fuel moisture content, with about 80 percent consumption expected during the flaming phase and 20% in the smoldering stage (Brown *et al.* 1991, Prichard *et al.* 2007). Consumption of large dead woody fuel (>3 in. in diameter) depends on moisture content of the woody fuel and loading, but only 50 percent of the consumption occurs during the flaming phase (Prichard *et al.* 2007, Brown *et al.* 1991). Forest duff consumption depends on depth of duff, fire duration of woody fuels, and duff moisture content (Ottmar and Baker 2007, Prichard *et al.* 2007) and occurs primarily during the smoldering stage.

Consumption of tree crowns in forests, shrub crowns in shrublands, large rotten logs, and fuel beds with deep organic soils such as in the pocosin region of the Southeast and boreal forest region of Alaska are poorly understood components of biomass consumption and additional research is needed (Wright and Prichard 2006, Reardon *et al.* 2007, 2009, Hyde *et al.* 2011, Wright 2013a, 2013b). For example, in areas of the Gulf States and along the Atlantic seaboard, deep organic soils may exist and if ignited under drought conditions, can burn for days, months, and even years producing large amounts of smoldering smoke. At present, tools for evaluating the potential for smoldering combustion in organic soils are limited although the estimated smoldering potential (Reardon 2009) has been developed to evaluate the risk of smoldering smoke and shows promise for use in the southern states.

Because consumption during the flaming phase is more efficient than during the smoldering phase, and different emission factors are applied depending on the pollutant of interest, separate calculations of flaming consumption and smoldering consumption are required for improved assessment of total fire emissions. Equations for predicting biomass consumption by combustion phase are widely available in two major software packages including Consume (Prichard *et al.* 2007, 2014; Fire and Environmental Research Applications Team 2012) and the First Order Fire Effects Model (FOFEM) (Reinhardt *et al.* 1997, Reinhardt and Keane 2000, Reinhardt 2003). Consume uses a set of physical based and data-derived models to predict the amount of fuel consumption from the burning of natural fuels or logging slash, and piled woody debris. Input variables include the amount of fuel, woody fuel and duff moisture content, and weather data. The system also estimates loading of piles and assumes 90 percent consumption (Hardy *et al.* 1996, Wright *et al.* 2010a, 2010b). The software product incorporates the Fuel Characteristic Classification System (Ottmar *et al.* 2007) for assigning default fuel loadings. It also incorporates features that allow users to receive credit for applying fuel consumption reduction techniques.

The First Order Fire Effects Model (FOFEM) estimates fuel consumption for different regions of the country by fuel bed category using data-derived equations, rules of thumb, and the Burnup model (Albini 1994, Albini and Reinhardt 1995, 1997, Albini *et al.* 1995, Lutes 2013). Burnup is a mechanistic woody fuel consumption model of heat transfer and burning rate of woody fuel particles as they interact over the duration of a burn (Lutes 2013). The consumption of the canopy fuels is not predicted in FOFEM and requires the user to input an estimate of the proportion of the canopy that will consume. Shrub consumption is modeled with rules of thumb (Reinhardt *et al.* 1997). All grasses and herbaceous fuels are assumed to consume unless the season is spring where 90 percent consumption is assigned. The consumption of litter is calculated by Burnup. Generally, 100 percent of the litter is consumed. Duff consumption is calculated using algorithms from various scientific studies (Hough 1978, Brown *et al.* 1985, Harrington 1987, Reinhardt *et al.* 1991, and Hungerford 1996).

A study completed in 2011 to collect a fuel consumption dataset, including pre- and post-burn fuel characteristics and day-of-burn environmental variables to assist in determining CONSUME and FOFEM uncertainties, biases, or application limits in the eastern United States (Prichard et. 2014, Ottmar and Dickinson, 2011). CONSUME and FOFEM performed well in predicting consumption of the shrub, grass, 1-hr, 10-hr, and 100- hour woody fuel bed components in southern pine fires. However, both performed poorly in predicting 1-hr, 10-hr, and 100-hr woody fuel consumption in mixed hardwood sites. Although Consume better predicted large woody fuel consumption in both the pine and mixed hardwoods, both models poorly predicted litter consumption.

CONSUME and FOFEM packages are updated on a regular basis as new consumption models are developed and tested. Consume, for example, has been reprogrammed into a distinct, maintainable module that has been integrated into Fuel and Fire Tools (Fire and Environmental Research Applications Team 2014) that will include the natural fuels digital photo series, Fuel Characteristic Classification System (FCCS), and Fire and Emissions Production Simulator (FEPS). FFT is in the Interagency Fuels Treatment Decision Support System (IFTDSS) (JFSP 2012). The IFTDSS is an attempt to support manager’s requests to provide a “one-stop shopping” system for fire and fuels software systems.

The Pile Calculator (Wright *et al.* 2010a, 2010b) is a web based application that uses formulas for different geometric shapes to estimate pile volume, and empirically derives relationships between volume and biomass to estimate pile weight for different pile types (machine versus hand) composed of different material (different types of coniferous vs. hardwood/shrub material). The system assumes percentage consumption of 90 percent unless the user specifies a different value when more or less consumption is expected. Studies are currently ongoing to develop a pile consumption model (Wright 2011).

Smoke Emissions

The chemistry of the fuel as well as the efficiency of combustion governs the physical and chemical properties of the resulting smoke from fire. Although smoke from different sources may look similar to the eye, it is often quite different in terms of its chemical and physical properties. Generally, the emissions we cannot see are gas emissions and the emissions we can see are particulate emissions.

Carbon dioxide and water

Carbon dioxide (CO_2) and water are two products of complete combustion during wildland fires and generally make up over 90 percent of the total emissions generated. Under ideal conditions complete combustion of one ton of forest fuel requires 3.5 tons of air and yields 1.84 tons of CO_2 and 0.54 tons of water (Prescribed Fire Effects Working Team 1985). Under wildland conditions, however, inefficient combustion produces different yields. Water vapor is a greenhouse gas, but is not considered an air pollutant in the usual sense, even though water vapor will sometimes condense into liquid droplets and form a dense, white haze near the fire. This fog/smoke mixture (sometimes called superfog) can form quickly and dramatically reduce visibility, creating hazardous driving conditions (Achtemeier 2009). Carbon dioxide is a greenhouse gas and is considered by EPA and the U.S. Supreme Court as a pollutant. It is covered by the Federal Clean Air Act although there is no ambient standard established at this time.

As combustion efficiency decreases in a wildland fire, less carbon is converted to CO_2 and more carbon is available to form other combustion products such as CO, CH_4, and NMVOC, all of which are considered pollutants. Furthermore, secondary chemical reactions can form downwind in a smoke plume creating additional pollutants such as ozone.

Carbon monoxide

Carbon monoxide (CO) is one of the most abundant emission products from wildland fires. It is one of the six common air pollutants of concern called criteria pollutants defined in the Clean Air Act of 1970 (Clean Air Act, 1970). Its negative effect on human health depends on the duration of exposure, CO concentration, and level of physical activity during the exposure. Generally, dilution occurs rapidly enough from the fire that carbon monoxide will not be a problem for local citizens unless a large fire occurs and inversion conditions trap the carbon monoxide near rural communities. Carbon monoxide is always a concern for wildland firefighters however, both on the fireline at prescribed fires and wildfires, and at fire camps (Reinhardt and Ottmar 2000, Reinhardt *et al.* 2000, Reinhardt and Ottmar 2004).

Non-methane volatile organic compounds

Non-methane volatile organic compounds (NMVOC) are an extremely diverse class of compounds containing hydrogen, carbon and sometimes oxygen. Usually, the classes of hydrocarbon compounds are identified according to the number of carbon atoms per molecule. Emission inventories often lump all gaseous hydrocarbons together. Although most NMVOC pollutants may have no harmful effects, there are a few that are toxic. One type of NMVOC is volatile organic compounds (VOCs). Some VOCs have been shown to be dangerous to human health (Naeher *et al.* 2007). Volatile organic compounds can also combine with NO_x in the presence of sunlight to form ozone downwind of wildland fires. Over the past decade, emission factors have been measured for many NMVOCs (Akagi *et al.* 2001, Wiedinmyer *et al.* 2011).

Nitrogen oxides

In wildland fires, small amounts of NO_x are produced, primarily during the flaming phase from oxidation of the nitrogen contained in the fuel. Most fuels contain less than 1 percent nitrogen. Of that about 20 percent is converted to NO_x when burned. Another nitrogen containing compound found in smoke is ammonia (NH_3), primarily emitted from smoldering combustion. These compounds are considered criteria pollutants and have been shown to irritate the respiratory system.

Secondary chemical formation

There are many secondary chemical reactions that can occur in the smoke plume downwind from the fire. One of the most important secondary aerosol reactions is the formation of ozone (O_3). In the presence of sunlight, the photochemical reactions of NO_x and volatile organic compounds (VOC), can lead to the production of O_3 and secondary organic aerosol (SOA) (Hallquist *et al.* 2009, Jaffe and Wigder 2012). The ozone and its precursors can be transported a long distance downwind from the fire contributing to background ozone levels that can lead to days that exceed air quality standards (Jaffe and Widger 2012). Ozone in the lower atmosphere is a criteria air pollutant with harmful effects on the respiratory systems of humans (Environmental Protection Agency 2012a) and is known to damage plants (Heck *et al.* 1986, Bell and Treshow 2002, U.S. Department of Agriculture 2012).

Particulate matter

Particulate matter produced from wildland fires is a criteria pollutant. Particulate matter can negatively affect human health both in the short term and long term, absorb harmful gases, and limit visibility. Particulate matter can range in size from 100 microns to the size of a few atoms (figure 4.1.9). Over 90 percent of the mass of particulate matter produced by wildland fire is less than or equal to 10 microns in diameter (PM_{10}) and over 70 percent is less than or equal to 2.5 microns in diameter ($PM_{2.5}$) (figure 4.1.10). The smaller particles pose a greater health risk as they can be drawn deep into the lungs upon inhalation causing upper and lower airway distress such as coughing, sore throat, and diminished breathing. The fine particles are more difficult for the lungs to expel. Small smoke particles stay suspended in the atmosphere for long periods of time while scattering, absorbing, and refracting visible light, reducing visibility and contributing to regional haze in Class I areas throughout the United States (Brewer and Moore 2012). In the eastern United States the sulfate contribution from power plants and industrial sources often overwhelms the smoke contribution (see Chapter 2.4 Visibility in Natural Areas).

Black carbon, commonly called soot, is a carbonaceous component of particulate matter that absorbs all wavelengths of solar radiation and is the major light absorbing component of air pollutant emissions. These particles affect human health (Environmental Protection Agency 2011) and have been implicated in climate change through deposition on snow and sea ice increasing melting (Flanner *et al.* 2007). Black carbon is also incorporated into the soil, which can result in sequestering carbon (Kuhlbusch *et al.* 1996, Deluca and Aplet 2008, Rovira *et al.* 2009, Brewer 2012).

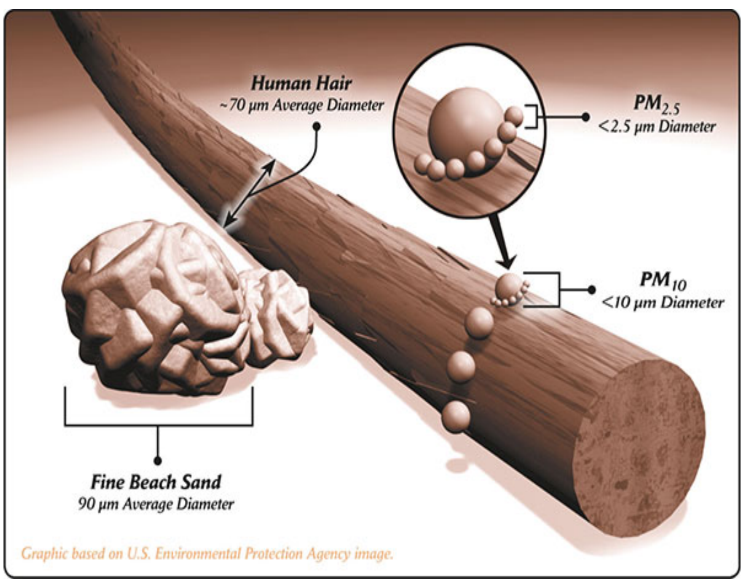

Figure 4.1.9. Relative size of PM_{10} and $PM_{2.5}$ smoke particle relative to a human hair.

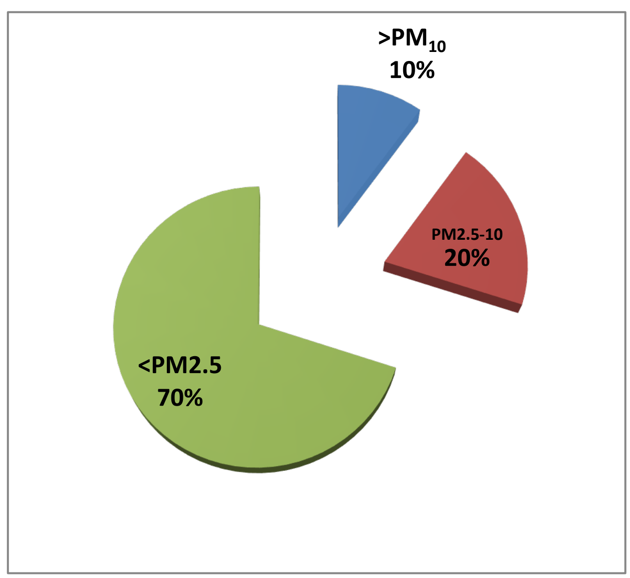

Figure 4.1.10. Particulate matter size-class distribution from typical wildland fire smoke.

Air toxics

Toxic air pollutants, also known as air toxics or hazardous air pollutants (HAPs), are those pollutants that are known or suspected to cause cancer or are associated with other serious health (e.g., reproductive problems, birth defects) or ecological effects (Environmental Protection Agency 2012b). Some air toxics are directly emitted from wildland fires. Secondary formation of air toxics can also occur when precursor chemicals react in the atmosphere. Several of the 187 compounds on the EPA Air Toxics list (Environmental Protection Agency 2012b) have been have identified in fresh smoke including acetaldehyde, acrolein, butadiene, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs). The toxics are generally created in limited quantities and often disperse very quickly. There is limited knowledge about the production, and dispersion or transformation of these air toxics.

Where heavy metals occur in the soils (e.g., copper, chromium, lead, zinc, or mercury), certain plants can uptake those metals and concentrate them in the tissues (Haque *et al.* 2008). If this vegetation is burned, it could represent a significant source of metal emissions. Furthermore, if heavy metals are precipitated onto the plant surface from other pollutant sources (e.g., factories and automobiles) there is a potential these metals could be emitted into the atmosphere upon burning.

Greenhouse gas and aerosol emissions

Gases that can absorb and emit infrared radiation and trap heat in the atmosphere are called greenhouse gases. Wildland fire generates several of these greenhouse gases including CO_2, CH_4, nitrous oxide (N_2O), and water vapor (H_2O) (Urbanski *et al.* 2009). Although large amounts of greenhouse gas can be emitted from wildland fires, charred carbon residues and ash remaining, can offset a portion of the carbon released into the atmosphere during the fire (Kuhlbusch *et al.* 1996, Deluca and Aplet 2008, Rovira *et al.* 2009, Brewer 2012). Furthermore, if the fire has made the area more productive over time, more carbon may be sequestered through the regrowth of trees and other vegetation. However, black carbon released from fire can be deposited on snow and sea ice decreasing albedo (reflectivity) and speeding melting (Flanner *et al.* 2007).

Emission Factors

An emission factor for a particular pollutant of interest is the mass of pollutant produced per mass of fuel consumed (lbs/t in the English system or g/kg as the metric equivalent) (Environmental Protection Agency 1996, Urbanski *et al.* 2009, Urbanski 2014,). Multiplying an emission factor, in grams per kilogram, by two will convert the emission factor to pounds per ton.

Emission factors vary depending on type of pollutant, type and arrangement of fuel, region, and combustion efficiency or combustion phase as shown in table 4.1.1. These are emission factors developed in the 1980s and 1990s from field data collection efforts in the western United States (Ward *et al.* 1989, Hardy *et al.*1992, Hardy *et al.* 1996) and reported by fuel bed type and flaming and smolder combustion phase. Table 4.1.2 is a more recent compilation of emission factors for different fuel bed types as reported in the literature (Urbanski 2014). The emission factors are not reported by flaming and smoldering combustion phase, but rather as a fire average only. Non-methane volatile organic hydrocarbons (NVMOC) and sulfur dioxide (SO_2) were included in table 4.1.2 because these emissions factors were recently developed for wildland fire (Urbanski 2014). NMVOC are important in the formation of ozone (O_3). A SO_2 emission factor is important to show regulators little is generated during wildland fire. Additional emission factors have been determined for other species of pollutants and by fuel type (Urbanski *et al.* 2009, Urbanski 2014).

The emission factors in table 4.1.2 vary by a factor of two or more for certain compounds as compared to emission factors found in table 4.1.1. For example, the $PM_{2.5}$ emission factor for pile and burn mixed conifer slash in table 4.1.1 are 9.6, 23.6, and 18.8 pounds of emissions per ton of fuel consumed for the flaming phase, smoldering phase, and fire average respectively. The fire average for $PM_{2.5}$ in table 4.1.2 for a comparable fuel bed type (West Forest) is 46.4 pounds of emissions per ton of fuel consumed. The large difference in emissions factors between the two tables is because the emission factors in table 4.1.2 are based on more recent and a broader selection of research and only include a fire average. In general, fuels consumed by flaming combustion produce less smoke than fuels consumed by smoldering combustion and a fire average does not account for this difference. Carbon dioxide and NO_x are exceptions to this rule and are produced in larger quantities during the flaming combustion phase than during the smoldering phase.

Emission factors can be used by air quality agencies to calculate local and regional emissions inventories, by managers to develop strategies to mitigate downwind smoke effects, and by scientists to evaluate the tradeoffs of smoke effects from wildland fire versus prescribed fire. If the emission factors in table 4.1.2 are used in place of table 4.1.1, the $PM_{2.5}$ contributed to the atmosphere by wildland fire will increase and managers will not get credit for smoke management techniques that reduce smoldering smoke.

Table 4.1.1. Forest and rangeland emission factors from Ward *et al.* 1989[1], Hardy *et al.* 1996[2], and Hardy *et al.* 1992[3]).

Burn type	Fuel species or type	Combustion phase [a]	PM	PM_{10} [b]	$PM_{2.5}$	CO	CO_2	CH_4	NMHC [c]
			Pounds of emissions per ton of fuel consumed						
Broadcast burned (slash)[1]	Douglas fir/hemlock	Flaming	24.7	16.6	14.9	143	3,385	4.6	4.2
		Smoldering	35.0	27.6	26.1	463	2,804	15.2	8.4
		Fire Average	29.6	23.1	21.8	312	3,082	11.0	7.2
	Hardwoods	Flaming	23.0	14.0	12.2	92	3,389	4.4	5.2
		Smoldering	38.0	25.9	23.4	366	2,851	19.6	14.0
		Fire Average	37.4	25.0	22.4	256	3,072	13.2	10.8
	Ponderosa/lodgepole pine	Flaming	18.8	11.5	10.0	89	3,401	3.0	3.6
		Smoldering	48.6	36.7	34.2	285	2,971	14.6	9.6
		Fire Average	39.6	25.0	22.0	178	3,202	8.2	6.4
	Mixed conifer	Flaming	22.0	11.7	9.6	53	3,458	3.0	3.2
		Smoldering	33.6	25.3	23.6	273	3,023	17.6	13.2
		Fire Average	29.0	20.5	18.8	201	3,165	12.8	9.8
	Juniper	Flaming	21.9	15.3	13.9	82	3,401	3.9	5.5
		Smoldering	35.1	25.8	23.8	250	3,050	20.5	15.5
		Fire Average	28.3	20.4	18.7	163	3,231	12.0	10.4
Pile and Burn (slash)[1]	Tractor-piled	Flaming	11.4	7.4	6.6	44	3,492	2.4	2.2
		Smoldering	25.0	15.9	14.0	232	3,124	17.8	12.2
		Fire Average	20.4	12.4	10.8	153	3,271	11.4	8.0
	Crane-piled	Flaming	22.6	13.6	11.8	101	3,349	9.4	8.2
		Smoldering	44.2	33.2	31.0	232	3,022	30.0	20.2
		Fire Average	36.4	25.6	23.4	185	3,143	21.7	15.2
	"Average" Piles	Fire Average	28.4	19.0	17.1	169	3,207	16.6	11.6
Broadcast burned (brush)[2]	Sagebrush	Flaming	45.0	31.8	29.1	155	3,197	7.4	6.8
		Smoldering	45.3	29.6	26.4	212	3,118	12.4	14.5
		Fire Average	45.3	29.9	26.7	206	3,126	11.9	13.7
	Chaparral	Flaming	31.6	16.5	13.5	119	3,326	3.4	17.2
		Smoldering	40.0	24.7	21.6	197	3,144	9.0	30.6
		Fire Average	34.1	20.1	17.3	154	3,257	5.7	19.6
Wildfires in forests[3]		Fire Average		30.0	27.0				

[a]Fire average values are weighted-averages based on measured carbon flux.
[b]PM_{10} values are calculated, not measured, and are derived from known size-class distributions of particulates using PM and $PM_{2.5}$.
[c]Non-methane hydrocarbons.

Table 4.1.2. Fire average emission factors, in pounds per ton, for common pollutants resulting from prescribed and wildfires in different fuel types (Urbanski 2014). Estimated uncertainties are displayed in parenthesis.

Pollutant	Prescribed fire Southeast conifer forest	Prescribed fire Southwest conifer forest	Prescribed fire Northwest conifer forest	Prescribed fire Western shrub land	Prescribed fire grassland	Wildfire Northwest conifer forest	Wildfire boreal forest
Carbon dioxide CO_2[a]	3,406 (342)	3,306 (68)	3,196 (78)	3,348 (76)	3,410 (88)	3,200 (38)	3,282 (214)
Carbon monoxide CO[b]	152 (30)	174 (36)	210 (26)	148 (36)	122 (42)	270 (22)	190 (72)
Methane CH_4[a]	4.6 (2.2)	6.3 (1.8)	9.7 (2.7)	7.4 (2.7)	3.9 (2.1)	14.6 (1.2)	6.8 (2.9)
NMOC[c]	32.1 (21.8)	37.3 (34.7)	54.0 (31.1)	35 (26.9)	33.5 (23.2)	67.7 (34.7)	46.3 (26.3)
Particulate matter $PM_{2.5}$[b]	25.2 (8.0)	28.8 (10.0)	35.1 (10.3)	14.1 (1.6)	17.0 (10.2)	46.4 (20.8)	43 (9.6)
Nitrogen oxides NOx	3.4 (1.9)	3.8 (2.1)	4.1 (0.1)	4.4 (1.6)	4.4 (1.6)	4 (2)	2 (0.2)
Ammonia NH_3	0.3 (0.3)	1 (1.4)	3.1 (0.8)	3 (2.9)	3 (2.9)	3 (1.5)	1.6 (0.8)
Nitrous oxide N_2O	0.3 (0.4)	0.3 (0.4)	0.3 (0.4)	0.5 (0.4)	- (-)	0.3 (0.4)	0.8 (-)
Sulfur dioxide SO_2[b]	2.1 (0.8)	2.1 (0.8)	2.1 (0.8)	1.4 (0.3)	1.4 (0.3)	2.1 (0.8)	2.1 (0.8)

[a] Greenhouse gas
[b] Criteria pollutant
[c] Non-methane organic carbon.

Total Emissions, Source Strength, and Heat Release Rate

Total emissions from a fire or class of fires (that is, a set of fires similar enough to be characterized by a single emission factor) can be estimated by multiplying an emission factor by the biomass consumed and an accurate assessment of the total acreage burned (Ottmar *et al.* 2009). For instance, assume that 10 t/ac of fuel will be consumed during a 200-acre landscape prescribed fire in a ponderosa stand in the western United States. After the fire, ground surveys and aerial reconnaissance indicate a mosaic fire pattern and only 100 ac of the 200 acres within the fire perimeter actually burned (black acres). Because the emission factor for $PM_{2.5}$ for pine fuels is about 46 lbs/ton, then total emission production would be:

Fuel consumed (t/ac) x PM $_{2.5}$ emission factor (lb/t) x area burned (ac) = total emissions PM $_{2.5}$ (lbs)

Therefore:

10 t/ac x 46.4 lb/t[1] x 100 ac = 46,400 lbs, or 23.2 t of $PM_{2.5}$

Managers can make better estimates of emissions produced from a wildland fire if the amount of fuel consumption in the flaming and smoldering combustion periods is known. The same general approach is used although it is slightly more complicated. The fuel consumed during the flaming period and smoldering period are multiplied by the appropriate flaming and smoldering emission factor for an average fuel bed, and then summed. Computer software such as Consume (Prichard *et al.* 2007) and FOFEM 5.9 (Reinhardt 2003) use this approach to improve estimates of total emissions produced from wildland fire, as compared with using a fire average fuel consumption and emission factor. Currently, both fuel consumption models provide fuel consumption by fuel bed category, although emission factors by fuel bed category are not available at this time. Emission factor research is ongoing to fill in this gap (Urbanski *et al.* 2009, Ottmar and Baker, 2007).

Source strength is the rate of air pollutant emissions in mass per unit of time or in mass per unit of time per unit area and is the product of rate of biomass consumption and emission factor for the pollutant of interest. Source strength can be calculated by the equation:

Source strength (lbs/min) = fuel consumption (t/ac) x emission factor (lbs/t) x rate burning (ac/min)

Emission rates vary by fuel loading, fuel consumption, and emission factors. Figure 4.1.11 graphically depicts general trend differences in emission production rate and total emissions production (area under each curve) for various prescribed fire scenarios. Mechanically treating fuels before burning, mosaic burning, burning under high fuel moisture contents, and burning piles are specific ways emission rates can be reduced to meet smoke management requirements.

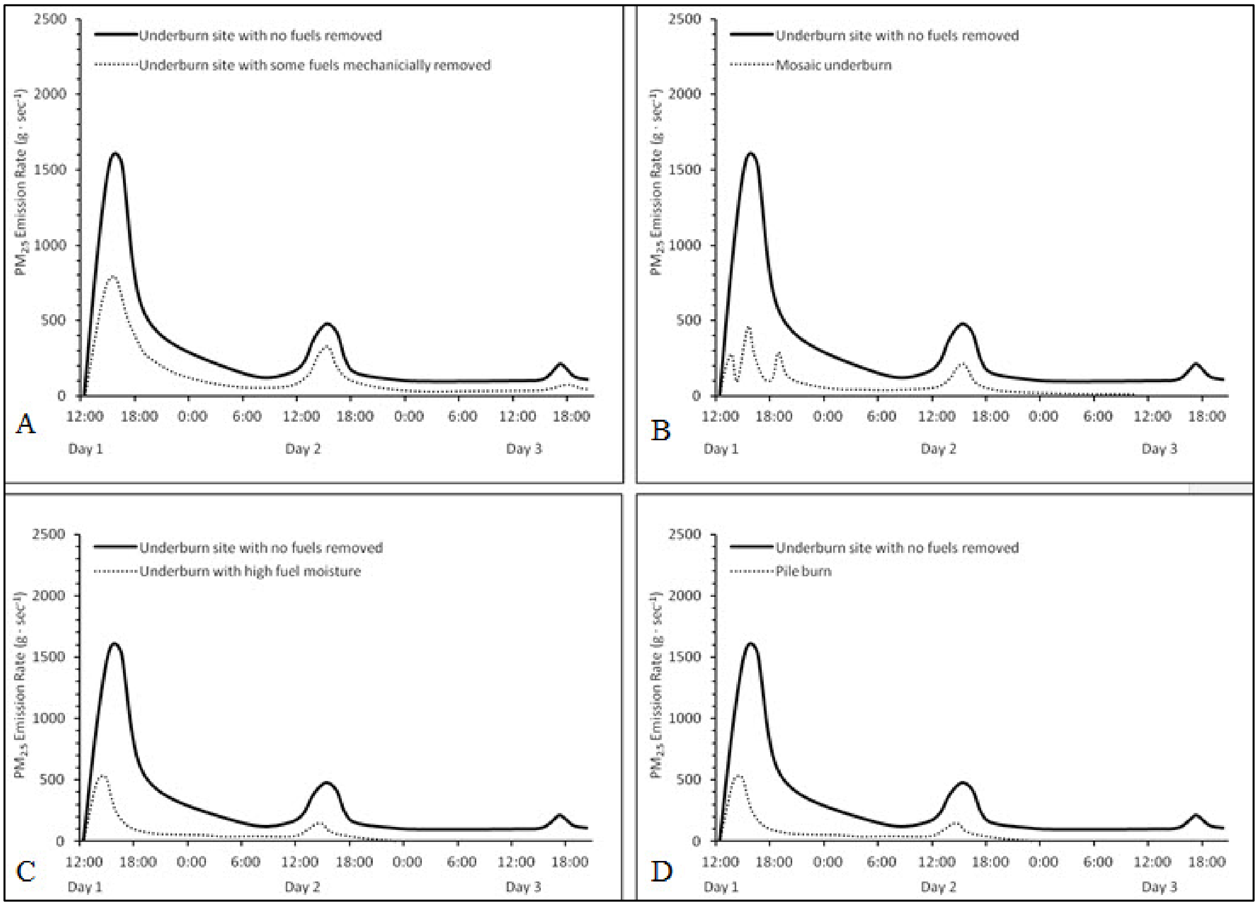

Figure 4.1.9. Simulated emission production rate over time for $PM_{2.5}$ during (A) an underburn with and without fuels mechanically removed; (B) during a mosaic burn and a burn where fire covers the entire area within the perimeter; (C) during an underburn with low and high fuel moisture content; and (D) during an underburn and a pile burn.

The consumption of biomass produces thermal energy and this energy creates buoyancy to lift smoke particles and other pollutants above the fire. Heat release rate is the amount of thermal energy generated per unit of time or per unit of time per unit of area. Heat release rate can be calculated by the equation:

Heat release rate (Btu/min) = fuel consumption (t/ac) × rate of area burned (ac/min) × heat output (Btu/t)

Both source strength and heat release rate are required by all sophisticated smoke dispersion models (Breyfogle and Ferguson 1996) to generate plume buoyancy and predict smoke concentrations downwind from the plume.

The Fire Emissions Production Simulator (FEPS) (Sandberg *et al.* 2004) predicts hourly emissions, heat release, and plume rise values for wildland fires. The program requires area burned, ignition period, fuel characteristics, and fuel moisture conditions as input variables. Fuel consumption may be added as an input or calculated internally. Although the system provides default input values for fuel characteristics, fuel moisture, and ignition period to calculate source strength, heat release rate, and plume rise, FEPS can also import consumption and emissions data from CONSUME and FOFEM. It is one of the few models available for generating source strength and heat release and has not been validated. Most scientists that build models for operational purposes, such as plume rise (DaySmoke) and dispersing wildland fire emissions (CMAQ or WRF-Chem) (Achtemeier *et al.* 2011) consider these calculations extremely important and more research in this area is needed.

Uncertainties in Estimating Emissions from Wildland Fire

The process of estimating emissions from wildland fire is prone to many uncertainties and potential errors but some knowledge of the sources of these errors can help minimize them. Estimates of emissions from prescribed fires are generally more accurate than from wildfires because more of the factors contributing to emissions are known. As mentioned earlier, the six primary variables needed for a basic calculation of total emissions from wildland fire are: area burned, burning period, fuel characteristics, fire behavior, fuel consumption by combustion phase, and emission factors.

Reports of acres burned may result in an overestimate of emissions if the total acres within the perimeter of a burned area are reported as blackened. To accurately estimate emissions, only the area that was touched by fire and where fuels were consumed should be reported as burned. Often the entire acreage within a burned area perimeter may be counted as treated for fuels treatment accomplishment reporting or reported on the ICS-209 form for a wildfire so this source of overestimation is not uncommon. In addition, a prescribed fire may be registered and planned for a given day but not accomplished due to weather or other circumstances. If official state or acreage reported by the respective dispatch office (which is transmitted to NIFC) records are not updated, large overestimates of acres burned may result. Knowledge of the acres actually blackened during a fire is likely the largest source of potential error in calculations of emissions from prescribed fire, although with a little effort in the field to obtain accurate estimates of acres blackened plus diligent follow-up reporting, this error can be minimized.

Besides total acres burned, it is important to accurately report how long it takes to ignite a unit. If the ignition period reported is not accurate, the emissions rate and plume rise will not be calculated correctly within dispersion models resulting in a poor assessment of smoke concentrations and air quality impacts downwind of the fire.

All fuel bed components should be included in estimates of total fuel loading including some that are commonly left out of fire behavior estimates such as duff, litter, rotten logs, and stumps. Errors in estimating fuel loading can contribute as much as 80 percent of the error of calculating emissions produced per acre if little is known about the quantity of fuels available for burning (Peterson 1987, Peterson and Sandberg 1988) although generally the error contribution is not that large.

Fuel consumption and fire behavior during a prescribed fire varies with environmental variables like fuel moisture content and meteorology at the time of the burn. Errors of estimating fuel consumption can contribute about 30 percent of the error in estimating prescribed fire emissions when estimates of fuel loading are poor (Peterson 1987). If estimates of fuel loading are good, then fuel consumption estimation uncertainties will contribute a greater percentage of the total error of estimating emissions.

Fine particulate emission factors are multiplied by total fuel consumed to give emissions per acre. Older studies of prescribed fire emission factors found them to be fairly consistent between fuel types meaning the contribution of uncertainty in the emission factor to calculation of total prescribed fire emissions could be as low as about 15 percent of the total error if little was known about the fuels in a burned area (Peterson and Ward 1989). More recent wildland fire emission factor studies have increased the estimated uncertainties associated with wildland fire emission factors (Urbanski 2014) so the errors they contribute may be more significant than previously thought. In addition, many emission factors for smoke components other than fine particulate have been measured and some are highly uncertain (Urbanski 2014).

A combination of fuel loading, fuel consumption, emissions production and dispersions models can be used to estimate air quality impacts from wildland fire. The Smoke and Emissions Model Intercomparison Project (SEMIP) examined the compounding uncertainties in information produced by the emissions and smoke modeling chain (Larkin *et al.* 2012) (See call box).

Smoke and Emissions Model Intercomparison Project
Sim Larkin (USDA Forest Service), Tara Strand (Scion Research)

Background: Managers, regulators, and others often need information on the emissions and smoke impacts from wildland fire. To generate this information, combinations of models are often utilized that follow a logical progression beginning with fire activity estimates, through to fuel consumption models, and finally to emissions and dispersion models. Often several models or datasets are options for each step, resulting in a large number of potential combinations of models to estimate the end result of fire emissions or smoke impacts.

SEMIP: The Smoke and Emissions Model Intercomparison Project (SEMIP) was sponsored by the Joint Fire Science Program to examine the compounding uncertainties in information produced by the emissions and smoke modeling chain. Multiple test cases ranging from simple, single fires to national emissions inventories were queried and numerous model combinations were examined. Model output at each step in the modeling chain (figure a) was examined across various spatial and temporal scales (Larkin *et al*. 2012).

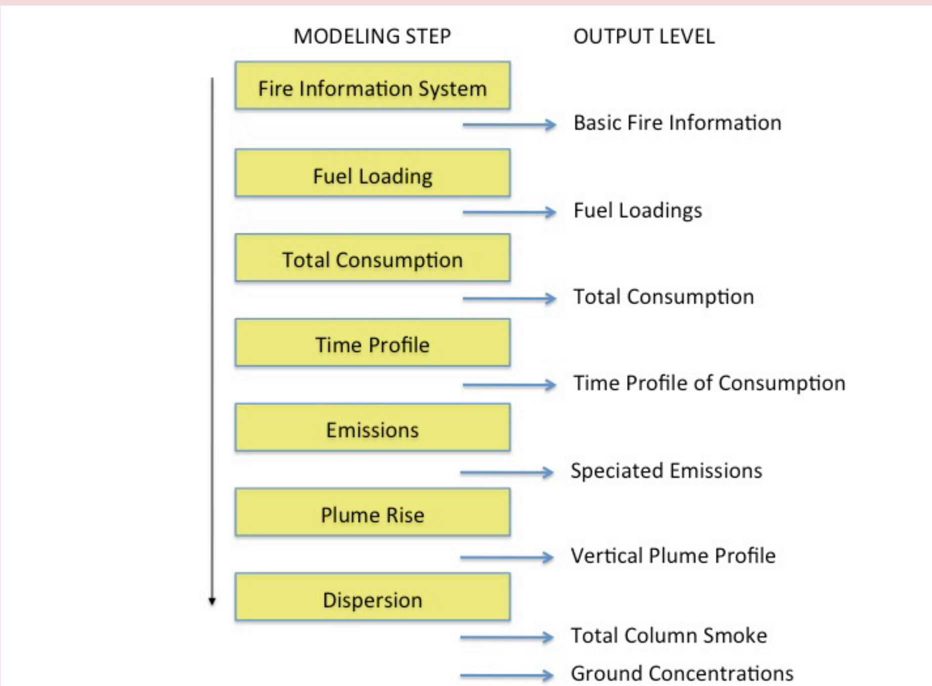

Figure a. Modeling chain for getting from fire information to smoke impacts showing the various types of output available at each step (Larkin *et al.* 2012).

The SEMIP analysis found the largest sources of uncertainty in estimating fire emissions and smoke concentrations vary depending on the purpose of the modeling and the type of model used. The conclusions from the SEMIP project should be viewed with caution as they reflect only the analyses performed, and other, more local or fire-specific issues may dominate model uncertainties in any given case.

The SEMIP study found overall uncertainty in *fire emissions estimates* are dominated by:

1. Fuels information (overall fuel loading and fuel loading in specific important fuel categories, such as canopy fuels and deep organic fuels);
2. Fire information (overall total area burned and area burned by type of fire);

3. Consumption model assumptions (especially for canopy and deep organic fuels); and
4. Emission factors.

The SEMIP study found overall uncertainty in *modeled smoke concentrations* is dominated by:
1. Estimation of how high the plume with loft above the ground;
2. Assumptions about when the emissions are released throughout the day (the diurnal time profile); and
3. Uncertainties and unknowns about the overall amount of emissions and how they react in the atmosphere (particularly for ozone and other secondarily created pollutants).

Recommendations

Use local knowledge: The results from SEMIP show the value of having local information for understanding smoke from a fire. One of the most critical pieces of quality information is fuel loading. Current fuel maps are not considered a substitute for ground-truthed information. Figure b demonstrates how widely fuel maps can differ for the area of a single fire. Other inputs involved in emissions and smoke modeling also benefit from local information – for example observed and expected fire growth information, local fuel moistures, and observed deep organic consumption rates.

Understand the uncertainties in the modeling chain: It is critically important to use model-based information within the limitations of those models. Most models produce output at a much higher level of precision (exactness) than is warranted by their actual accuracy (correctness). Often what is important is crossing a threshold rather than knowing an exact value. The exact timing of smoke movement is difficult for models to predict. Additionally, all models are only as good as their input information, and in many cases the underlying information available about a fire is not as good as might be wished.

Use multiple model runs if possible: To protect against overreliance on the subtleties in a model, use different models or multiple model runs with a range of inputs wherever possible. Even if two model runs are not of equal quality, the level of agreement (or disagreement) in their outputs will provide some sense of the underlying certainty in the output. Some modern tools, such as the Interagency Fuels Treatment Decision Support System or the BlueSky Playground, are now making performing multiple model runs and/or using multiple models easier and more accessible.

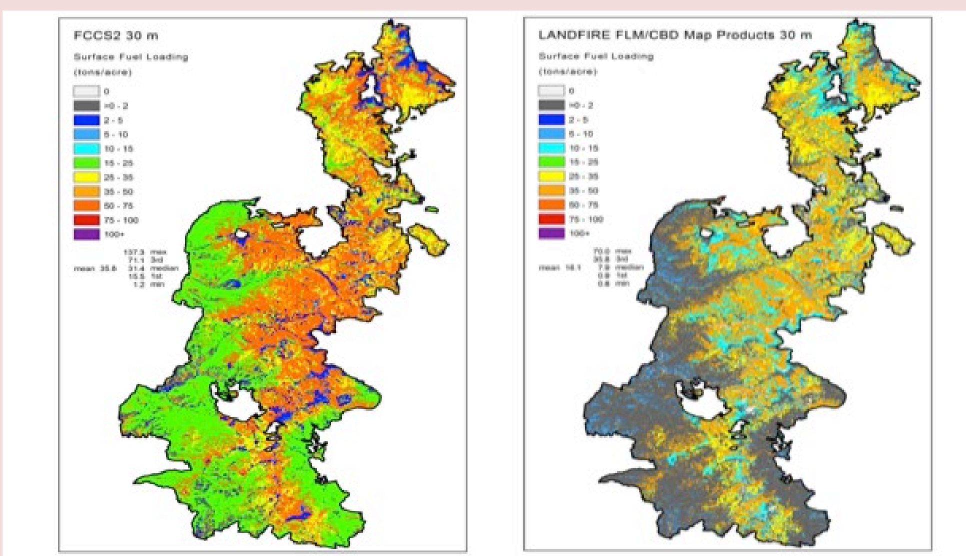

Figure b. Two recent fuel loading maps for the area of the 2006 Tripod fire in Washington State. Significant differences can be seen. In this case, the FCCS map on the left was a better match to the fuels map created by the local forest. Adapted from Drury *et al.* 2014.

Implementation

The amount of smoke produced during wildland fire can be derived from area burned, burning period, fuel characteristics (loading in particular), fire behavior, fuel consumption, and emission factors. Several of these inputs can be estimated from measured values or models. Knowing the amount of smoke produced will provide the information needed to better understand potential impacts to human health and visibility and provide the building blocks for NEPA documents, state regulatory and permitting requirements, regional and national emissions and greenhouse gas inventories, Exceptional Events Rule requirements, general conformity, and general fire planning.

The approach to emissions calculations has improved over the years as new research and better models have been created. Considering current, available knowledge and models, a relatively accurate estimate of emissions can be generated. Additional improvements in estimating smoke emissions will require better fire reporting or remote sensing of fire perimeters and period of burning; improved ability to assign fuel bed characteristics to the landscape, and development of more robust fuel consumption models that account individually for all combustion phases and all fuel bed components that have a potential to burn. Although there have been numerous studies on emission factors (Hardy *et al.* 2001, Urbanski *et al.* 2009), there are still high uncertainties and additional research and evaluation are needed to improve the accuracy and the resulting contribution of wildland fire emissions to air quality.

The uncertainty associated with the approach described in this chapter to estimate emissions from wildland fire may change in the future. New and improved reporting and remote sensing methodologies will provide improved burned area information reducing the uncertainty associated with this estimation. Climate change may also cause fuel bed components to be more or less complex and consume differently, increasing or decreasing the associated uncertainty. For example, an increasing temperature and drought climatic pattern for a region may result in a less complex fuel bed, reducing uncertainty. However, the fuel bed may be drier, increasing the amount of fuel available to consume and changing the ratio of flaming and smoldering combustion by fuel bed component. This may result in an increase in uncertainty of this variable.

As shown in this chapter, estimating source strength and heat release is complex and requires several different modeling systems to complete the calculations. To simplify and streamline this process, the BlueSky modeling framework (Larkin *et al.* 2009) was designed to incorporate not only the models for estimating source strength and heat release, but also meteorology and dispersion models to predict cumulative impacts of smoke from forest, agricultural, and range fires.

Although research characterizing fuel and modeling fuel consumption has progressed over the past 20 years (Brown *et al.* 1991, Ottmar 2007, Ottmar 2014), more studies are needed, especially as climate changes. Future emission production research would be best served by concentrating efforts in the area of burn area assessment, fuel bed characterization, and fuel consumption modeling.

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4.2 Techniques to Reduce Emissions from Prescribed Fire

Roger D. Ottmar

Introduction

This chapter summarizes fire management practices that are often employed by fire managers to reduce air quality impacts from prescribed fire. Emission reduction techniques, their uses and their effectiveness, are reviewed. All prescribed fires release various amounts of carbon monoxide (CO), methane, nitrogen oxides (NO_x and N_2O), particulate matter ($PM_{2.5}$ and PM_{10}), non-methane organic hydrocarbons, and other chemicals into the atmosphere. These particles and gases can be hazardous to human health, threaten human welfare and ecosystems, degrade visibility, and contribute to greenhouse emissions (Battye and Battye 2002, Hardy *et al.* 2001, Sandberg and Dost 1990, Sandberg *et al.* 2002).

A fire manager's decision to use a specific burning technique to reduce emissions is influenced by many considerations including the need to meet specific land management objectives such as reducing fuels and fire hazard, thinning abundant regeneration, and eliminating undesirable vegetation; complying with environmental regulations; minimizing operational costs; and reducing the effect of smoke on the general public. These objectives have to be met while maintaining control of the prescribed fire. Techniques to reduce prescribed fire smoke vary widely in their applicability and effectiveness by vegetation type, burning objective, region of the country, and by whether fuels are natural created or generated from human activity such as logging. In certain instances, such as when burning fuels with high moisture content, emission reduction techniques may reduce emissions by more than 80%. In other cases, such as grazing cattle in a forested area, emission reduction may be minimal because only the grass fuel bed component is being reduced.

The use of emission reduction techniques can benefit public health and reduce the impact on visibility. These same techniques will often reduce the risk of overexposure to smoke of wildland firefighters igniting and controlling prescribed fires. Techniques that reduce emissions do this by limiting total fuel consumption or by consuming as much of the fuel as possible during the more efficient flaming stage. Techniques for reducing emissions include:

- Burning fewer acres
- Burning when fuels have a higher fuel moisture content
- Removing fuels before ignition
- Shifting combustion from the smoldering phase to the flaming phase

Use of emission reduction techniques should be considered for every prescribed burn due to their potential to protect air quality although not all techniques are appropriate to every situation. In certain cases, techniques to reduce emissions can impair or prevent the accomplishment of land management objectives; be too expensive; or negatively affect other valuable resources through soil compaction, loss of nutrients, impaired water quality, and increased tree mortality.

There are two general approaches to managing the effects of prescribed fire smoke on air quality:

- Reduce total prescribed fire emissions produced for a given area
- Reduce the impacts of prescribed fire emissions

This chapter concentrates on the first approach, smoke management techniques that reduce emissions.

Use of Emission Reduction Techniques

Emission reduction techniques described in this document may be used independently or in combination on any given prescribed burn. Furthermore, a number of different firing methods potentially can be applied to any parcel of land depending on the objectives and judgment of the fire manager. As a result, no two burns are the same in terms of pollutant emissions, smoke impacts, fuel consumption, or other parameters.

Significant changes in public land management policy have occurred since the U.S. Environmental Protection Agency's release of its first document describing the best available control measures for prescribed burning (U.S. EPA 1992). Today, Basic Smoke Management Practices may be part of a state's smoke management program. Some of these changes have dramatically affected when and how emission reduction methods for prescribed fire can be applied. On federal lands, the choice of emission reduction technique may be constrained by competing land management objectives such as water quality protections and prevention of impacts on riparian areas; administrative constraints imposed by Congress, such as those in roadless or wilderness areas; impacts on archaeological resources; smoke management program requirements; and other state environmental or forestry regulations. Similar constraints may exist on non-federal lands.

A comprehensive list of emission reduction techniques was compiled from the literature and from a national survey conducted in 1999 specifically for the 2001 Smoke Management Guide. These techniques are still appropriate today and have been reproduced for this updated guidebook. Any one of these may or may not be applicable in a given situation depending upon specifics of: (1) fire use objectives, (2) project locations, (3) time and cost constraints, (4) weather and fuel conditions, (5) public and firefighter safety considerations, (6) smoke dispersion impacts, (7) local air quality issues (or lack thereof), (8) post-burn invasive plant concerns, and (9) endangered species requirements.

Emissions Reduction Techniques

Emissions from prescribed fire are complex and contain many pollutants and toxic compounds. Emission factors for hundreds of compounds have been identified and described in the literature (Urbanski *et al.* 2009, Ward and Hardy 1991, Peterson and Ward 1989, Ward *et al.* 1993). The chemical composition of smoke is related to the combustion characteristics of the fire, especially the relative amounts of fuel consumed during the flaming and smoldering combustion phases. Some species are produced exclusively during the flaming or smoldering phase while others are produced during both phase. Flaming combustion produces more gases such as CO_2, NO, NO_2, as well as black carbon. The gases CO, CH_4, many non-methane hydrocarbons, and particulate matter are associated with smoldering combustion (Urbanski 2014). A simplified finding is that emission reduction actions that reduce both flaming and smoldering consumption will reduce all emissions while emission reduction techniques that target a specific combustion phase will be more efficient at reducing the emissions generated during that phase.

These techniques may reduce potential emissions by as much as 100% (e.g., utilizing all material without burning) to as little as zero (e.g., burning under dry conditions to meet mineral soil exposure objectives). If emission reduction techniques were optimally used around the entire United States, emissions could potentially be reduced by 20 to 25%, assuming land management goals were being met (Peterson and Leenhouts 1997). Certain regions of the country may be able to achieve greater or lesser emission reductions depending on economic and climatic factors such as local biomass utilization potential and the decomposition rates of fuels. Within this framework, land managers can use fuel consumption and emission models to determine the degree an emission reduction method will reduce emissions.

Prescribed fire fuel and emission models such as the Fuel Characteristic Classification System (Ottmar *et al.* 2007), First Order Fire Effects Model (Reinhardt *et al.* 1997), Consume 4.1 (Prichard *et al.* 2007), and Fire Emission Production Simulator (Sandberg *et al.* 2004) can be used to estimate fuels; fuel consumption; and particulate, gaseous and hazardous pollutant emissions based on the specifics of each burn. There are seven general categories that encompass techniques described in this document. Each is described below.

Reduce the Area Burned

The most obvious way to limit prescribed fire emissions is to burn less area. When applying this emission reduction technique, it is important to report for smoke management accounting, only the area that was actually blackened since only that part of the prescribed fire actually burned and produced smoke. The total area within the perimeter may be reported for management accomplishment depending on the land management objectives established in the burn plan.

Area burned can be reduced by not burning at all, or by burning only a portion of the area within a designated perimeter. Caution must be applied because reducing the area burned may simply result in a delay of emissions produced. Delaying the production of emissions may be a good or a bad idea depending upon (1) how much fuel accumulates, (2) how much fuel is consumed, (3) how much emissions are produced, and (4) the environmental conditions during which the emissions are produced.

Reducing the size of the area to be burned, or the area that is blackened is an effective and generally easy way to reduce emissions. When considering application of this technique, fire managers must weigh potential downsides such as the effect on ecosystem function in fire-adapted vegetation types, or where fire is required for ecosystem, habitat, or forest health management. In some vegetation types, when fire is used to eliminate an undesirable species or dispose of biomass waste, alternative methods can be used to mimic effects similar to what burning would accomplish.

Examples of specific techniques that reduce the area burned include:

<u>Burn concentrations</u>

Sometimes natural concentrations of fuels can be burned rather than burning the entire area requiring treatment. This technique is generally used where the fuel loading is high. Determining the total area burned or blackened using this technique can be difficult since the entire unit is not burned.

<u>Isolate fuels</u>

Large logs, snags, deep pockets of duff, sawdust piles, squirrel middens, and other fuel concentrations that have the potential to smolder for a long time can be isolated from the prescribed fires and left unburned. This can be done by: (1) constructing a fireline around specific fuel bed components to be left unburned that could produce a large amount of smoke, (2) not lighting individual or concentrated fuels, (3) using natural barriers such as rock outcroppings or residual snow, (4) scattering the fuels, or (5) spraying fuels with fire retardant. Preventing these fuels from burning is often faster, safer, and less expensive than mop-up operations.

Mosaic burning

Figure 4.2.1. This prescribed fire in northeast Oregon created patches of burned and unburned areas resulting in reduced emissions.

Landscapes often include fuel types that are discontinuous and vary in their fuel moisture content. Fire prescriptions and lighting patterns can be assigned to use this fuel and fuel moisture heterogeneity to mimic a natural wildfire and create patches of burned and unburned areas or to burn only selected fuels. Areas or fuels that do not burn do not contribute to emissions. For example, an area may be continuously ignited during a prescribed fire but because the fuels are not continuous, patches within the unit perimeter may not ignite and burn (figure 4.2.1). Wetlands, swamps, and hardwood patches will be naturally excluded from burning when soil moisture is high. Furthermore, if the burn prescription calls for low humidity and high live-fuel moisture, continuous burning may occur in dead fuels while the live fuels are too wet to burn. In both cases, the unburned live fuels may be available for future burning in a prescribed or wildfire during droughts or dormant seasons. Although it may be difficult to estimate, it is important to report only the area burned or blackened for smoke accounting purposes, although the total area can be reported as a management accomplishment.

Reduce Fuel Load

Some or all of the fuel can be permanently removed from the site or biologically decomposed. Overall emissions can be reduced when fuel is permanently excluded from burning.

Mechanical removal

Mechanically removing fuels from a site reduces emissions proportionally to the amount of fuel removed. This is a broad fuel reduction category and can include such techniques as mechanical removal of logging debris from timber harvest sites, on-site chipping of woody material or brush for use offsite, and mechanical removal of fuels which may or may not be followed by offsite burning in a controlled environment such as around homes in the wildland urban interface. Mechanical treatments (such as whole-tree harvesting) may sufficiently reduce fuels so that burning is unnecessary. Mechanical treatments are applied only on lands where such activities are allowed (e.g., not in wilderness areas), slopes are relatively gentle (less than 20%), when supported by an access road network, and where there is an economic market for disposal of the removed fuel. This technique is most effective in forest fuels and has a limited applicability in shrub fuels. A portion of the emission reduction from this technique may be offset by increased fossil fuel and particulate emissions from equipment used for harvest, transportation, and disposal operations. Mechanical treatments may cause undesirable soil disturbance or compaction, stimulate exotic plant invasion, remove natural nutrient sources, or impair water quality.

Mechanical processing

Mechanical processing of dead and live vegetation into wood chips or shredded biomass is effective in reducing emissions if the material is removed from the site or biologically decomposes (figure 4.2.2). If the biomass is spread across the ground as litter fuel, emission reductions are not achieved if that litter is later consumed either in a prescribed or wildfire. Furthermore, the consumption of wood chips and biomass will often consume during the smoldering phase producing more smoke that is less buoyant and stays close to the ground. Use of this technique may eliminate the need to burn if the chips are spread out enough to reduce the continuity between fuel particles eliminating a fire behavior problem.

Figure 4.2.2. Mechanical processing of biomass.

Firewood sales

Firewood sales may facilitate sufficient removal of woody debris, making on-site burning unnecessary. This technique is particularly effective for piled material easily accessible to the public. It is generally applicable in forests with large diameter trees. Emissions from wildland fuels burned for residential heating are not assessed as wildland fire (wild and prescribed fire) emissions but as residential heating emissions. The effect of these emissions on the human environment is not attributed to wildland fire in national or State emissions inventories. However, the emissions emitted from residential heating may result in a larger impact on air quality than a prescribed burn conducted using emission reduction techniques.

Biomass for electrical generation

Woody biomass can be removed and used to provide electricity in regions with cogeneration facilities. The efficiency of combustion in producing electricity from woody biomass is generally greater than that from open burning, and emissions from biomass fuel used in this way offset that of fossil fuel emissions. Although this method of reducing fuel loads is cost-effective where there is a market for wood chips, there may be significant administrative, logistical, and legal barriers that limit its use.

Biomass utilization

Woody material can be used for many purposes other than fire, including as pulp for paper, methanol production, wood pellets, garden bedding, and specialty forest products. Demand for these products varies widely from place to place and from year to year. Biomass utilization is most applicable in areas of forest and shrublands that include large loadings of woody biomass, and where fuel density and distance to a population center makes biomass utilization economically viable.

Ungulates

Grazing and browsing live grasses or brush by sheep, cattle, or goats can reduce fuels before burning, or reduce the burn frequency. Goats will sometimes eat even small, dead woody biomass. However, ungulates are selective, favoring some plants over others. The cumulative effect of this selectivity can significantly change plant species compositions and long-term ecological processes in an area, eventually converting grassy areas to brush. On moderate to steep slopes, large ungulate populations contribute to increased soil erosion.

Reduce Fuel Production

Management techniques can be used to shift the species composition of an area toward vegetation types that produce less biomass per acre, produce biomass that is less likely to burn, or that burn more efficiently.

Site conversion

Site productivity can be affected by a change in vegetation type. For example, frequent ground fires in southern pine forests will convert an understory of flammable shrubs (such as palmetto and gallberry) to open woodlands with more grass and herbs, reducing total fuel loading. Grass and herbs tend to burn more cleanly than shrubs. Total fuel loading can also be reduced through conversion of current vegetation to species that are less productive.

Chemical treatments

Broad spectrum and selective herbicides can be used to reduce live vegetation, or alter species diversity, respectively. This often reduces or eliminates the need for prescribed burning. Chemical production and application have their own emissions, environmental, and public relations problems. A National Environmental Policy Act (NEPA) analysis is generally required before using any chemicals on federal lands, and States often require similar analyses prior to chemical use on State or private lands. Current literature does not indicate discernible air toxic emissions from burning vegetation treated with herbicides (McMahon and Bush 1992).

Reduce Amount of Fuel Consumed

Emissions can be reduced when significant amounts of fuel are at or above the moisture of extinction, and therefore unavailable for combustion. Even though wet fuels burn somewhat less efficiently and produce more emissions per ton of fuel consumed, total emissions are significantly reduced because so much less fuel is consumed. This technique can be especially effective when a significant portion of large woody fuels are left unburned. Burning when fuels are wet may leave large amounts of unburned fuel in the treated area which may not result in a reduction in total emissions, but rather a delay if the fuels are later burned during wildfire or subsequent prescribed fire. Real emission reductions are achieved if the unburned fuels remain long enough to decompose or be otherwise incorporated into the soil and, therefore, unavailable for future consumption.

In areas with large logs (e.g., logging slash or decadent lodgepole pine stands) or deep organic layers (e.g., boreal forests or pocosin), burning only the fuels necessary to meet management objectives is one of the most effective methods of reducing emissions. When the objective of burning is to reduce wildfire hazard, removal of fine and intermediate-size fuels may be sufficient, and those fuels can be targeted when the small fuels are dry and the large logs and organic layers are wet. Limiting large woody fuel and organic layer consumption can reduce emissions by up to 80%.

High moisture in large woody fuels

Figure 4.2.3. Burning when large woody fuel moisture is high can result in less total fuel consumption and less emissions.

Burning when large woody fuels (those 3 inches or more in diameter) are wet can result in lower fuel consumption and less smoldering. When large fuels are wet they will not sustain combustion on their own and are extinguished by their own internal moisture once the small twigs and branch-wood in the area finish burning (figure 4.2.3). Large logs, therefore, are consumed less, smolder less, and don't cause much of the organic layer on the forest floor to burn. This can be a very effective technique for reducing total emissions from a prescribed burn and can have secondary benefits by leaving more large-woody debris in place for nutrient cycling. This technique can be effective in natural and activity fuels in forest types. When large woody fuel consumption is needed, burning under high moisture conditions is not a viable alternative.

Moist litter and duff

The layer that forms from decayed and partially decayed organic matter on the forest floor often burns during the less efficient smoldering phase. Consequently, reducing the consumption of this material can be very effective at reducing emissions. Consumption of this litter or duff layer can be greatly reduced if the material is quite moist. Surface fuels can be burned and the organic layer remains virtually intact. The appropriate condition for use of this technique generally occurs within a few days of a soaking rain or shortly after snowmelt. This technique is most effective in forest and brush types not accustomed to frequent fire. It may not be appropriate in areas where removal of the organic layer is desired. Burning litter or duff to expose mineral soil is often necessary for plant regeneration in fire-adapted ecosystems. In areas with deep organic peat layers like the pocosin or boreal forest regions of Alaska and the Lake States, the moisture content of those layers will determine if there will be extended periods of smoldering consumption. Research is limited on what that moisture threshold is for continued long-term smoldering and it is suggested the managers rely on local expertise on when to burn (and when not to burn) to limit consumption of those fuels when possible, reducing air quality effects.

Burn before precipitation

Scheduling a prescribed fire before an expected precipitation event will often result in the decreased consumption of large woody material, snags, stumps, and organic ground matter, thus reducing the potential for a long smoldering period and associated emissions. Successful application of this procedure depends on accurate meteorological forecasts for the area.

Burn before large fuels cure

Living trees contain very high internal fuel moistures and take a number of months to dry after harvest. If an area can be burned within 3 to 4 months of timber harvest, many of the large fuels will still contain a significant amount of moisture. This technique is generally restricted to logging debris or windthrow-generated fuels.

Schedule Burning Before New Fuels Appear

Burns can sometimes be scheduled before new fuels appear. This may interfere with land management goals if burning is forced into seasons or moisture conditions where increased mortality of desirable species can result.

Burn before litter fall

When deciduous trees and shrubs drop their leaves, this ground litter contributes volume to the fuel bed. If burning takes place before litter fall, there is less fuel available, less fuel consumed, and lower emissions.

Burn before green-up

Burning in vegetation types with a grass or herbaceous component can produce lower emissions if burning takes place before these fuels green-up for the year. Less fuel is available to burn.

Increase Combustion Efficiency

Increasing combustion efficiency, or shifting most of consumption away from the smoldering phase and into the more efficient flaming phase, reduces emissions.

Burn piles or windrows

Fuels concentrated into clean piles or windrows that are dry generate greater heat and burn more efficiently than dirty and wet piles (figure 4.2.4). More of the consumption occurs in the flaming phase and the emission factor is lower. This technique is primarily effective in forest fuels but may have some applicability in brush fuels. Concentrating fuels into piles or windrows generally requires the use of heavy equipment, which can negatively affect soils and water quality. The burning of piles and windrows also causes temperature extremes in the soils directly underneath and can sterilize soil. If fuels in piles or windrows are wet or mixed with dirt, extended smoldering can result in residual smoke problems.

Figure 4.2.4. Dry, clean piles burn efficiently and generally generate fewer emissions per ton of fuel than dirty, wet piles or broadcast burns (photo courtesy of Richie Harrod).

Piles are often covered with polyethylene plastic sheeting to keep their centers dry until it is time to burn them. However, questions have been raised about the possibility of toxins being released as the plastic burns. Studies indicate that the plastic sheeting is mostly carbon and vaporizes at a much lower temperature than the biomass of the pile. Also, the amount of plastic is small compared to the biomass burned. No increase in toxic emissions has been documented as a result of plastic burning (Jung *et al.* 2009, Wrobel and Reinhardt 2003, Hosseini *et al.* 2014). Plastic keeps the pile dry so it burns more efficiently, thereby reducing overall emissions.

Backing fires

Figure 4.2.5. A backing fire burns more efficiently than a heading fire, since more consumption takes place in the cleaner flaming phase, but may result in more total fuel consumed resulting in more emissions.

Flaming combustion is cleaner than smoldering combustion for most components of smoke (three exceptions being CO_2, NO_X, and black carbon). A backing fire takes advantage of this relationship by consuming more fuel in the flaming phase than does a heading fire (figure 4.2.5). Where fuels are continuous and dry, the flaming front backs more slowly and, by the time it passes, most of the available fuel is consumed and the fire quickly dies out with very little smoldering. It is important to note that, even though a majority of the consumption during a backing fire occurs during the flaming combustion phase, much more fuel is often consumed, reducing the emission reduction potential of this practice. In a heading fire, the flaming front passes quickly and, if the fuels are dry, the ignited fuels continue to smolder causing more smoke than a backing fire; if the fuels are wet, limited smoldering will occur resulting in much less smoke than during a backing fire. The use of backing fires is not always an option and may increase both operational costs and time needed to complete the burn.

Dry conditions

Burning under dry conditions improves combustion efficiency and will generally produce lower emissions than burning when fuel moisture contents are high. However, drier conditions often make fuels that were previously at or above the moisture of extinction now available to burn. The increased emissions from this additional fuel generally will more than offset emission reductions gained by greater combustion efficiency. This technique is effective only if all fuels will consume under either wet or dry conditions.

Rapid mop-up

Figure 4.2.6. Mop-up reduces smoldering consumption and total emissions (photo courtesy of George Broyles).

Rapidly extinguishing a fire can reduce fuel consumption and smoldering emissions somewhat, although this technique can be very costly and is not particularly effective at reducing total emissions (figure 4.2.6). Rapid mop-up primarily affects smoldering consumption of large woody fuels, stumps, snags, and duff. Rapid mop-up is more effective as an avoidance technique by reducing residual emissions that tend to get caught in drainage flows and end up in smoke sensitive areas. However, rapid mop-up can expose fire personnel to large concentrations of smoke over long periods of time; this needs to be considered in using the practice.

Aerial ignition/mass ignition

Mass ignition can shorten the smoldering phase and reduce the total amount of fuel consumed (figure 4.2.7). When properly applied, mass ignition quickly consumes dry surface fuels and creates a very strong plume or convection column which draws much of the heat away from the fuel bed. This prevents drying and preheating of the larger and moister fuels. The plume may improve smoke dispersal. The fire dies out shortly after the fine fuels are completely consumed, and there is little smoldering or consumption of the larger fuels and duff. Conditions necessary to create a true mass ignition include rapid ignition of a large, open area with continuous, dry fuels (Hall 1991).

Figure 4.2.7. Mass ignition can shorten the duration of the smoldering phase and reduce total fuel consumption, resulting in fewer emissions.

Air curtain incinerators

Burning fuels in a large metal container or pit, with the aid of a powerful fan-like device to force additional oxygen into the combustion process, results in a very hot and efficient fire that produces little smoke (figure 4.2.8). These devices are commonly used to clear land, highway right-of-ways, or demolition debris in areas sensitive to smoke, and their use may be required by air quality agency regulations. Although incinerators do reduce emissions, they are expensive to operate, need a flat area for set up, take time to process the biomass, and may require a special permit and fees.

Figure 4.2.8. Air curtain incinerators result in very hot and efficient fires that produce little smoke.

Balancing Use of Emission Reduction Techniques with Land Management Objectives

Land managers are concerned about the repeated application of fuel treatment techniques that do not replicate the ecological role of fire. Such applications may result in unintended resource damage such as the loss of soil nutrients if too much woody debris is removed from the site, or soil compaction from use of machinery. The application of herbicides and other chemicals, or the effects on soils or tree mortality if intense heat is achieved during mass ignition, are also of concern. These consequences are difficult to measure but are of universal importance to land managers, who must weigh the effect of their decisions on maintaining a healthy ecosystem. Many resource values must be considered in conjunction with benefits to air quality before emission reduction techniques are prescribed. Professional experience and judgment are key to the informed selection of emission reduction techniques, and the decision to use a specific emission reduction technique should be made on a case-by-case basis. Emission reduction goals may be the target, but the appropriate mix of emission reduction techniques to achieve those goals requires careful analysis of the short- and long-term ecological and social costs and benefits. It is essential that air quality regulators and land managers work together to better understand the effectiveness, options, difficulties, applicability, and tradeoffs of emission reduction techniques.

The Use and Effectiveness of Emission Reduction Techniques

The overall effectiveness and potential to reduce emissions from prescribed fire depends on how often emission reduction techniques are used and the amount of emission reduction that each method offers. This section provides information on the potential for emission reduction from prescribed fire based on (a) how often each emission reduction and emission redistribution technique is used, by region of the country; (b) the relative effectiveness of each smoke management technique; and (c) constraints on application of the technique (administrative, legal, physical, etc.). Much of the information in this section was provided by participants in three regional workshops held across the country in 1999 to support preparation of the 2001 version of the Smoke Management Guide. This information is still pertinent although it can, and should, be improved upon by local managers who will have better information about specific burning situations.

Use of emission reduction techniques is influenced by many factors including land management objectives, smoke management concerns, type and amount of vegetation being burned, safety considerations, costs, laws and regulations, geography, and more. The effect of some of these factors can be assessed through general knowledge of the frequency of use of a particular technique in a specific region.

Table 4.2.1 provides general information about frequency of use of each smoke management technique by region of the country. Each region has its own vegetation types, climatology, and terrain, all of which influence the burn and the appropriateness of various emission reduction techniques.

Table 4.2.1. Frequency of use of smoke management methods in each smoke management region as described in regional workshops held in 1999[a].

Smoke management method	Commonly used	Occasionally used	Rarely used
1. Reduce the area burned—			
Burn concentrations	INT[b]	MW, NW, PNW, SW	SE
Isolate fuels	INT, PNW	MW, NE, SE, SW	
Mosaic burning	INT, PNW, SW		MW, NE, SE
2. Reduce fuel load—			
Mechanical removal	INT, PNW, SW	SE	MW, NE
Mechanical processing		INT, MW, NE, PNW, SE	SW
Firewood sales		SW	INT, MW, NE, PNW, SE
Biomass for electrical generation			All regions
Biomass utilization			All regions
Ungulates	INT, PNW, SW	MW, NE, SE	
3. Reduce fuel production—			
Chemical treatment		SE	INT, MW, NE, PNW, SW
Site conversion			All regions
4. Reduce fuel consumed—			
High moisture in large fuels	PNW, SE	INT, MW, NE, SW	
Moist litter or duff	PNW, SE	INT, MW, NE	SW
Burn before precipitation		All regions	
Burn before large fuels cure	MW, NE, PNW		INT, SE, SW
5. Schedule burning before new fuels appear—			
Burn before litter fall			All regions
Burn before green-up	MW, NE, SE, SW	INT, PNW	
6. Increase combustion efficiency—			
Burn piles or windrows	INT, PNW, SW,	MW, NE	SE
Backing fires	MW, NE, SE, SW	PNW	INT
Dry conditions			All regions
Rapid mop-up	MW, NE, PNW	INT, SE, SW	
Aerial ignition / mass ignition	All regions		
Air curtain incinerators			All regions

[a] Refer to figure 4.2.9 for map of prescribed burning regions.

[b] INT = Intermountain region, MW = Midwest region, NE = Northeastern region, PNW = Pacific Northwest region, SW = Southwest region, SE = Southeast region.

Table 4.2.1 summarizes regional applicability of each of 29 smoke management methods. Interviews with fire practitioners indicate, that on a national scale, methods most commonly applied at the time of the 1999 survey include aerial ignition/mass ignition, burning when smoke dispersion is good, taking turns burning, and avoiding sensitive areas. The survey also indicated there were several smoke management techniques that are rarely used. These include biomass for electrical generation, biomass utilization, site conversion, burning before litter fall, burning under dry conditions, air curtain incineration, and burning smaller units. In most of the regions, firewood sales and chemical treatments are seldom used.

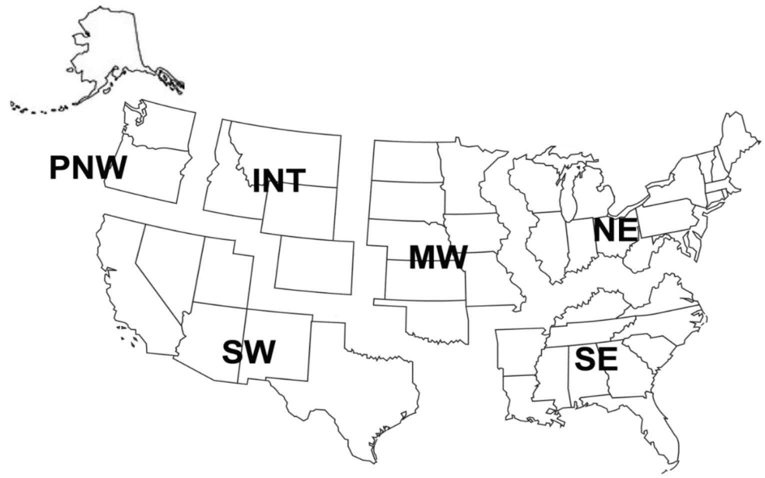

Figure 4.2.9. Prescribed burning regions including Pacific Northwest including Alaska (PNW), Intermountain (INT), Midwest (MW), Northeast (NE), Southeast including Hawaii (SE), and Southwest (SW).

Evaluation of the general effectiveness of emission reduction and redistribution techniques is based on information from managers as rated in table 4.2.2. Local managers will have the best information about specific situations than can be found in the tables. Each technique was assigned a rank of "high" for those techniques more effective at reducing emissions or "low" for those techniques that are less effective. Some emission reduction techniques have secondary benefits of delaying or eliminating the need to use prescribed fire. Some smoke management techniques are also effective for reducing local smoke impacts if they promote plume rise or decrease the amount of residual smoldering combustion where smoke is more likely to get caught in drainage winds and carried into populated areas. These factors are also addressed in table 4.2.2.

Table 4.2.2. Relative effectiveness of various smoke management techniques.

Smoke management technique	General emission reduction potential	Can eliminate or delay need to burn?	Effective for reducing local smoke effects (if burned)?
1. Reduce the area burned—			
Burn concentrations	High	N/A	Yes
Isolate fuels	High	N/A	Yes
Mosaic burning	High	N/A	Yes
2. Reduce fuel load—			
Mechanical removal	High	Yes	Yes
Mechanical processing	Low	Yes	Yes
Firewood sales	Low	Yes	Yes
Biomass for electrical generation	High	Yes	Yes
Biomass utilization	Low	Yes	Yes
Ungulates	High	Yes	Yes
3. Reduce fuel production—			
Chemical treatment	Moderate	Yes	Yes
Site conversion	High	Yes	Yes
4. Reduce fuel consumed—			
High moisture in large fuels	High	N/A	Yes
Moist litter or duff	High	N/A	Yes
Burn before precipitation	High	N/A	Yes
Burn before large fuels cure	High	N/A	Yes
5. Schedule burning before new fuels appear—			
Burn before litter fall	Low	N/A	Yes
Burn before green-up	Low	N/A	Yes
6. Increase combustion efficiency—			
Burn piles or windrows	Low	N/A	Yes
Backing fires	Moderate	N/A	Yes
Dry conditions	Low	N/A	Yes
Rapid mop-up	Low	N/A	Yes
Aerial ignition/mass ignition	Low	N/A	Yes
Air curtain incinerators	High	N/A	Yes

Table 4.2.3 summarizes significant constraints identified by fire managers that limit the wider application of techniques to reduce and redistribute emissions. This table excludes consideration of the objective of the burn, which is generally the overriding constraint. Some of the techniques might be used more frequently if specific constraints could be overcome.

Table 4.2.3. Constraints to the use of emission reduction techniques as reported in 1999 by regional workshop participants.

Smoke management method	Administrative constraints	Physical constraints	Legal constraints	Cost constraints	Other constraints
1. Reduce area burned—					
Burn concentrations	Few	Slope and access	Few	High	Only applicable to small pockets of fuel
Isolate fuels	Few	Slope	Few	High	Incompatible fuels
Mosaic burning	Few	Few	Few	Moderate	Incompatible fuels
2. Reduce fuel load—					
Mechanical removal	Moderate	Slope	Few	Moderate	Slope
Mechanical processing	Moderate	Slope and access	Few	High	Incompatible fuels
Firewood sales	High	Access	High	Few	No markets, incompatible fuels
Biomass for electrical generation	High	Slope and access	Moderate	High	No markets, incompatible fuels
Biomass utilization	High	Slope and access	Moderate	High	No markets, incompatible fuels
Ungulates	Few	Few	High	High	Incompatible fuels
3. Reduce fuel production—					
Chemical treatment	High	Few	Very high	Very high	Controversial policy, adverse water quality impacts
Site conversion	High	Few	High	High	Ecosystem impacts
4. Reduce fuel consumed—					
High moisture in large fuels	Few	Few	Few	Few	Incompatible fuels in some regions
Moist litter or duff	Few	Few	Few	Few	Not used in the Southwest region
Burn before precipitation	Few	None	None	Few	Difficult to plan
Burn before large fuels cure	Few	Few	Few	Few	Limited to activity fuels, incompatible fuel types
5. Schedule burning before new fuels appear—					
Burn before litter fall	Few	Few	None	Few	Incompatible fuels in most regions
Burn before green-up	Few	Slope	Few	Few	Limited use in many fuel types
6. Increase combustion efficiency—					
Burn piles or windrows	Few	Slope	Few	High	
Backing fires	Few	Fuel continuity	Few	Few	Need correct meteorological conditions
Dry conditions	High	Dry conditions	High	High	Increased escape potential
Rapid mop-up	Few	Slope and access	Few	High	
Aerial ignition/mass ignition	Few	Few	Few	Moderate	Trained crews and equipment; fuel types
Air curtain incinerators	Few	Access	Few	Very High	

In the opinion of workshop participants, smoke management techniques that show particular promise for wider use in the future are:

- **Mosaic Burning:** Because this method reduces the area burned and can be used to replicate the natural type of fire, it is increasingly being used for landscape forest health restoration.
- **Mechanical Removal:** In areas where slope and access are not barriers, and fuels have economic value, the wider use of whole-tree yarding, yarding of unmerchantable material, cut-to-length logging practices, and other methods that remove fuel from the unit before burning (if the unit is to be burned at all) may be more widely applied if economic markets for the removed fuels can be found.
- **High Moisture in Large Woody Fuels, Litter, or Duff:** In situations where the prescribed fire objective does not include maximizing the consumption of large woody debris, litter, or duff, this option is favored by fire practitioners as an effective means of reducing emissions, smoldering combustion, and smoke impacts.
- **Pile and Windrow Burning:** Pile burning, although already widely used across the country, is gaining in popularity among land managers because it offers flexibility in burning schedules and decreases the effects on smoke-sensitive locations. These decreased effects may not be achieved if piles or windrows are wet or mixed with dirt.
- **Aerial/Mass Ignition:** Little clear information exists about extent to which aerial ignition achieves mass ignition and its associated emission reduction benefits. True mass ignition, using aerial ignition techniques, may significantly reduce emissions.
- **Burn More Frequently:** Fire managers generally favor frequent prescribed burning to reduce the fuel loads subsequent fires, reducing total emissions over a long period of time. This will increase daily or seasonal emissions.

Estimated Emission Reductions

While the qualitative assessment of emission reduction techniques and their effectiveness is a useful way to gauge how relatively successful a particular technique may be in reducing emissions (table 4.2.2), it is also useful to model potential quantitative emission reduction. Table 4.2.4 summarizes potential emission reductions that may be achieved by employing various techniques as estimated by the fuel consumption and emissions model Consume 4.1 (Prichard *et al.* 2007). For example, the use of mosaic burning techniques in natural, mixed conifer forests in which half of a 200-acre project is burned is projected to reduce $PM_{2.5}$ emissions by 50%, from 27.2 to 13.6 tons. An 83% reduction can be achieved by burning in a black spruce forest when litter, moss, and duff are moist. By burning mixed conifer piles under conditions listed in table 4.2.2, $PM_{2.5}$ emissions can be reduced by as much as 74%. Specific simplifying assumptions were made in each case to produce the estimates of potential emission reduction seen in table 4.2.4. Other models using the same assumptions would yield similar trends.

Table 4.2.4. Emission reduction potential for various emission reduction techniques by vegetation type[a].

Vegetation type	Emission reduction technique	FCCS fuelbed[b]	Total fuel loading (tons/acre)	Fuel type	Size (acres)	Ignition time (minutes)	Large fuel moisture (percent)	Duff moisture (percent)	Total fuel consumption (tons)	Total $PM_{2.5}$ emissions (tons)	$PM_{2.5}$ emission reduction potential (%)
Southern pine	Mosaic burning	242	51.2	Natural	100	180	25	70	1,295	13.6	50
Southern pine	Non-mosaic burning	242	51.2	Natural	200	180	25	70	2,591	27.2	50
North central red /white pine	Mechanical removal	138	65.17	Activity[c]	100	180	25	70	2,453	34.2	37
North central red / white pine	No mechanical removal	138	91.9	Activity[c]	100	180	25	70	4,263	54.7	37
Midwest grassland	Ungulates	131	2.5	Natural	100	180	25	70	228	0.68	54
Midwest grassland	No ungulates	131	5.4	Natural	100	180	25	70	497	1.49	54
Interior mixed conifer	High moisture in large fuels	29	75.4	Activity[c]	100	180	45	70	1773	19.9	62
Interior mixed conifer	Low moisture in large fuels	29	75.4	Activity[c]	100	180	15	70	4,386	51.7	62
Alaska black spruce	Moist litter or duff	86	63.64	Natural	100	180	25	150	714	4.16	83
Alaska black spruce	Dry litter or duff	86	63.64	Natural	100	180	25	50	2,536	24.3	83
Pacific Northwest Douglas fir/hemlock	Burn before large fuels cure	4	76.4	Activity[c]	100	180	100	70	2042	21.9	66
Pacific Northwest Douglas fir/hemlock	Burn after large fuels cure	4	76.4	Activity[c]	100	180	25	70	4,080	65.1	66
Southwest ponderosa pine	Piled fuels	29	57.5	Piled	100	180	25	70	2,342	15.7	74
Southwest ponderosa pine	Non-piled fuels	29	75.4	Activity[c]	100	180	25	70	4,182	60.3	74
Pacific Northwest Douglas fir/hemlock	Mass ignition	4	73.1	Activity[c]	100	30	25	70	3,680	39.2	7
Pacific Northwest Douglas fir/hemlock	No mass ignition	4	76.4	Activity[c]	100	180	25	70	3,970	42.2	7
California chaparral	Burn more frequently	44	7.9	Natural	100	180	25	70	556	3.9	65
California chaparral	Burn less frequently	44	12.6	Natural	100	180	25	70	1,005	11.0	65

[a] Values generated with Consume 4.0 (Prichard *et al.* 2007).
[b] Fuelbeds from Fuel Characteristic Classification System (Ottmar *et al.* 2007, Prichard *et al.* 2014).
[c] Activity fuel beds are woody debris resulting from management activity such as logging.

Wildfire Emission Reduction

Little thought has been given to reducing emissions from wildfire, but many fire management actions do affect emission production from wildfires because they intentionally reduce wildfire occurrence, extent, or severity. For example, fire prevention efforts, aggressive suppression actions, and fuel treatments (mechanical or prescribed fire) all reduce emissions from wildfires. However, fire suppression efforts may only delay the emissions rather than eliminate them altogether. All fire management plans that allow limited suppression consider air quality impacts from potential wildfires as a decision criterion. So, although only specific emission reduction techniques for prescribed fires are discussed in this chapter, it should be remembered that there is an inextricable link between fuels management, prescribed fire, wildfire severity, and emission production.

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CHAPTER 5 – TECHNIQUES AND TOOLS FOR SMOKE MANAGEMENT

5.1 Smoke Management Meteorology

Brian Potter, Miriam Rorig, and Sue A. Ferguson

Once smoke enters the atmosphere, its concentration at any one place and time depends on mechanisms of transport and dispersion. By transport, we mean whatever carries a plume vertically or horizontally in the atmosphere. Vertical transport is controlled by the buoyancy of the smoke plume and stability of the atmosphere. Horizontal transport is controlled by wind. The larger the volume of space that smoke is allowed to enter and the farther it can be transported, the more disperse and less concentrated it will become. To begin understanding atmospheric stability and winds that control transport and dispersion, we begin with a few elementary concepts. Definitions for many of the technical terms used in this chapter can be found on the National Weather Service website (U.S. Department of Commerce, National Oceanographic and Atmospheric Administration, National Weather Service 2009).

Temperature, Pressure and Height

Atmospheric pressure is the weight of the atmosphere over a horizontal unit area. At higher altitudes there is less atmosphere above the unit area, so pressure is lower. Sea level pressure (the surface or ground level pressure at locations at sea level) is generally between 970 and 1,030 millibars (mb). Typical surface pressures in Denver, roughly 5,000 feet above sea level, are about 150 mb lower because there is less atmosphere above it. Low sea level pressure corresponds to frontal passages and hurricanes, while high sea level pressure commonly produces clear skies and heat (cold) waves in summer (winter).

> A comment about units is necessary here. While this chapter uses Imperial measures, such as feet, pounds, and degrees Fahrenheit whenever possible, this is not feasible in the discussion of profiles, soundings, and atmospheric pressure. These are always provided in units of meters, degrees Celsius, and millibars, and so the reader will eventually need to become familiar with these units. For the present discussion, the main focus is on the visual interpretation of the data and the units are of minimal importance.

Atmospheric pressure decreases with increasing height, and as a result, a bubble (commonly called a parcel) of air that rises will expand. If no energy is added to or removed from the parcel, this is called an *adiabatic* process. Air expanding adiabatically cools, and air adiabatically contracting warms. Perfectly adiabatic ascent (descent) results in a temperature decrease (increase) of 5.5 °F per 1000 feet of ascent. The rate at which the atmosphere cools with increasing height is called the lapse rate, and this particular rate of cooling is referred to as the dry adiabatic lapse rate (DALR).[1] The DALR is illustrated by the dry adiabatic lines on a skew-T diagram (see figure 5.1.8 in the skew-T section below).

Adiabatic movement is an idealized concept and in general, movement of air in the atmosphere is not truly adiabatic. Parcels mix with air around them, friction adds or removes energy, and absorption or emission of infrared radiation adds or removes energy. Because of these processes, the actual dry lapse rate in the atmosphere is usually closer to 3.5 °F per 1000 feet, rather than the DALR.

As a parcel of air rises, it can cool to the point that water vapor condenses into droplets (the maximum possible amount of water vapor decreases with temperature). Condensation releases stored energy (known as latent heat) into the parcel of air, partially offsetting the adiabatic cooling. For air in the lower 5,000 to 10,000 feet of the atmosphere, this offsetting energy reduces the parcel's lapse rate to approximately 3 °F per 1000 feet. The lapse rate for saturated (moist) air is called the saturated adiabatic

[1] This is for dry air. Moisture complicates matters, and is discussed later.

lapse rate (SALR) or moist adiabatic lapse rate (MALR). Air that is initially drier has less moisture to release heat and offset cooling, and so may have a SALR close to the DALR.

Stability

Stability is a measure of how strongly the atmosphere inhibits or supports vertical movement of air. When the atmosphere is stable, a small movement or perturbation (up or down) of a parcel results in forces that push it back towards its original state. In an unstable atmosphere such a change is amplified or increased by the forces involved, and the parcel will continue moving in the direction of the perturbation. Neutral stability is the case when the small change is neither counteracted nor enhanced, and the parcel remains in its new position. A parcel of air that has the same temperature as the air around it is said to be at its thermodynamic equilibrium level, often just referred to as the equilibrium level.

The key to determining atmospheric stability lies in the lapse rates discussed earlier. A parcel of air that is warmer than the air around it is less dense and so it will start to rise. A parcel cooler than its environment will similarly sink. If the parcel rises, it expands and cools at the DALR, while the surrounding environmental temperature, pressure, and density all decrease. Consider a dry parcel warmer than its environment at some starting height. It will rise, and as it does so it will cool at the DALR. If the environment cools more slowly with increasing height, the parcel will eventually be the same temperature as the environment. If it rises any farther, it will be colder and denser than its environment. In this case the environment is stable to movement of the air parcel. If the environment cools more rapidly with height than the DALR, the parcel will become increasingly warmer than the environment and will continue to rise. This environment is unstable to movement of the air parcel (box 1).

Stability is important because it determines how high smoke will rise in the absence of wind. In a stable atmosphere, smoke released near the ground will remain near the ground. The heat energy the smoke processes from the fire may allow it to rise some distance before reaching its equilibrium level, but whatever height the smoke reaches, it will typically have a clearly defined, smooth, uniform top. High stability generally impedes winds, while low stability or any instability may allow wind to influence the smoke dispersion and produce more diffuse edges to the smoke plume.

Box 1—Application of lapse rates

Consider an environment with a lapse rate of 4 °F per 1000 feet. A parcel of air that starts at the same temperature as the environment and rises 100 feet will cool at the DALR, thus cooling 0.55 °F. The environment, however, is only 0.4 °F cooler at this height, and the parcel is now 0.15 °F colder than the surrounding air. The parcel will be denser, and will descend towards its starting height because the atmosphere is stable. This air was initially at its equilibrium level.

Suppose the parcel had started at 70 °F, and the environmental temperature around it was initially 69.4 °F. After rising 100 feet, the parcel would be 69.45 °F (70.0 °F - 0.55 °F = 69.45 °F) in an environment at 69 °F, and would continue to rise because it is warmer than the surrounding air. But if the parcel rose 400 feet, it would cool by 2.2 °F (0.55 °F/100 ft × 400 ft) to 67.8 °F. The environment, 400 feet above where the parcel started, is 1.6 °F cooler than at the starting height (0.4 °F/100 ft, × 400 ft), or 67.8 °F. The parcel and environment are now at the same temperature, and if the parcel rises any farther it will be colder than the environment. This air parcel has reached its equilibrium level. If the parcel of air is smoke from a fire, that smoke will reach this equilibrium level and remain there. A similar process applies to downward displacement, or displacement of a parcel that is initially colder than its environment. If a parcel is saturated with respect to water, then the appropriate SALR would be used in the calculations and comparison. A parcel could also start out unsaturated, and rise to a height where it is cooled to saturation. In this case, the DALR applies first, and the SALR once saturation is reached.

Inversions

Typically, temperature decreases with height (with warmer temperatures near the ground). Sometimes, however, the environment is cooler near the ground than it is above, a situation known as an inversion. A surface or surface-based inversion extends from the ground upward, to the level where the air temperature resumes its normal decrease with height. If the bottom of the inversion layer is elevated, above the ground, it is an upper-level inversion. There are several causes of inversions, but regardless of the cause, an inversion is extremely stable and has the effect of trapping smoke near the ground. Inversions vary in how high they reach (their depth), and their duration. They can be enhanced or diminished by the terrain. There are three types of surface inversions: radiation, marine, and frontal. Upper-level inversions are almost always subsidence inversions. The various types of inversions can interact, and there can be multiple inversion layers in the atmosphere at a given place and time.

Radiation Inversions

A radiation inversion develops on calm, clear nights when the heat radiated from the ground at night passes through the atmosphere relatively easily. This cools the ground, which in turn cools the air next to it. As the night continues, the air at the base of the inversion cools the most, and the depth of the inversion grows. If dew or fog begins to form, the rate of cooling decreases. When the sun rises, it begins to heat the ground and “burn away” the inversion from the bottom. If the inversion trapped heavy smoke, or if thick fog formed, less sunlight will penetrate and the inversion will persist later into the day.

Marine Inversions

Marine inversions occur when cool marine air flows inland. They are most common during the summer, when the sea breeze develops more strongly, and along the West Coast where prevailing winds blow onshore. Cooler, denser marine air moving inland will slide beneath warmer air that was heated over the ground. As heating from the sun weakens later in the day, the inversion can intensify (just as a radiation inversion would do). There is usually only a light breeze during the onset of a marine inversion. Marine inversions usually break up the same way a radiation inversion breaks up, with the sun heating the ground and the ground then heating the air next to it. Because the marine air is relatively moist, marine inversions often result in morning fog that delays break-up.

Frontal Inversions

Frontal inversions result when a cold or warm front moves into an area, and can occur at any time of the day or night. Arrival of a cold front (figure 5.1.1a) results in cooler air sliding underneath warm air. A cold frontal inversion increases in depth, as more cold air moves in and lifts the warm air farther from the surface. Cold frontal inversions are often accompanied by moderate to strong winds.

Warm frontal inversions precede the arrival of the warm front at the ground. The approaching warm air rides up over cooler air in a region, producing an inversion that becomes weaker and shallower as the front approaches (figure 5.1.1b). The winds associated with warm fronts are usually light to moderate.

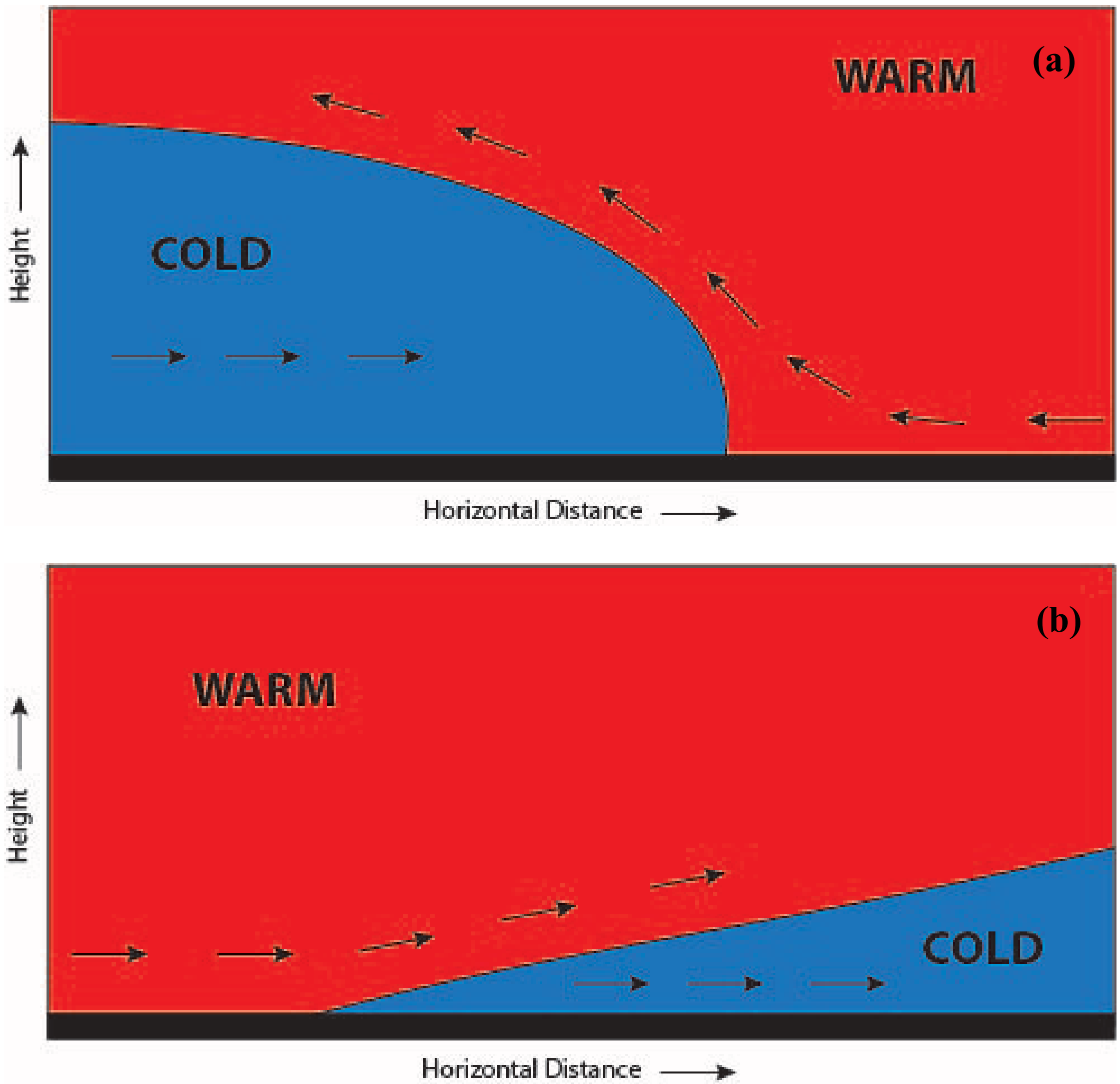

Figure 5.1.1. Vertical cross section illustrations of (a) an inversion created by a cold front sliding (left to right) under a warm front, and (b) an inversion resulting from a warm front moving (left to right) over a cold front (not to scale). Typically winds associated with cold fronts are stronger than warm frontal winds.

Subsidence Inversions

Large regional (also called synoptic-scale) high pressure systems extending several thousands of feet above the surface produce areas of sinking (subsiding) air, and that sinking air warms adiabatically. Figure. 5.1.2 shows a high pressure system located over Arizona and New Mexico. Because the subsiding air is warming, it becomes warmer than the air below it and produces an inversion. The inversion forms 3,000 to 5,000 feet above the ground, and descends a few hundred feet each day. The subsidence is very slow, and can persist for as long as five days. Eventually, it moves close enough to the ground that surface-based mixing (see Mixing Height Box 2 section below) can dissipate it.

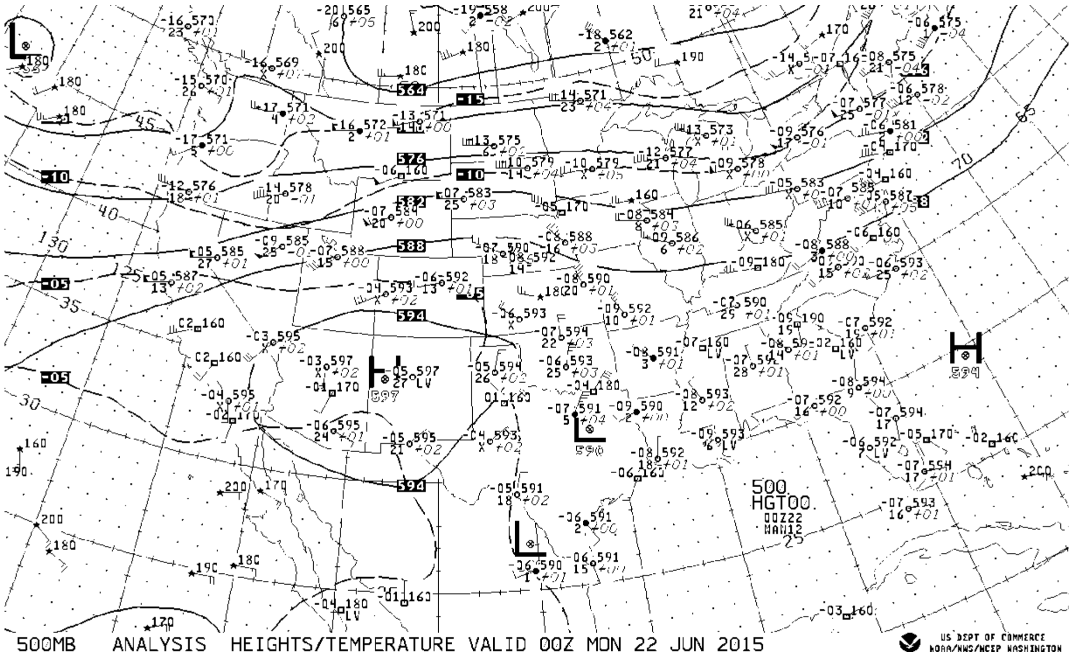

Figure 5.1.2. Synoptic upper-level map showing a high pressure system over Arizona and New Mexico. Solid lines indicate the height above sea level (in tens of meters) where pressure is 500 mb.

Inversion Interactions with Terrain

Any surface-based inversion can trap smoke close to the ground, but this can be especially problematic in valleys and other low-lying areas. Inversions in valleys cause tremendous problems for those who manage long-duration fires that continue into the night. Figure 5.1.3 shows smoke, caught under a valley inversion, being transported by down-valley winds in the early morning.

In areas of high topographic complexity, an upper-level inversion can complicate smoke management because the inversion may be close to the ground in high elevation regions. Because of this, smoke may rise well above ground at the site of a fire, but be trapped near the ground at higher elevations downwind. Alternatively, fires burning for long periods may spread to higher elevations and potentially rise above an upper-level or surface inversion. For these reasons, smoke management in areas of complex topography during weather prone to inversions requires great attention to details of terrain, wind, and vertical temperature structure.

Figure 5.1.3. Smoke flowing out of a mountain valley with down-slope winds during the early morning. (Photo by Roger Ottmar)

Mixing Height

Mixing height, also called mixing depth, is the height (above ground level) in which instability and mechanical mixing due to winds and friction create near-constant vertical distributions of moisture and particulate concentrations, and an approximately adiabatic lapse rate. Low mixing heights mean that the air is generally stagnant with very little vertical motion; pollutants usually are trapped near the ground. High mixing heights allow vertical mixing within a deep layer of the atmosphere and more efficient dispersion of pollutants. The depth of the mixed layer depends on complex interactions between the ground surface and the atmosphere. At times, it is possible to estimate the mixing height by noting the tops of cumulus clouds. Similarly, the presence of an upper-level inversion may be inferred from a layer of stratus clouds (figure 5.1.4).

Figure 5.1.4. Layer of stratus clouds. (Photo by Miriam Rorig).

Mixing heights are sometimes used to estimate how high smoke will rise, and therefore, the speed and direction of the winds that will disperse the smoke. The actual rise of a smoke plume, however, involves complex interactions between the temperature and wind profiles of the environment and the temperature and moisture characteristics of the smoke from the fire. Therefore, mixing height provides only an initial estimate of plume height. The more vigorously a fire is burning, the stronger an inversion must be to stop the air rising in the fire's smoke column. When a plume loses the intense energy source of a vigorous fire, atmospheric stability may dominate that energy and serve to prevent smoke from rising. The combination of decreased fire intensity and increased low-level atmospheric stability at night traps almost all smoke near the ground at night.

Holzworth (1972) created a climatology of mixing heights, approximating them by using equilibrium heights (box 2). Mixing heights usually are lowest late at night or early in the morning, and highest during middle to late afternoon. This daily pattern often causes smoke to concentrate in basins and valleys during the morning and disperse aloft in the afternoon. Average morning mixing heights range from about 980ft to more than 2900ft above ground level. The highest morning mixing heights occur in coastal areas that are influenced by the moist marine air and cloudiness that inhibit nighttime radiative cooling. Average afternoon mixing heights are typically higher than morning heights and vary from less than ~2,000ft to over ~4,600ft above ground level. The lowest afternoon mixing heights occur during winter and along the coasts. Mixing heights vary considerably between locations and from day-to-day. Detailed maps and statistics related to historic mixing heights in the United States are available in Ferguson *et al.* (2003).

Numerical meteorological models provide calculated depths for the planetary boundary layer (PBL), closely related to the mixing depth (box 2). These calculations are more detailed than those involved in determining thermodynamic equilibrium height, because they consider wind as well as buoyancy. While these are useful for anticipating poor ventilation conditions, there are limitations in the way PBL height is computed in numerical models, therefore model-generated PBL heights may be less reliable than a human-generated forecast.

Box 2—Mixing height, equilibrium height, and planetary boundary layer

These three terms describe related concepts. They are, however, not identical.

(Thermodynamic) equilibrium height: The height at which a parcel of air has the same temperature as its surrounding environment after rising or descending (dry or moist) adiabatically. This depends only on the temperature profile of the environment and the temperature and moisture content of the parcel.

Mixing height: The height to which pollution (or water vapor) from the ground mixes due to the combined effects of thermal buoyancy and mechanical mixing. This can be higher or lower than the equilibrium height. The key distinction is that mixing height recognizes the effects of wind and turbulence, while equilibrium height is based solely on temperature considerations. The mixed layer is the layer of the atmosphere extending from the ground up to the mixing height.

Planetary boundary layer (PBL): The layer of the atmosphere in contact with the earth. It is the layer where the turbulence and radiative processes related to the ground drive temperature and wind changes. It extends from the ground, through the mixed layer, to a capping inversion during the day. At night, it includes the stable layer that forms near the ground, as well as a residual layer up to the capping inversion. This is an idealized concept, easier to describe than to identify in reality. It is a measure predicted by numerical weather models, but is difficult to use as an estimate of how high the smoke will actually be lofted.

Diurnal Cycles

The diurnal cycle in atmospheric stability and mixing is an extremely important consideration for smoke management. Even if burning operations will be completed during the daytime, any residual smoldering or smoke near the ground will be affected by nighttime atmospheric conditions. While some aspects of the diurnal cycle appeared above, this section focuses specifically on the cycle and its importance to smoke management (figure 5.1.5).

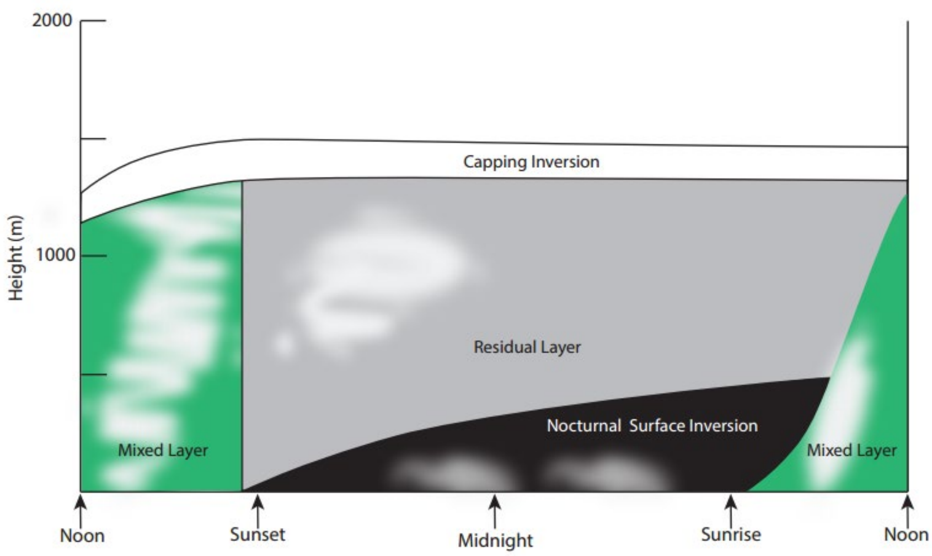

Figure 5.1.5. Illustration of the mixed layer diurnal cycle. Black indicates the nocturnal inversion, green shows the mixed layer, and the white band is the capping inversion atop the mixed layer. White puffs illustrate the distribution of smoke at various times. Smoke emitted during the day disperses through the mixed layer as it exists at that time, and may linger in the residual layer at night. Smoke emitted at night will remain in the surface inversion layer.

In the absence of strong winds (an assumption that will apply to the rest of this discussion), calm conditions and a nocturnal surface inversion characterize early morning conditions. As the sunlight heats the ground, temperatures there begin to increase. This creates a weak unstable layer near the ground, which begins to mix with air above it. Mixing and energy re-radiated from the heated ground gradually erode the inversion from the bottom up. This bottom-up process applies even in foggy situations, but can be substantially slowed.

Under moderate sunlight and with damp or heavily vegetated ground, the surface unstable layer remains shallow. When sunlight is intense and the ground heats rapidly, usually due to dry or barren ground, the unstable layer can grow to become tens to hundreds of meters deep as the stabilizing effect of turbulent mixing struggles to keep up with the destabilizing effect of surface heating. This mixing can bring stronger winds down from above, further reducing the surface heating effect. The net result is more wind at the ground, as well as more turbulence. Smoke produced by the head of the fire during the day when this is occurring will rise upward to the base of any remaining inversion. Less buoyant smoke, from flanks or smoldering, will be mixed by the turbulence and gradually fill the mixed layer downwind of the fire.

As the sun lowers toward the horizon again, surface heating will decrease and surface cooling will once again begin to create a stable surface layer. Smoke near the ground will remain there, unable to rise, but smoke that had already risen will be cut off from returning to the surface. Winds, too, become isolated above the growing inversion and diminish at the ground. Additional smoke produced during the night will remain at the ground and near the fire, as stability and low winds prevent vertical and horizontal movement, respectively.

Plume Characteristics

The key concern with smoke is whether it rises above the ground in a plume[1], or stays close to the ground. If it rises, then one needs to consider whether it is likely to return to the ground farther away. Any time the atmosphere near the ground is stable, whether or not it is so stable that an inversion is present, smoke from less intense parts of the fire will tend to remain close to the surface, producing the highest concentrations of smoke at the ground. When the atmosphere is neutrally stable or unstable, the smoke can rise freely, and disperse through a deeper layer of the atmosphere. The greater vertical dispersion reduces concentrations near the ground. When smoke rises to the base of an inversion, and there is mixing below—typical daytime conditions for burning—that mixing has the potential to bring smoke back towards the ground. This can create smoke impacts well downwind of the burn, even when there is no detectable smoke at the ground immediately downwind of the fire.

Soundings and Profiles

A sounding is a series of measurements of the temperature, humidity, pressure, and wind speed and direction in a vertical column of the atmosphere. The most common source for these measurements is weather balloons carrying radiosondes. These are small electronic instruments that transmit those measured variables back to a ground-based receiver. Radiosondes are released by the National Weather Service, twice a day, across the United States. Technology has made it possible, in recent years, for other organizations or individuals to release their own radiosondes at sites and times of particular interest. For example, incident meteorologists on wildfires often use this capability to measure atmospheric stability and winds aloft at the location of the fire. The measurements from a radiosonde,

[1] The terms *fanning*, *looping*, *lofting*, *coning*, and *fumigating* have previously been applied to smoke plumes from wildland fires. These were borrowed from urban air pollution usage, and are not particularly suited to smoke produced at the ground. These terms may be encountered in other literature; however, they will not be used here.

taken together, constitute the vertical profile of the atmosphere at that time and place—though "sounding" and "raob" (short for radiosonde observation) are also commonly used to refer to the profile. An atmospheric profile can be presented as a series of numerical values for the measured properties at various heights, or it can be presented graphically. A graphical profile is generally much easier to understand or analyze. Both graphical and text-based soundings are readily available from various sources on the internet. The following section explains graphical soundings, followed by several examples of their use in smoke management.

Because upper-air observations are not always available at the time and/or location of the fire, Pasquill (1961, 1974) developed a scheme to estimate stability of atmospheric layers from ground-based observations. While the use of this scheme has been largely replaced by more widely available ventilation forecasts calculated from weather models, the basic principle is that nighttime conditions are typically less windy and, if there are few or no clouds, more stable, making it more likely that existing smoke will be trapped near the surface.
An objective way of determining stability classification is shown in Lavdas (1986) and Lavdas (1997). For further examples see Chapter 5.2 Practical Tools: Meteorology and Simple Models for Predicting Smoke Movement and Potential Smoke Effects.

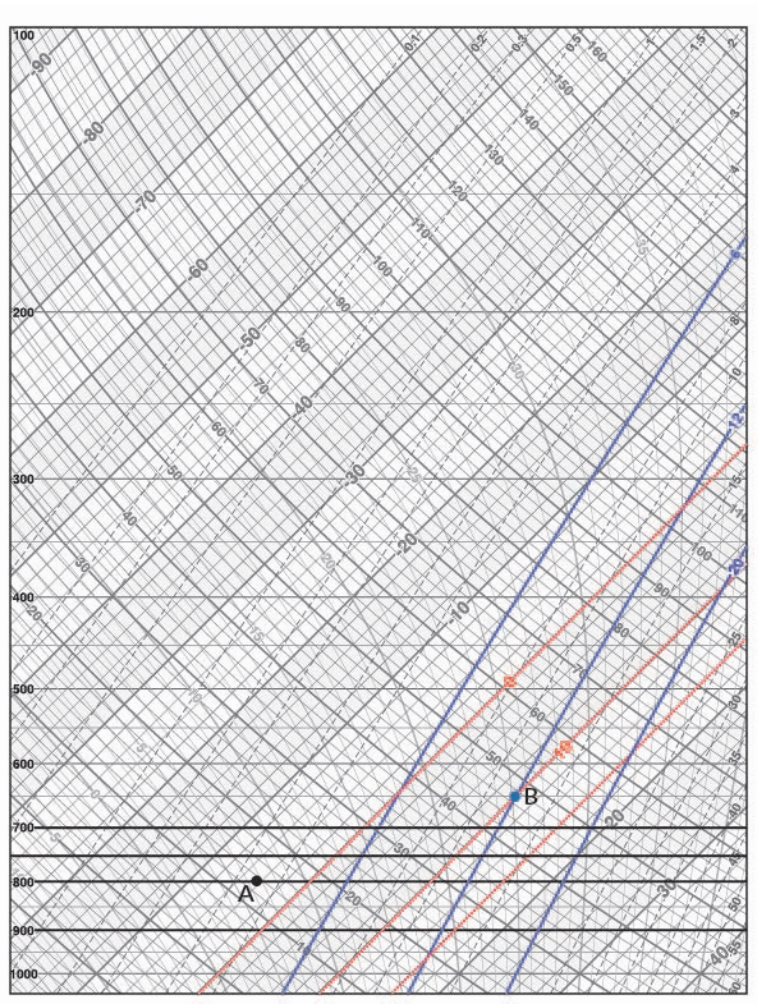

Figure 5.1.6. Skew-T chart. Horizontal lines indicate pressure levels. Solid lines running from lower left to upper right (examples in red) indicate temperature, dashed lines (examples in solid blue) indicate water vapor mixing ratio. The black dot (point A) and blue dot (point B) are examples of specific conditions, discussed in The Skew-T Diagram section.

The Skew-T Diagram

A skew-T diagram is a useful tool for quickly visualizing soundings and the vertical locations of inversions, allowing the fire practitioner to estimate how high smoke will loft. Skew-T diagrams contain a great deal of information, and require some practice to understand and use. This section breaks them down into their components and provides examples. There are several types of diagrams used to plot an atmospheric profile.

The most common in the United States is the skew-T (sometimes called skew-T log-p) diagram. This consists of grids of lines showing temperature, pressure, and moisture, with winds indicated to the side of the grid. Figure 5.1.6 shows a blank skew-T diagram.[1] The first set of lines to note on a skew-T plot are the horizontal lines representing constant pressure. Typically when data are shown on the plot, there will be physical height values noted

[1] There are no winds on this blank skew-T because there are no data plotted. See figure 5.1.7 for an example with plotted winds.

beside the pressures, or on the opposite side of the graph, to indicate the height where that pressure was measured. Some of these lines are shown in black. Lines indicating temperature run diagonally from lower left to upper right, with examples indicated in red on figure 5.1.6. When a sounding indicates the temperature at a given pressure level, that is plotted on the diagram at the intersection of the appropriate temperature line and the appropriate pressure level. Figure 5.1.6 has a black dot (point A) plotted to indicate a temperature of -5 °C at a pressure of 800 mb. The collection of measured temperatures at various pressure levels is called the temperature trace, and on a skew-T diagram appears as a zig-zag line as temperature varies with height.

One other set of lines runs lower-left to upper-right on a skew T, and those are lines of constant water vapor mixing ratio. Water vapor mixing ratio is the mass of water in a unit mass (1 kg) of air, usually expressed as grams per kilogram. It is an absolute measure of moisture in the air (unlike relative humidity, which changes with temperature). The water vapor lines on the skew-T are colored blue on figure 5.1.6, and are steeper than the temperature lines. The moisture in a sounding can be expressed as mixing ratios or as dew point temperatures. When given as mixing ratios at stated pressure levels, the intersections of the lines are used analogous to the way temperature is plotted: the value is plotted where the stated mixing ratio line intersects the stated pressure. When given as dew point temperatures at stated levels, the values are again plotted where those temperature lines intersect the matching pressure lines. The blue dot (point B) at 650 mb on figure 5.1.6 indicates air with a mixing ratio of 12 g/kg and a dew point temperature of 10 °C. Whether the data are provided as mixing ratios or dew point temperatures, the series of points at various levels are connected in a second zig-zag line on the chart, always to the left of the temperature trace. Figure 5.1.7 shows an actual sounding, with the moisture profile on the left and the temperature profile on the right.

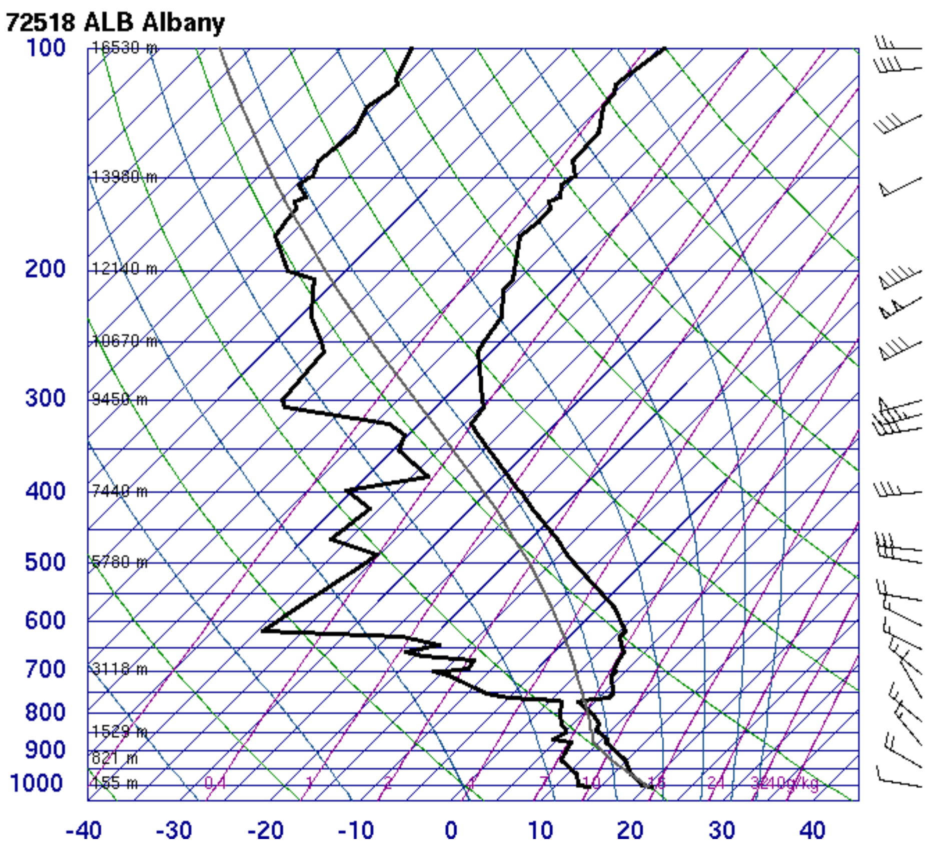

Figure 5.1.7. Example of a sounding, showing observations for 00 UTC August 28, 2015 at Albany, NY. The heavy black line on the left indicates observed dew point temperatures, the heavy black line on the right indicates observed actual air temperatures. Winds are indicated by the arrows along the right side, with the barbs pointing toward the direction from which the wind is blowing.

The next important set of lines on the skew-T diagram are called the dry adiabats, gently curving lines running from lower right to upper left (examples shown in green on figure 5.1.8). These lines indicate how the temperature of a dry parcel of air would decrease as it rises to heights with lower pressures. These lines, in other words, show the DALR defined earlier. They are labeled with the temperature an air parcel would have if it was lowered dry adiabatically to 1000 mb. In figure 5.1.8, the green square (point A) indicates a parcel of air with a temperature of 15 °C at 1000 mb. The heavy line going up to the left is the dry adiabat from here, showing how this air would cool as it rose to 800 mb, with a final temperature there of just below -2 °C, the green "X" (point B) on the figure.

The last set of lines on the skew-T diagram that are important for smoke management are the saturated adiabats. These lines rise almost vertically from the bottom of the graph, curving up to the left (examples highlighted in blue on figure 5.1.7). They represent how the temperature of a saturated parcel of air would change as it rises in the atmosphere. On figure 5.1.8, the blue square (point C) indicates a parcel of air starting at 1000 mb at 20 °C. If this air is saturated and rises to 700 mb, it will follow the blue line, up to the blue "X" (point D) where it will have a temperature of 16 °C. Note that if it had risen without saturation, along a dry adiabat, it would have a temperature of -8 °C (not shown). The difference between these temperatures indicates the heat released by condensing water vapor.

As noted earlier, winds are indicated as arrows along the right side of the skew-T plot (figure 5.1.7). The feathers, also called barbs or tails, indicate the wind speed, and the end of the arrow with the barbs indicates the direction from which the wind is blowing (tails upwind, tip downwind.) The tip of the arrow is also set at the height of the wind measurement. A half-barb indicates 2.5 m/s, a full barb is 5 m/s, and a flag is 25 m/s. The wind speed is determined by adding the barbs on a given arrow. In figure 5.1.7, the wind speed at 500 mb is 15 m/s, from the west; the winds at 800 mb are 7.5 m/s from the northwest.

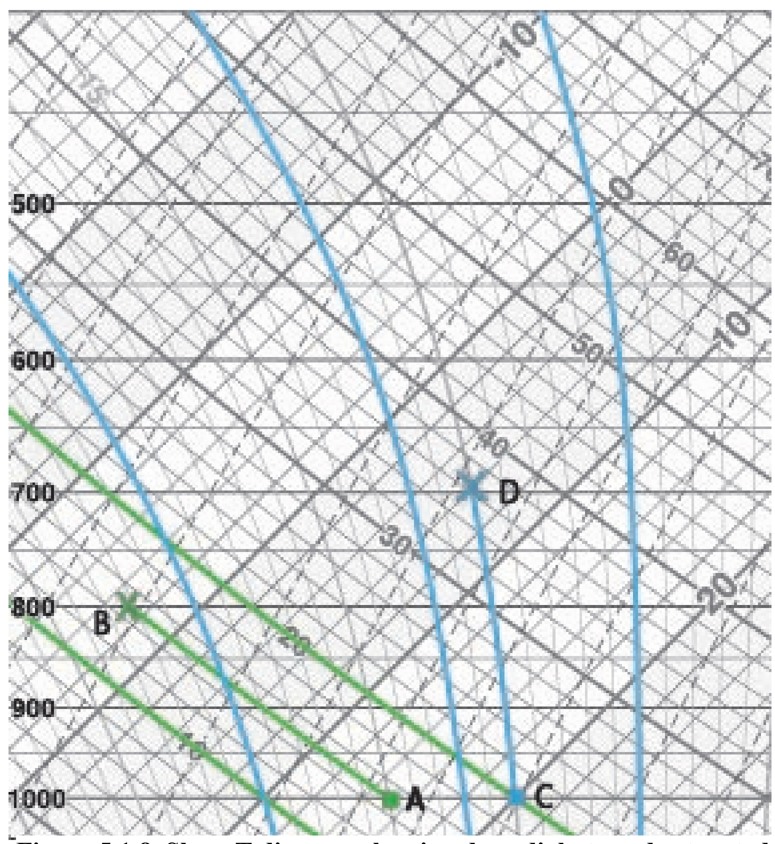

Figure 5.1.8. Skew-T diagram showing dry adiabats and saturated adiabats. Green lines from lower right to upper left indicate dry adiabatic lapse rate. Blue lines arcing upward and to the left are saturated adiabats. The short green line ending with a square (point A) and an X (point B) indicates the temperature change of a dry rising parcel, the short blue line ending with a square (point C) and an X (point D) indicates the temperature change of a saturated rising parcel.

Using a Skew-T Diagram

The power of a skew-T diagram becomes apparent when you see how easy it is to determine the stability of the atmosphere and the existence and locations of inversions (figure 5.1.9). The time standard for observations across the globe is 12 UTC. [1] Table 5.1.1 shows the conversion from UTC to local time for United States time zones. The temperature trace indicates an inversion at the ground. Surface temperature, just below 900 mb, is roughly 22°C, while the temperature at 850 mb is almost 30°C. Note that winds in this layer are very light.

There is also a very stable layer between 550 mb and 475 mb. The trace is more vertical than the dry adiabats here, but does not lean to the right with height to indicate an actual inversion. Smoke that penetrated the low level inversion would still have difficulty rising through this layer.

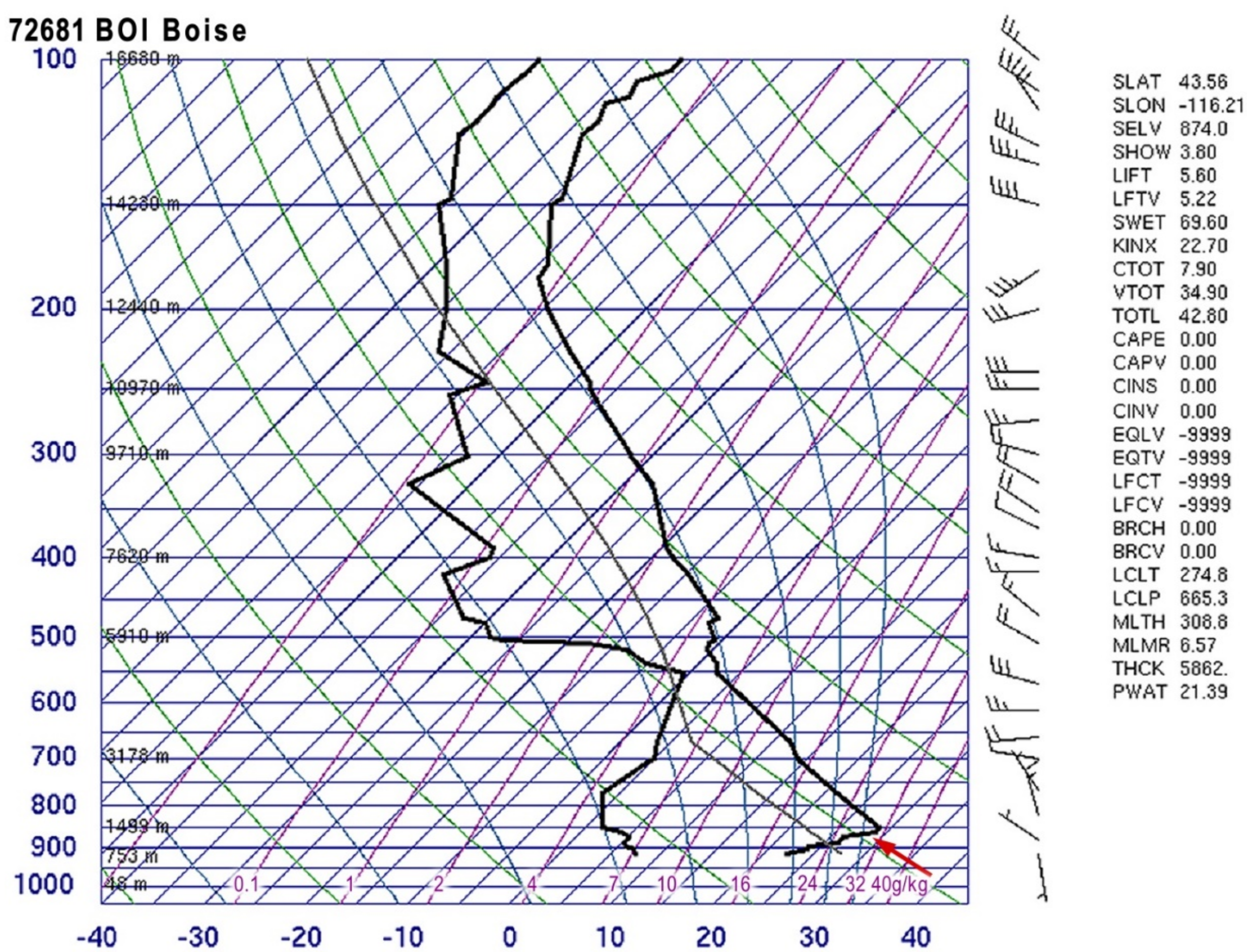

Figure 5.1.9. Observed profile for 12 UTC July 3, 2015 at Boise ID. The temperature trace—the heavy black line on the right—indicates an inversion exists at the ground (the red arrow points to the top of the ground-based inversion).

[1] UTC stands for Universal Time Coordinated, sometimes called "Zulu time."

Figure 5.1.10 shows smoke capped by a surface-based inversion (as demonstrated by the temperature trace in figure 5.1.9). Also visible is smoke pushing through the inversion, because of vigorous heat generated by the fire.

Figure 5.1.10. Example of a fire producing enough heat for the smoke plume to push through the ground-based inversion. (Photo from Sequoia and Kings Canyon National Park.)

Table 5.1.1. Conversion of Universal Time Coordinated (UTC) to local time for time zones in the United States.

Time Zone	UTC	Local Time	Diff.
Eastern Standard Time	0000	7:00 PM	-5
Eastern Daylight Time	0000	8:00 PM	-4
Central Standard Time	0000	6:00 PM	-6
Central Daylight Time	0000	7:00 PM	-5
Mountain Standard Time	0000	5:00 PM	-7
Mountain Daylight Time	0000	6:00 PM	-6
Pacific Standard Time	0000	4:00 PM	-8
Pacific Daylight Time	0000	5:00 PM	-7
Alaska Standard Time	0000	3:00 PM	-9
Alaska Daylight Time	0000	4:00 PM	-8
Hawaii-Aleutian Standard Time	0000	2:00 PM	-10

The sounding from 00 UTC August 20, 2015 at Tallahassee, FL is shown in figure 5.1.11. The small separation between the dew point and temperature traces from the ground up to 700mb indicates a humid environment. Smoke in this layer could readily turn to fog and produce visibility concerns. There is also an elevated inversion between 700 and 750mb, indicated by the rightward tilt of the temperature trace with increasing height.

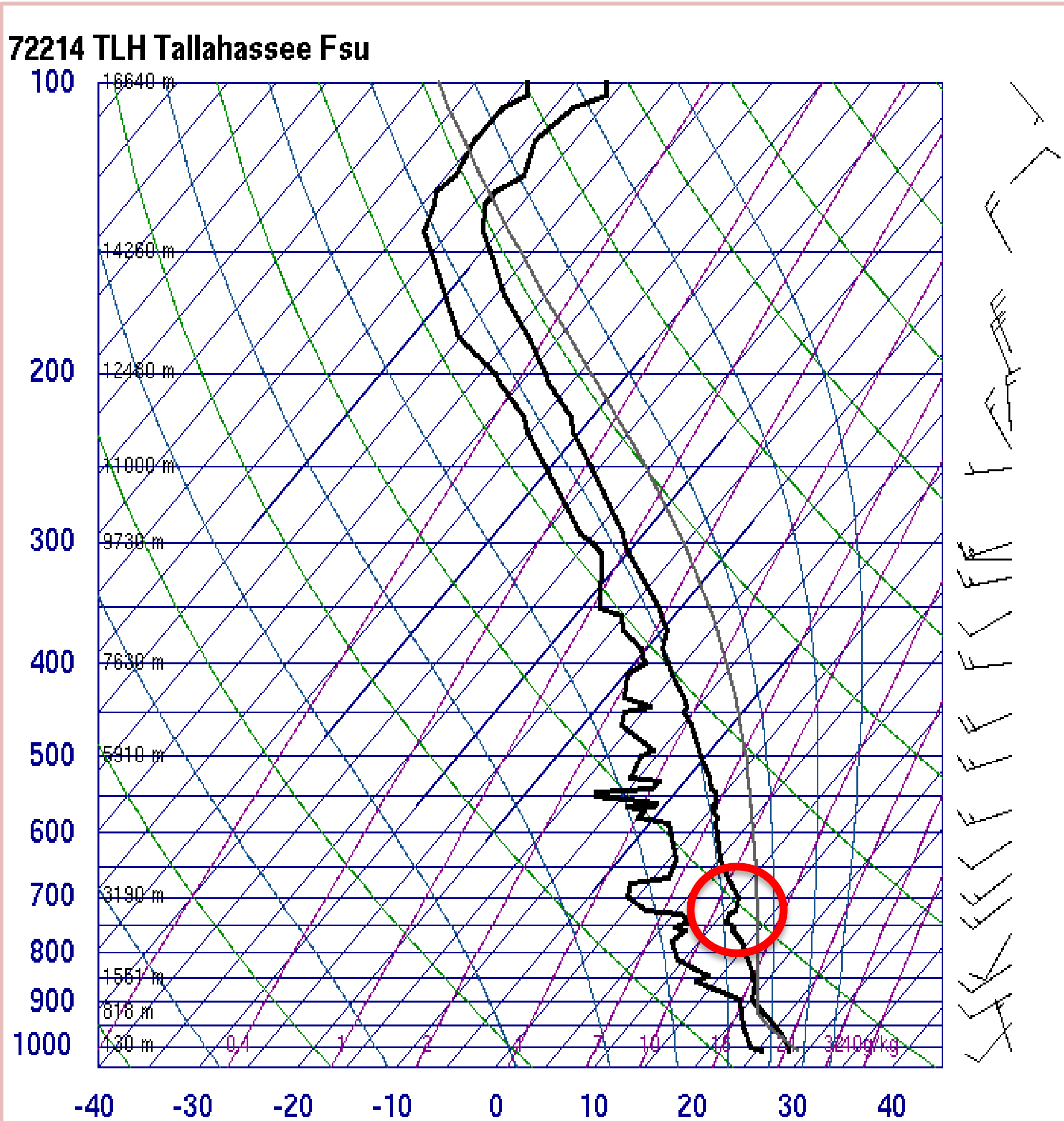

Figure 5.1.11. Observed profile for 00UTC August 20, 2015 at Tallahassee, FL. The small separation between the dew point and temperature traces from the ground up to 750mb indicates a humid environment. There is also an elevated inversion between 700 and 750mb, indicated by the rightward tilt of the temperature trace with increasing height (inside the red circle).

Figure 5.1.12 shows an example of an extremely well defined mixed layer. The temperature trace follows a dry adiabat, indicating neutral stability from the ground up to 800mb. The dew point trace lies along a line of constant mixing ratio (6.4 g/kg) showing moisture is evenly distributed through this layer. Wind, shown by the arrows on the right edge, is less uniform. It is important to recognize that the mixed layer is never perfectly uniform. There are degrees of mixing, and the atmosphere is constantly changing. Figure 5.1.13 shows smoke within a well-mixed layer under an inversion.

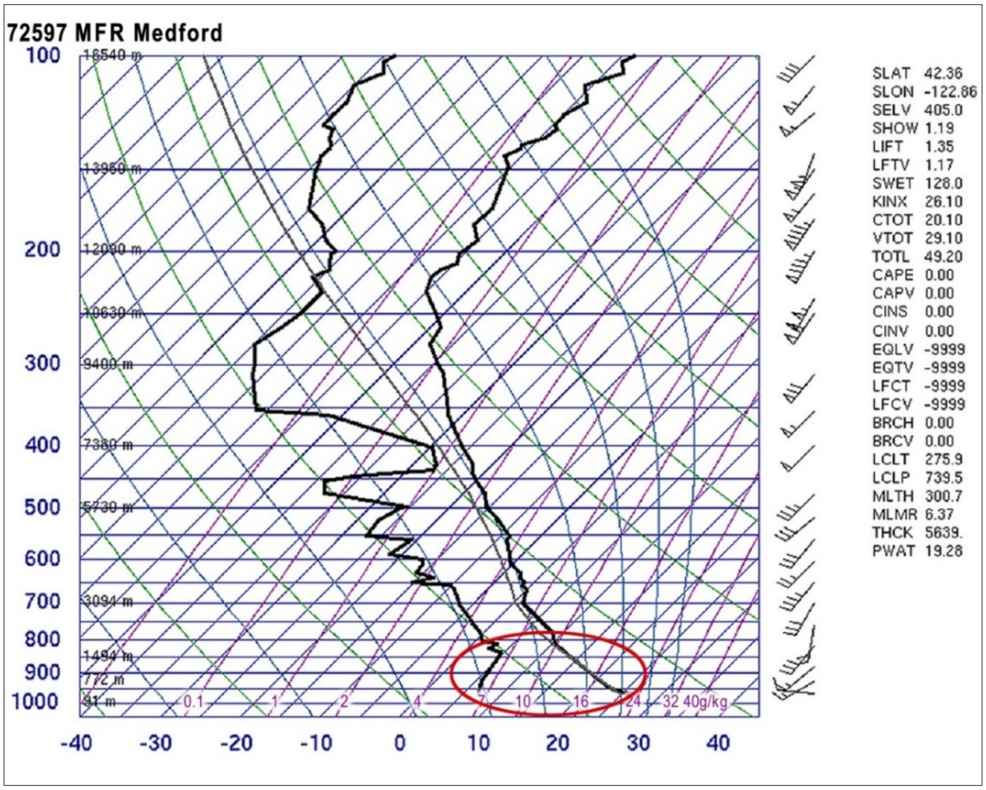

Figure 5.1.12. Observed profile for 00 UTC August 30, 2015 at Medford, OR. Below 800mb the temperature trace follows a dry adiabat, indicating a well-mixed layer with neutral stability (depicted by the temperature trace inside the red circle). The portion of the dewpoint trace inside the red circle also shows a constant mixing ratio (6.4 g/kg; the diagonal line next to and just to the right of the dewpoint trace has a mixing ratio value of 7 g/kg), indicating moisture is evenly distributed through this layer.

Figure 5.1.13. Example of smoke within a well-mixed, neutrally stable layer (as depicted by the temperature trace within the red circle in figure 5.1.12) under an inversion. (Photo from Okanogan-Wenatchee National Forest). Additional discussion of temperature fronts and their movement is found in the 'Meteorological Rules of Thumb for Smoke Management' section of Chapter 5.2.

Wind

While stability dominates the vertical movement of smoke in the fire's plume, horizontal winds dictate the transport and dispersion of the smoke across the landscape. The stronger the wind, the more scattered particles become and the less concentrated they will be. Strong winds at the surface, however, can increase fire behavior, fuel consumption and associated emission rates. Also, significant surface winds may "lay-down" a plume, keeping smoke close to the ground for long distances.

Winds are influenced by many factors, such as regional-scale (also called synoptic-scale) weather systems or local features such as terrain and canopy cover. Often these factors interact with each other. Additionally, friction with the ground causes wind to slow down. Therefore, wind speed usually increases with height, causing a smoke column to gradually bend with height as it encounters increasingly strong winds. Mixing with surrounding air, increased by strong wind, also reduces the buoyancy of the rising smoke column and contributes to its bending. This pattern is complicated in regions of complex terrain, and it is common to find strong surface winds in mountain passes, saddles, and gorges as air is squeezed and funneled through gaps or over ridges. Forest clearings also allow surface winds to accelerate because surface friction is lower in a clearing than over a forest canopy.

Because smoke from different stages or sections of a fire rises to different levels of the atmosphere, it is important to know wind speed and direction at several different heights. For example, nighttime smoldering responds to surface winds whereas daytime smoke from the ignition and flaming phase of a fire will respond to upper-level winds. Depending on the buoyancy of the smoke and stability of the atmosphere, winds that influence upper-level smoke trajectories may be from just above a forest canopy to 10,000 feet (about 3,000 meters) or higher. Because flaming combustion can create strong vertical motion, most smoke from flaming portions of a fire will be carried to at least the top of the mixed layer or an upper-level inversion height before dispersing. An intense fire that creates a strong convection column with inflow on all sides can decrease smoke concentrations near the ground. For such a fire and its smoke plume, winds at the top of the mixed layer or inversion level determine smoke trajectories and dispersion. Low intensity fires, including those that smolder, have weaker, less buoyant smoke plumes that are controlled largely by local winds and turbulence. As such, smoke dispersion and trajectories for these fires (or low intensity portions of a larger fire) depend on winds closer to the ground.

Cyclonic storms

Regional scale wind speeds and directions are largely determined by the location and strength of cyclonic storms, or cyclones (also called low pressure centers). These are broad regions of low atmospheric pressure, usually hundreds of miles in horizontal extent, that typically move from west to east. Air generally moves from high pressure to low pressure centers, but because of friction at the ground and the rotation of the earth, winds near the surface in a cyclone blow counterclockwise and slightly inward, toward the center of the low pressure center (figure 5.1.14).

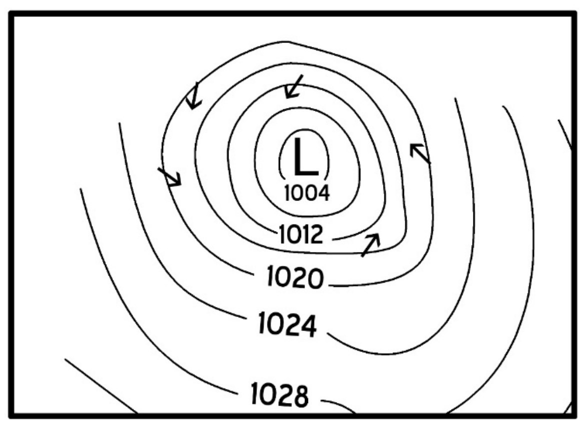

Figure 5.1.14. Schematic of surface winds associated with a typical cyclonic storm in the Northern Hemisphere. The letter, L, marks position of the surface low pressure center. Thin lines represent isobars (constant pressure contours that are labeled in millibars) at sea level. Arrows indicate the counterclockwise and inward flow of surface winds. North is at the top of the figure.

For smoke management decisions, the most important aspects of cyclones are their fronts that form and extend out from the low pressure core. A front is a boundary between two bodies of air (air masses) with contrasting properties, and is named for the conditions that it introduces. A cold front replaces warm air with colder air; a warm front replaces cold air with warmer air. A typical or ideal cyclone has a warm front extending to the east or southeast from the low center and a cold front extending to the southwest. An occluded front can sometimes form if the cold front outruns the warm front (figure 5.1.15), pushing the warm front above the surface, and leaving the unmodified cool air at ground level ahead of the occluded front.

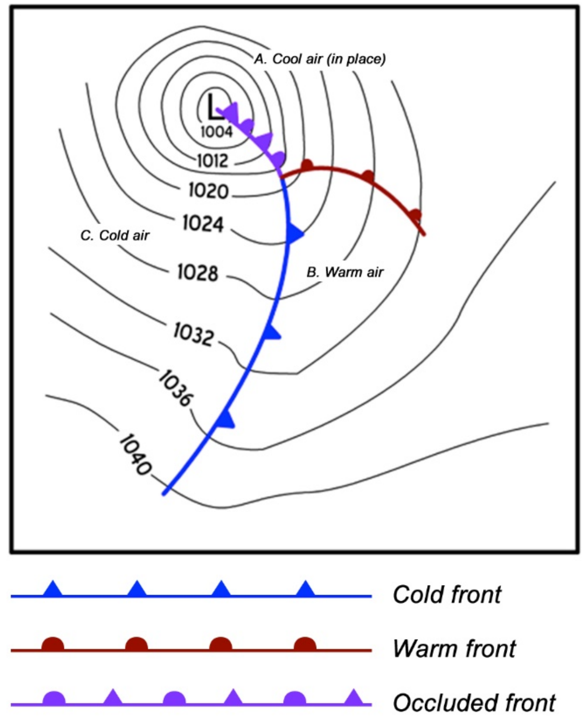

Figure 5.1.15. Schematic of temperature fronts associated with a typical cyclonic storm in the Northern Hemisphere. The letter L marks the position of the surface low pressure center. Thin lines represent isobars (constant pressure contours that are labeled in millibars) at sea level. The letter A marks the location of the cool air that is in place before any fronts pass. B marks the location of the warm air behind the warm front, and C shows the location of the cold air behind the cold front. North is at the top of the figure.

Cold fronts are typically stronger than warm fronts and have noteworthy wind effects. Winds ahead of a cold front are typically the strongest and gustiest in the entire cyclone. Passage of the cold front also brings a change in wind direction, with winds rotating clockwise as the front passes. Winds associated with a cold front tend to be stronger when the temperature contrast across the front is greater. Cold fronts also tend to be preceded by strong instability. While dispersion of smoke improves during and immediately after the cold front passes, behind the front winds weaken and stability increases. Therefore, caution must be used when planning to burn ahead of approaching cold fronts because smoke can be trapped close to the ground and disperse poorly behind the front

In contrast, warm fronts have little notable wind change. There may be a slight clockwise rotation as the warm front passes, but the more important change from a smoke management perspective is in stability. A warm front typically brings greater overall stability and an upper level inversion.

Smoke trajectories should be expected to change direction with the passage of a front, and cyclones can cause significant changes in fire behavior and resulting emission rates. Figures 5.1.14 and 5.1.15 illustrate a very simplified cyclone. In reality, the overall speed of a cyclone's passage and the number, strength, and orientation of its associated fronts are quite variable.

At higher levels of the atmosphere, friction from the ground has less influence on the wind. This causes winds in the upper atmosphere to follow lines of constant pressure instead of blowing inward toward low pressure areas or outward from high pressure areas. In the upper atmosphere the pressure pattern of a typical storm is shaped like a trough (figure 5.1.16). Upper air maps show the heights of a constant pressure surface, in tens of meters. For example, figure 5.1.16 shows that the height of the 700 millibar surface increases from 2,970 m to 3,090 m above sea level. As air follows the height contours around the trough, southwesterly upper-level winds develop ahead of the storm, becoming westerly as the storm trough passes, and northwesterly following the trough. The upper-level trough usually trails the surface low center in moving fronts, causing smoke trajectories aloft to change directions after trajectories at the surface have changed following a storm passage. For example, before a trough axis passes, the upper-level smoke will typically be carried to the northeast, and after the trough passes the upper trajectory will shift, carrying smoke to the southeast.

Thunderstorms

Thunderstorms are the result of strong convection. They are typically much smaller than cyclones, tens of miles rather than hundreds of miles in horizontal extent. They create different wind patterns than cyclonic storms do. Gusty, shifting surface winds are common at times of strong convection, often reaching miles ahead or to the side of the storm itself. Although mixing heights usually are quite high during thunderstorms, allowing for well-lofted plumes, the shifting wind directions and strong gusts can cause unpredictable smoke trajectories and fire behavior near thunderstorms. Strong downbursts within the storm can produce unpredictable gusts of wind that travel tens of miles outward from the thunder cells. These sorts of gusts have created dangerous fire behavior that has been the cause of firefighter fatalities.

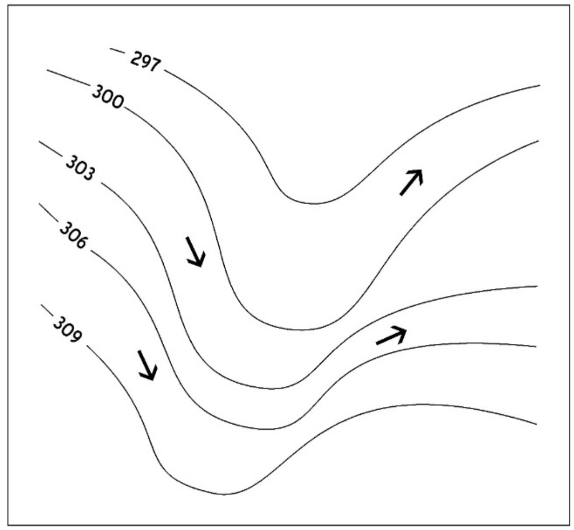

Figure 5.1.16. Schematic of upper-level (700 mb) winds associated with a typical stormy trough pattern in the Northern Hemisphere. The lines represent pressure height contours that are labeled in tens of meters (e.g., 306 represents 3060 meters and 309 represents 3090 meters). The arrows depict wind direction at those levels. South to southwest upper-level winds are common ahead of a 700mb trough, westerly winds are common as the trough passes, and northwesterly winds are common following an upper-level trough. North is at the top of the figure.

Diurnal winds

In the absence of strong pressure systems, fronts, or thunderstorms, diurnal wind patterns dominate trajectories of smoke near the ground. Diurnal wind patterns are caused by radiative cooling at night and solar heating during the day and the different thermal properties of land and sea surfaces that cause them to heat and cool at different rates. The differential heating causes changes in local surface pressure patterns that control air movement. Slope winds and sea and lake breezes, all of which are common in wildland smoke management situations, are typical diurnal patterns.

Downslope and upslope winds are caused by the same mechanisms that cause valley and basin inversions. When cold air from radiation cooling at night drains into a valley or basin, it causes a downslope wind. The cold air, being denser than surrounding air, usually hugs the terrain in such a way that smoke following a drainage wind will flow across the contours of the terrain. During the day, heated air from the surface rises, causing upslope winds. Because daytime heating causes more turbulence than nighttime cooling, daytime winds do not follow terrain as readily as nighttime winds, causing thermally-induced upslope winds to be less noticeable than downslope winds.

Downslope winds at night are notorious for carrying smoke into towns and across roadways (e.g., Achtemeier *et al.* 1998), especially where roads and bridges cross stream channels or when towns are located in valleys, basins, or near outwash plains. Downslope winds are most likely to occur when skies are clear and ambient winds are nearly calm. The speed and duration of a downslope wind is related to the strength of its associated valley inversion. Downslope winds usually begin around sunset and persist until shortly after sunrise.

Sea and lake breezes (so named because they occur near the shore of oceans and large lakes) usually occur during the afternoon when land surfaces have had a chance to heat sufficiently. The heated air rises, as if lifting the overlying column of air. This causes a region of low pressure at the surface. Because land heats more rapidly than water, the differential heating causes a pressure gradient to form. Relatively cool air remaining over a lake or ocean will flow into the low pressure formed over heated land surfaces. This cool air arrives as a front, changing temperature, humidity and wind direction as it moves inland. The sea or lake breeze not only can change smoke trajectories but incoming cool air can cause surface-based inversions that trap smoke near the ground. Strong sea breezes can bend plumes horizontally, increasing smoke concentrations near the ground.

Terrain-influenced wind

In the absence of differential diurnal heating, surface winds can also be strongly influenced by small undulations in terrain that channel, block, or accelerate air as it tries to move around or over features. For example, if ridgetop-level winds are oriented perpendicular to a terrain barrier (such as a mountain range) surface winds on the lee side of the barrier may be light and variable. They may even blow opposite to the winds at the ridge top. It is possible for strong downslope winds (such as "foehn winds" or Santa Ana winds) to develop, or for winds to be channeled through gaps in a mountain range, resulting in high wind speeds and turbulent conditions on the lee side of terrain barriers. Upper level winds oriented in the same direction as a valley can enhance or cancel up-valley or down-valley winds, depending on whether the upper level wind direction is aligned with or opposite to that of the valley winds. Upper level cross-valley winds can interact in unpredictable ways with valley winds.

The combination of wind and atmospheric stability determines whether smoke will collect on the windward side of a terrain barrier, move up, over and away, or traverse the barrier and accumulate on the leeward side. Weak winds and a stable atmosphere allow the terrain barrier to block smoke on the windward side. Strong winds in a stable atmosphere allow smoke to cross the terrain barrier and accumulate in leeward valleys and basins. Winds in an unstable atmosphere also allow smoke to cross the terrain barrier and be transported farther downwind. The height, steepness, and orientation of the terrain to the wind direction determine how strong the wind or unstable the atmosphere must be to influence smoke trajectories.

Small-scale undulations in topography can also affect smoke trajectories, especially at night when atmospheric stability keeps smoke close to the ground. Valley or drainage winds can occur under relatively stable conditions, with winds carrying smoke up-drainage during afternoon hours, and down-drainage during night and early morning hours. These may also be referred to as "canyon winds." Gentle saddles in ridges may offer outlets for smoke from a valley. Small streambeds can collect and transport smoke even with only shallow or weak downslope winds. A simple band of trees or brush may provide enough of a barrier to block or deflect smoke. In these circumstances smoke will tend to accumulate where fog preferentially forms in the absence of smoke. As the wildland urban interface becomes increasingly complex, the role of subtle topographic influences and surface structures becomes increasingly important.

Winds generated by these different-scaled phenomena (cyclonic storms, thunderstorms, diurnal winds, etc.) can interact with each other to affect smoke dispersion. Santa Ana winds in the Los Angeles Basin in southern California provide an example of this type of interaction. Winds around high pressure centers (also called anti-cyclones) blow in a clockwise direction deflected outward from the center of the high. When the high is located over the Great Basin (in the area around Nevada and Utah), winds blow from the NE toward southern California (figure 5.1.17a). As the air moves toward the SW it is channeled through a gap between two mountain ranges (figure 5.1.17b). The regional (synoptic) scale NE winds are channeled through the local scale terrain, resulting in increased surface wind speeds. The Santa Ana winds can usually occur from autumn through spring, and result in active fire behavior and winds that carry smoke offshore.

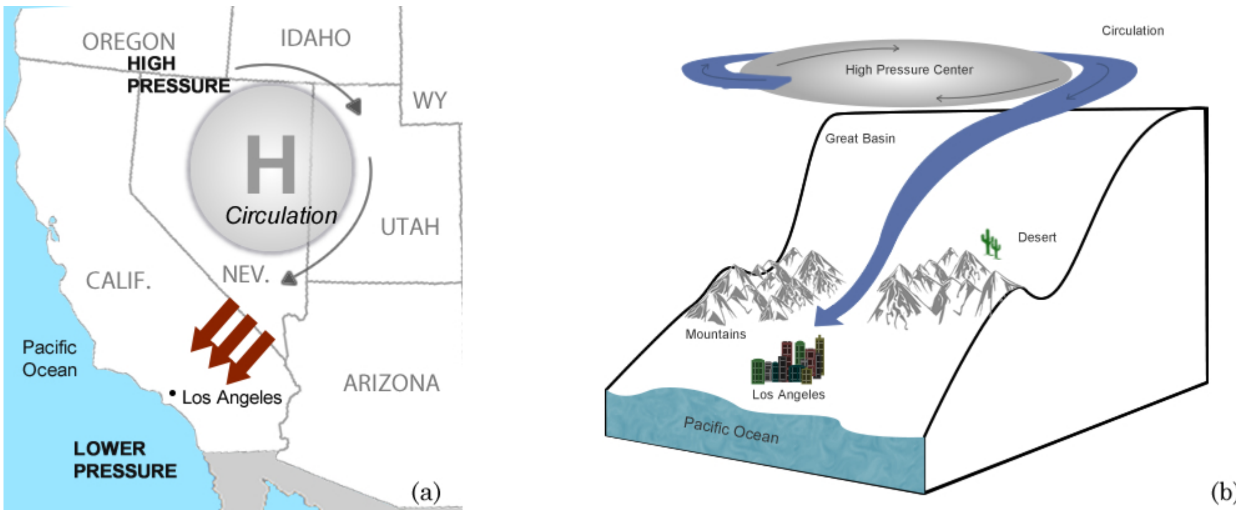

Figure 5.1.17. (a) High pressure center over the Great Basin resulting in a northeasterly wind flow into southern California (b). Northeast winds from a high pressure center over the Great Basin are channeled through gaps in the southern California mountains, generating Santa Ana winds, resulting in increased wind speeds and offshore flow.

Role of inversions on wind

Temperature inversions strongly influence wind direction and speed. Under many inversions there is little or no transport wind and smoke tends to spread out in all directions. Some inversions, such as those associated with sea breezes and valley inversions, may have significant surface wind but in a different direction to winds aloft. In these cases, smoke under the inversion may be transported in one direction while lofted smoke may move in the opposite direction. Winds above an inversion can be rather strong because the inversion separates air aloft from friction at the ground.

Wind observations

Because surface winds are strongly influenced by terrain, vegetation cover, obstacles and water bodies, it is important to know where a surface wind observation is taken in relation to the burn site. For example, observations from a bare slope near the ridgeline would not be very useful in predicting winds affecting surface smoke trajectories if most of the burn area is on a forested slope or in a valley, even if the two sites are very close. Also, if a burn site is in an east-west oriented valley and the nearest observation is in a north-south oriented valley, observed winds can be 90° different from those influencing the fire and its related smoke. Sometimes, a nearby Remote Automated Weather Station (RAWS) will be less indicative of burn-site conditions than one that is farther away if the distant station is in a location that better matches terrain at the burn site.

There are four principle sources of surface wind observations: (1) on-site measurements with a portable RAWS or hand-held anemometer, (2) observations that estimate winds using the Beaufort wind scale[1] or wind sock[2], (3) local measurements with a standard RAWS, and (4) measurements from National Weather Service (NWS) observing stations. Because the surroundings of weather stations vary, from small clearings on forested slopes to open fields, and because different types of anemometers are used and mounted at different heights, wind data is very difficult to compare between one site and another. For example, observations from NWS sites use 2-minute averaged wind speed and direction, and also include gusts (the maximum instantaneous speed in the past 10 minutes) while RAWS sites use 10-minute averaged wind speed and direction. Anemometer heights at RAWS sites are sometimes different than those at NWS sites, and anemometers at RAWS sites are often affected by terrain and vegetation, while those at NWS sites are located in large clearings. Therefore, it is useful to become familiar with measurements and observations from reliable sites, and to understand local effects that make data from each site unique. Also, smoke near the ground can be transported by winds that are too light to spin the cups or propeller of an anemometer or turn its tail. Light and variable wind measurements are the result of an anemometer responding to very light winds that have a preferred direction, often influenced by surrounding topography or land use.

Because free-air winds are above the influence of topography, it is often possible to use a radiosonde observation from some point well away from the burn site to estimate upper level smoke trajectories. Also, surface RAWS mounted on the tops of ridges or mountains may compare well with free-air winds at a similar elevation. Another method to measure upper-level winds is with a *pibal* (pilot balloon) and theodolite. The helium-filled pibal is released and then visually tracked with the theodolite to provide a vertical profile of wind speed and direction. While pibals use old technology and do not provide information on vertical moisture and stability profiles (as do radiosondes), they are a simpler alternative to radiosondes and remain a useful smoke management tool. This equipment is not always readily available, however. If clouds are visible, upper-level wind directions can be estimated by their movement relative to the ground. High clouds look fibrous or bright white. Because the base of high clouds ranges between about 16,000 and 45,000 feet (5 km and 13 km), their movement can indicate wind at those levels. Midlevel clouds may have shades of gray or bulbous edges with bases ranging from about 6,000 to 24,000 feet (2 km to 7 km). Midlevel clouds often have a stratiform or layered appearance, which may indicate the presence of an inversion. Therefore, movement of these types of clouds may closely approximate steering winds for a rising smoke plume.

If a prescribed fire is planned for an area with unique concerns (such as proximity to populated or smoke-sensitive receptor areas), an incident meteorologist (IMET) or an air resource advisor (ARA) can be requested to help with localized weather observations and smoke forecasts. The IMET can release pibals or radiosondes to obtain upper-level winds, and their expertise can be very helpful in anticipating and predicting drainage flows and pooling of smoke in areas of complex terrain.

In addition to observations, it is becoming increasingly common to have access to data from wind models. These data do not provide the detail of a point observation in the same way that an individual site measurement does, but they do provide a broad view of wind patterns over the landscape. Standard analyses from the NWS use models to interpolate between observations. These products help illustrate upper-level wind patterns and typically are available for 850mb, 700mb, and 500mb heights, either from a state, federal, or private meteorological service, or a variety of websites. For surface winds, standard

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[1] The Beaufort wind scale estimates wind speed using observations of wind-effects in the landscape. For example, wind speeds of 1.6 to 3.3 m/s (4 to 7 mph) will cause leaves to rustle slightly. If leaves move around vigorously then the wind speed is approximately 3.4 to 5.4 m/s (8 to 12 mph). The Beaufort wind scale can be found at http://www.crh.noaa.gov/images/iwx/publications/Beaufort_Wind_Chart.pdf (or by internet search).

[2] Wind socks continue to be used at airports and are useful if trying to monitor winds on a nearby ridge that is visible.

NWS analyses are helpful in regions of flat or gently rolling terrain but meteorological models typically are needed to resolve surface wind fields in regions of complex topography. Local universities, research labs, state offices, and consortia of local, state, and federal agencies throughout the country are running mesoscale models (e.g., the Weather Research and Forecasting Model [WRF] [Skamarock *et al.* 2005], and the older fifth-generation NCAR/Penn State Mesoscale Model [MM5] [Grell *et al.* 1994]), producing wind maps with less than 4-km horizontal spacing. Predictions from these models usually can be found on a website through the local NWS forecast office, university, state regulator, or regional smoke manager. Also, many smoke dispersion models include wind models to generate surface winds at very fine spatial resolutions (less than 1-km grid spacing) from information on surface and upper-air observations or data from coarser meteorological models. Other "stand-alone" wind models (for example, WindNinja [Forthofer *et al.* 2011]) use fine-scale terrain data to generate a very-fine scale surface wind field for areas of complex terrain.

Atmospheric Moisture

Particles in the air, from smoke and other sources, may act as condensation nuclei causing water droplets to form. This can happen even if the RH is less than 100 percent. If smoke is added to an already humid environment, visibility can be severely degraded. Often a deadly combination occurs during the darkness of night when smoldering smoke drains down-valley, combined with high humidity in the cold air under a valley inversion, resulting in near-zero visibility. The effect can be fatal, especially along transportation corridors (Achtemeier *et al.* 1998).

Favorable conditions for fog occur when the dewpoint temperature is within a few degrees of the dry bulb temperature, wind is light or calm, and the soil is moist. Fog is most common at night when temperatures often drop to near the dew point and winds are weak. Common places for fog to form are over lakes and streams and in the vicinity of bogs and marshes.

There are times when atmospheric moisture can improve visibility, however. Smoke particles can adhere to rain droplets, causing them to be carried with the rain as it falls. This "scavenging" effect removes smoke particles out of the atmosphere, reducing smoke concentrations and improving visibility.

Weather Forecasts

Weather forecasts are typically produced twice each day and become available within 3 to 6 hours after 0000UTC and 1200UTC observations are complete. This is because predictive models require data from the 0000UTC and 1200UTC upper-air observations and a few hours of run-time on a super computer (with faster computers currently available, two additional forecasts, at 0600UTC and 1800UTC, are often produced). Predictive, or prognostic, models (progs) form the basis of most forecast products. For example, the first forecast of the day should be available between 0700 and 1000 local daylight time from Anchorage and between 1,100 to 1,400 local daylight time from Miami (subtract an hour if daylight savings time is not in effect). Earlier forecasts, or forecasts updated throughout the day, are possible if the most recently available upper-air observations and prognostic model results are combined with updated surface observations. While public forecasts issued by the NWS and the media are useful, they typically lack the detail needed for smoke management. For this reason, spot-weather forecasts may be requested from state, federal, or private weather services that provide predictions of critical variables that influence smoke at specific times and locations.

Even though there are more and more numerical guidance tools, weather forecasting is still an art, especially in places with few observations or where there are complex local interactions with terrain, water bodies, and vegetation cover. The primary source of smoke weather forecasts remains the NWS. Their rigorous training, fire weather program, and state-of-the art equipment and analysis tools help maintain a unique expertise. All NWS forecast office websites include a fire weather forecast page, most of which include special smoke management forecasts or fire weather planning forecasts that contain smoke dispersion indices. In addition to NWS forecasters, highly-skilled meteorologists can be found in any one of the many states which have a smoke management program. Also, the number of interagency fire weather offices and private meteorological services is growing and can provide reliable forecast products specifically designed for managing smoke. Whatever the source of a forecast, it is helpful to combine the forecast with your own general understanding of weather conditions by reviewing the many satellite pictures, current observation summaries, on-site field observations, and prognostic model results now available on the internet. In this way, apparent trends and local influences can be determined and quick changes in smoke management strategy can be made. For example, increasing afternoon cloudiness in the forecast may have indicated an approaching storm predicted for the following morning. If clouds did not increase when predicted, however, it could be suspected that the storm has been delayed or it was diverted elsewhere. A check with the forecaster or updated satellite picture may confirm the suspicion and the management plan may be altered.

Because the atmosphere behaves chaotically, the accuracy of a weather forecast improves the closer you get to your planned burn. For example, it is possible to obtain an indication of storminess within 30 to 90 days in advance of a burn. A storm passage, however, may not be predicted until about 14 days in advance, and with about 2 days accuracy. Within 5 days, 1-day accuracy on storm passage may be possible. Increasing accuracy should be expected within 48 hours, and the timing of storm passage within 1/2 hour may be possible with 12 hours advance notice. Spot weather forecasts are usually requested the day of the burn, but usually are available 24 hours in advance of a scheduled burn. Each NWS office provides online forms for requesting spot forecasts.

Our increasing knowledge of air-sea interactions is making it possible to predict some general weather patterns several months in advance based on historical impacts. For example, weather in some (but not all) regions of the country responds to the El Niño/Southern Oscillation (ENSO). Precipitation and temperature during winter and spring are very strongly related to ENSO. For example, drier than normal conditions over the course of a winter season may be associated with El Niño events; however, this doesn't mean there will be drought conditions during every El Niño event, and large rainstorms are possible. Relating the key factors for smoke management such as wind, mixing height, and stability to ENSO is more difficult, especially during summer. Nevertheless, an ENSO-based seasonal prediction gives prescribed fire practitioners an idea of general weather conditions to be expected, thereby helping prioritize scheduled burns and decide if marginal days or weekends early in the burning season should be used or whether a more optimum season will ensue.

Climate

Climate simply describes the weather patterns that prevail in an area over many years. Understanding climate patterns can help develop long-range smoke management plans or adapt short-range plans. For example, afternoon mixing heights in most coastal regions of the United States are typically lower than those in the interior because moist marine air is relatively stable. This means that there may be fewer days with optimum dispersion along the coast than interior. It usually is windier along the coast, however, and burns might be scheduled in the early morning if offshore breezes are preferred to reduce smoke effects on cities and towns.

It is possible to infer climate just by local proximity to oceans, lakes, rivers, and mountains, as depicted by the Koppen climate classification (Peel *et al.* 2007). Also, vegetation cover can give an indication of climate. Desert landscapes, with a lot of bare soil or sand, heat and cool rapidly, causing them typically to have high daytime mixing heights and very low nighttime mixing heights. Natural landscapes of lush green forests tend to absorb sunlight while releasing moisture, both of which modify heating and cooling of the air close to the ground surface. This can reduce daytime mixing heights and keep nighttime heights relatively high in comparison to drier landscapes. Also, the structure of trees, where the direction of branches or flagging point away from prevailing wind directions often indicates persistent high winds.

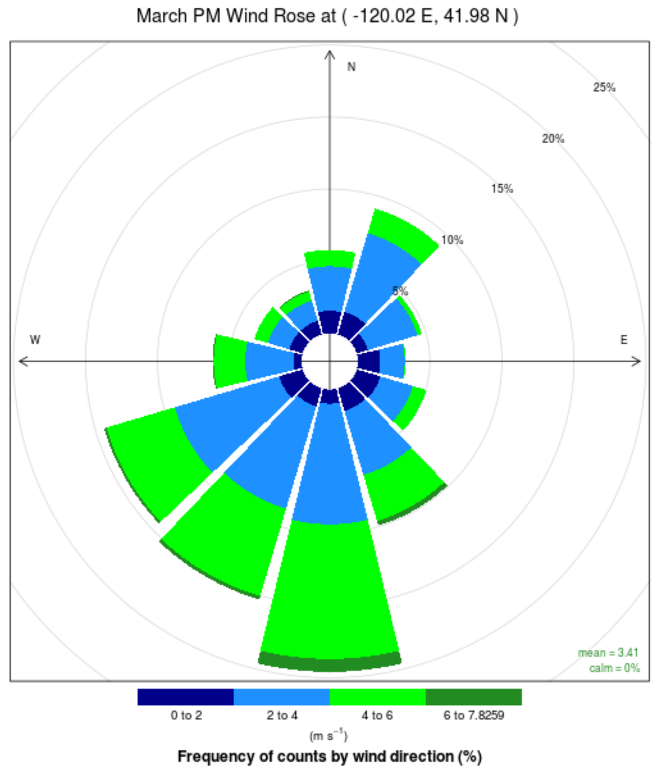

Figure 5.1.18. Wind rose summarizing 30 years of wind speed and direction data for afternoon hours in March, at 41.98N, 120.02W from VCIS.

Quantitative summaries of climate can be obtained from the state climate office or regional climate center, many of which also maintain informative internet sites and can be reached through the National Climatic Data Center (NCDC) (www.ncdc.noaa.gov). It is very common to find temperature and precipitation data in climate summaries. Monthly or annual averages or extremes are readily available, while climate summaries of daily data are just beginning to emerge. For example, a climate database (Ventilation Climate Information System [VCIS][1] Ferguson *et al.* 2003) provides information on twice-daily variations in surface wind, mixing height, and ventilation index over a 30-year period. The wind speed and direction are presented as "wind roses." Wind roses (figure 5.1.18) are polar plots that simultaneously display wind speed, wind direction, and relative frequency. Other features common to wind roses are:

- The percentage of calm winds (<1 m/s) is shown in the lower right corner of each wind rose graph.
- Wind speeds are represented by line thickness and color. Higher wind speeds are indicated by thicker lines and are light to dark green in color.
- The direction that the wind comes from is represented by the angle in which a ray radiates out from the center of the plot. Straight up indicates winds coming from true north.
- Wind frequency is indicated by the length of each line segment of a given thickness and direction. The numerical labels on the concentric circles provide a scale for each graph.

There are year-to-year variations in climate (e.g., ENSO) so at least 10 years of weather data are needed to obtain a preliminary view of climate in a particular area. There also are natural "decadal" patterns in climate that last from 7 to 20 years. Therefore, it is appropriate to analyze 30 to 50 years of weather observation data for any reliable climate summary.

[1] Available online at www.smoke.airfire.org/vcis.

Summary

Managing smoke—from single burns or multiple burns occurring simultaneously—in ways that prevent serious effects on smoke-sensitive areas requires knowledge of the weather conditions that will affect smoke emissions, trajectories, and dispersion. Not only is it necessary to anticipate the weather ahead of time through the use of climatology and forecasts, but it also is useful to monitor conditions before and during the burn with regional forecasts, local forecasts, and on-site observations. On-site observations are helpful because air movement, and therefore smoke movement, is influenced by subtle variations in terrain and vegetation cover, and distance to large bodies of water, which off-site observations usually cannot capture. Also, forecasts are not always accurate and last-minute changes in a burn or smoke management plan may be needed. To gain more insight into the physical process of weather in wildlands and its effect on biomass fires, refer to what is commonly called the fire weather handbook (Schroeder and Buck 1970).

In using weather observations, forecasts, and climate summaries effectively for smoke management there are three general guidelines: (1) become familiar with local terrain features that influence weather patterns, (2) develop a dialogue with a reliable local weather forecaster, and (3) ask for and use climate summaries of wind and mixing height. By combining your knowledge of local weather effects, trust and communication with an experienced forecaster, and understanding of climate patterns, it is possible to fine-tune or update forecasts to meet your specific smoke management goals.

English Equivalents—

When you know:	Multiply by:	To get:
Millibars (mb)	0.02953	Inches of mercury
Meters (m)	3.28	Feet (ft)
Kilometers (km)	0.621	Miles
Hectares (ha)	2.47	Acres
Meters per sec (m/s)	2.24	Miles per hour
Meters per sec (m/s)	1.94	Knots

List of Abbreviations

DALR	Dry diabatic lapse rate
ENSO	El Niño-Southern Oscillation
IMET	Incident meteorologist
MALR	Moist (or saturated) adiabatic lapse rate
MM5	Fifth-Generation NCAR / Penn State Mesoscale Model
NCDC	National Climatic Data Center
NWS	National Weather Service
PBL	Planetary boundary layer
Pibal	Pilot balloon
Raob	Radiosonde observation

RAWS Remote automated weather station

SALR Saturated (or moist) adiabatic lapse rate

UTC Universal Time Coordinated

WRF Weather Research and Forecasting Model

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5.2 Practical Tools: Meteorology and Simple Models for Predicting Smoke Movement and Potential Smoke Effects

Chuck Maxwell, Scott Goodrick and Gary Curcio

This chapter describes the practical use of, and access to, common meteorological tools and indices for smoke management decision making. Tools used for predicting smoke movement and potential smoke effects are essentially an attempt to translate the complex physics of plume dynamics and particulate dispersion into relatively simple displays or indices suitable for decision support. As such, all have strengths and weaknesses in accuracy and application and it is rare that any one tool by itself will adequately inform smoke management decisions. Experience with the various tools will help fire managers better understand each approach, and how well it performs in a local area and assists with local decisions. While Chapter 5.1 of this guide focuses on the general principles of meteorology, this chapter focuses on using meteorological information and tools to aid in day-to-day smoke management decisions.

NOTE: It's important to stay in touch with forecasters on the accuracy and outcomes of their forecast products. This aids in calibrating and refining future forecasts to better address your needs and improve performance in the local area.

Common Smoke Movement and Impact Tools

In this chapter common tools that help predict smoke effects, dispersion, and trajectory will be discussed. These include:

- Ventilation Index (VI)
- Turner Stability Index
- Lavdas Atmospheric Dispersion Index (ADI)
- Low Visibility Occurrence Risk Index (LVORI)
- Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)
- Estimated Smoldering Potential (ESP)
- Superfog Potential Table (SFP)
- Planned Burn-Piedmont Surface Dispersion Model (PBP)

Units & Thresholds: Be aware that units of measure for the indices may vary from state to state. Acceptable thresholds for burning and smoke management suggested in the tools may not apply in every state.

Ventilation Index

The ventilation index (VI) (sometimes referred to as the clearing index) is a simple approximation of smoke dispersion potential obtained by multiplying the mixing height by the transport wind speed (Ferguson *et al.* 2003).

Ventilation Index = mixing height x transport wind speed

Where

Ventilation index is expressed in knot-feet (kt-ft) or meters squared per second (m^2/s),

Mixing height is expressed in feet or meters (ft or m),

Transport wind speed is expressed in knots or meters per second (kts or m/s).

Mixing height is the altitude above ground level (AGL) of the top of the mixing layer, and the transport wind is the average of winds within the mixing layer; calculation of the VI becomes simple given these inputs. For example, with the top of the mixing layer at 2000 feet AGL and the average wind speed within the mixing layer at 12 kts; VI = 2000 ft x 12 kts = 24,000 kt-ft. Note that winds above the mixing layer do not factor into the VI (figure 5.2.1).

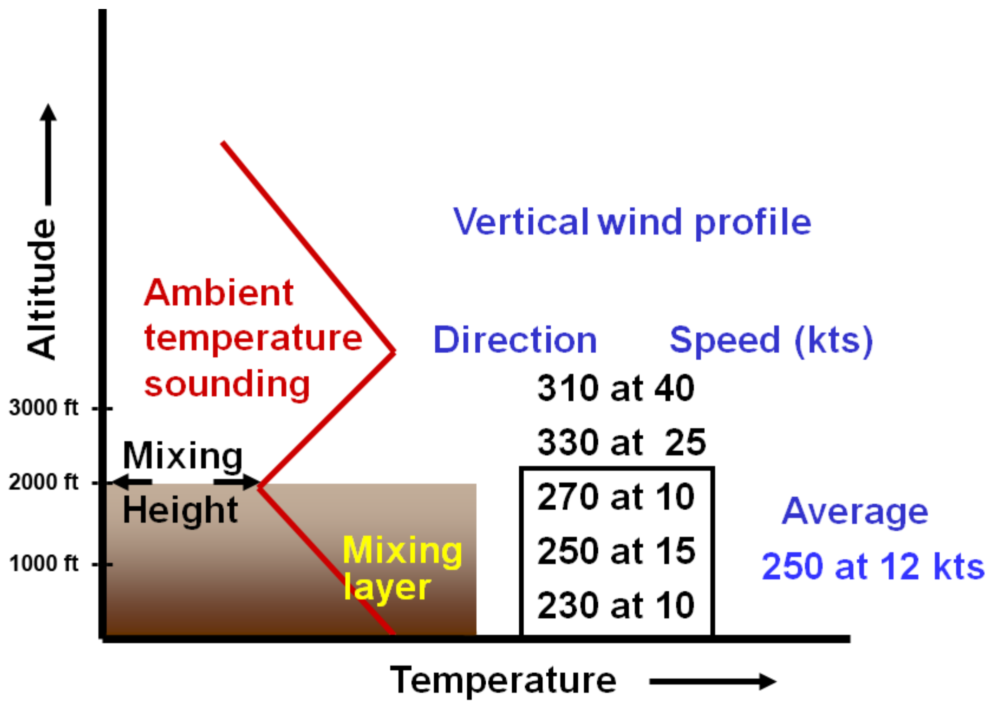

Figure 5.2.1. A vertical wind profile showing components of the atmosphere used to calculate ventilation index (VI) including mixing height and average wind speed within the mixing layer. Note that wind direction, wind speed above the mixing layer, and temperature are not used to calculate VI.

Information similar to that shown in figure 5.2.1 is commonly available in meteorological observations and forecasts, making it possible for burn boss validation of VI forecasts through visual observation of smoke dispersion. Ventilation index can also be found in the fire weather forecasts available from the National Weather Service (NWS).

High VI values indicate better smoke dispersion potential and possible clearing events, while low values indicate the potential for smoke to concentrate near the fire and local area. Ventilation index values are often compared to a lookup table (usually in kt-ft or m²/s), and translated into an adjective rating category (Good, Poor, etc.) for communication and interpretation. In applying this tool it is critical to note that the VI calculation method and adjective rating categories assigned to VI value ranges can vary substantially in different locations, potentially making a 'Good' rating into 'Poor' on the other side of a state border or between forecasting offices (table 5.2.1). It is critical to gain experience with VI in a particular location before making management decisions based on its value. Fire weather annual operating plans are a good resource for this purpose; these are annual agreements between the NWS offices and the fire/land management agencies in a respective state. They outline roles, responsibilities, expectations, performance and describe specific products that make up fire weather forecasting for an area.

Table 5.2.1. Example of the variability of ventilation index classification ranges used throughout the United States. It is critical to get localized information on ventilation index from a local National Weather Service forecast office.

	State name and index names					
	New Mexico	North Carolina	Oklahoma	Oregon	Utah	Wisconsin
Ventilation index class	Ventilation	Ventilation rate	Ventilation rate	Ventilation index	Clearing index	Dispersion rate
	Mixing height (ft) × transport wind speed (kts)	*Mixing height* (ft) × transport wind speed (mph)	*Mixing height (m)* × transport wind speed (m/s)	*Mixing height (100s of ft)* × transport wind speed (kts)	*Mixing depth (100s of ft)* × transport wind speed (kts)	*Mixing height (ft)* × transport wind speed (kts)
Excellent	>150,000	—	>16,000	—	>1000	≥60,000
Very good	100,000–149,999	≥112,000	—	—	—	—
Good	60,000–99,999	60,000–111,999	8,000–16,000	600–1,000	—	30,000–59,999
Fair	40,000–59,999	44,500–59,999	4,000–8,000	300–600	—	13,000–29,999
Marginal	—	33,500–44,999	2,000–4,000	—	—	—
Poor	<40,000	0–33,499	<2,000	0–300	<500	≤13,000

Ventilation index strengths

- Fairly simple to understand, observe (or calculate) and forecast.
- Tracks well with changes in large scale weather patterns so conditions can be evaluated days in advance using forecast information.

Ventilation index weaknesses

- Does not consider wind direction, so determining where the smoke will go requires further information unless direction is provided with the transport wind information.
- Represents only the period of peak temperatures, not the periods before or after. The burn period can begin before this peak and last well after which means the ventilation will change as well.
- Does not account well for when local wind systems (slope/valley winds, land/sea breezes, etc.) have a strong influence on transport winds.
- Does not account for variability in mixing depths and resulting ventilation caused by complex terrain or fires which significantly alter the local mixing depth.
- Nighttime ventilation index is infrequently seen in fire weather forecasts; this does not mean it is not valuable. Knowing the time of the onset of the nighttime inversion—low nighttime ventilation index—helps to forecast nighttime smoke movement.
- Index adjective ratings are NOT universally comparable due to different thresholds and calculation methods.

Ventilation index tips for use

- Use to look at 'big picture' daytime dispersion potential out 5 to 7 days to assess 'good' dispersion windows.
- Within 1 to 3 days from planned ignition, look at the variance in VI conditions throughout each daytime period as opposed to using maximum daily values or those from a set time each day.
- Focus more on the VI numeric values and constituent mixing heights and transport wind speeds and directions, as these are more universally applicable (in contrast to the adjective rating categories and their numeric thresholds, which can vary significantly from state-to-state). Be aware of the units as these may also vary from state to state.
- Use other tools to augment when in complex terrain, when local wind systems are prevalent, or for considering nighttime dispersion potential.
- Consider using pilot balloons to observe local ventilation conditions in real time. This approach factors in localized influences that most forecasts will not.
- Consider that VI may be completely misleading for high elevation locations that may be above an inversion that is defining the generalized mixing height for the area. Opportunities may therefore exist to burn above well-established inversions, despite prevailing ventilation conditions.

Turner Stability Classification System

Turner stability classes (sometimes referred to as Pasquill-Turner stability classes) are a means of describing turbulence within the mixed layer that is generated at the ground either convectively due to surface heating or mechanically by air flowing over a rough surface. Turner stability class is derived from the combination of wind speed, solar radiation, and cloud cover. These stability classes were first developed by Pasquill (1961), modified by Gifford (1961), then reformatted by Turner (1964) and are most commonly used in conjunction with air quality models to describe how plumes are likely to spread in both the vertical and horizontal directions. This makes it a useful system for gauging transportation safety-related stability as it addresses stability near the ground.

Turner stability classes (tables 5.2.2, 5.2.3, and 5.2.4) represent the stability within the mixing layer and take into account wind speed, temperature, moisture, and other factors. It is comprised of classes A through G (or 1 through 7 in some applications) defining different meteorological conditions characterized by wind speed and solar radiation during the day, and cloud cover at night. The conditions in these classes influence atmospheric turbulence which, in turn, influences smoke dispersion. Smoke will disperse best when the Turner stability class is lower in the alphabet (or a lower number) and becomes worse as it increases, with class G (or 7) representing extremely stable atmospheric conditions and very poor smoke dispersion potential.

Table 5.2.2. Turner stability classes and their interpretation (Turner 1964). (The stability class numbers are used later in this chapter under Calculating ADI in the field.)

Turner Stability Class	Stability Class For Determining ADI	Interpretation
A	**1**	Extremely unstable
B	**2**	Unstable
C	**3**	Slightly unstable
D	**4**	Neutral
E	**5**	Slightly stable
F	**6**	Stable
G	**7**	Extremely stable

Table 5.2.3. Turner stability classes during the day for strong, moderate, and slight incoming solar radiation levels, modified from Turner 1971.

Surface wind speed (33 ft AGL)	Strong (sunny)	Moderate (partly cloudy)	Slight (cloudy)
Miles per hour			
<4.5	A	A-B	B
4.5 to 6.5	A-B	B	C
6.5 to 11	B	B-C	C
11 to 13.5	C	C-D	D
>13.5	C	D	D

Table 5.2.4. Turner stability classes at night, modified from Turner 1971.

Surface Wind Speed (33 Ft AGL)	Thinly Overcast Or ≥4/8 Low Clouds	≤3/8 Cloud
Miles per hour		
<4.5	F	G
4.5 to 6.5	E	F
6.5 to 11	D	E
11 to 13.5	D	D
>13.5	D	D

Turner stability classification strengths

- Simple method to characterize turbulence within the mixed layer.
- Provides a general idea of how a smoke plume will behave. The more unstable, the more rapid the vertical and crosswind spread.
- Provides a general idea of how erratic wind direction could be. The more unstable, the more erratic wind direction could be.

Turner stability classification weaknesses

- Incomplete description of atmospheric stability because it only deals with turbulence and mixing generated near the surface.
- Does not account for inversions unless the inversions are cloud-topped.
- Does not readily provide incoming solar radiation information.
- Quite sensitive to cloud cover and ceiling height which can be highly variable and difficult to forecast.
- Does not account for turbulence generated by complex terrain.

Turner stability classification tips for use

- Use 1 to 3 days prior to ignition, especially in conjunction with atmospheric dispersion index (ADI), to assess potential smoke dispersion. (ADI is discussed in the next section.)
- While incoming solar radiation information is not readily available, day/night and wind speed alone will generally narrow the stability class to 2 or 3 choices. Evaluate the effect of each possible class on smoke dispersion.
- Daytime incoming solar radiation class of strong, moderate or slight can be estimated in the field based on season (summer: lean towards strong and moderate; winter: lean towards moderate and slight) and sun appearance (bright and unobscured: lean towards strong; totally obscured: lean towards slight). Understand that this is an estimate to use in the absence of information from a meteorologist.
- Be wary of potential inaccuracies as cloud cover and/or height are difficult to forecast.
- Be wary of conditions that put you on the border between classes as slight changes in wind speed and/or cloud information can dramatically change results.
- Greater instability (A and B) does not guarantee light or no smoke effects. Conditions may change downwind, through the day, or as night approaches. Higher wind speeds can overwhelm some degree of instability.

Lavdas Atmospheric Dispersion Index

The Lavdas atmospheric dispersion index (ADI) (Lavdas 1986) was designed to estimate the atmosphere's ability to disperse smoke from a prescribed fire and is a more complex metric of dispersion potential than the ventilation index (VI). The ADI incorporates transport wind speed, mixing height and stability class to develop an index value from 1 to over 100. Values of ADI range from ≥100 indicating "very good" dispersion to ≤6 indicating "very poor" dispersion. High values indicate potential clearing events while low values indicate the potential for smoke to concentrate nearer the fire (tables 5.2.5 and 5.2.6).

Table 5.2.5. Day time ADI and their meaning (Lavdas 1986, Lavdas and Achtemeier 1995, and Wade and Mobley 2007). This table has been developed for use with prescribed fire involving fuels that are less than one inch in diameter, typical of the southeast. These index values can also be extended to wildfire, or prescribed fire involving larger fuels with longer combustion periods but should be used with additional metrics as described in this chapter. If roadway impacts appear likely, take mitigation actions or consult the Roadway Response Plan (RRP) description in the *Smoke and Roadway Safety Guide*, PMS 477.

Day ADI	Smoke Dispersion Description	Interpretation Table – Sunrise to Sunset conditions
>70	**Excellent**	Ground impacts are unlikely, however very dense low surface smoke could impact nearby roadway visibility.
60 -69	**Very Good**	Ground impacts are unlikely, however very dense low surface smoke could impact nearby roadway visibility. Single fire smoke issues seem unlikely but be aware of cumulative smoke effects from multiple fires.
50 -59	**Good**	Ground impacts may occur. At this ADI level, only very dense low surface smoke can obstruct roadway visibility.
41 –49	**Generally Good**	Impacts are more likely under these typical afternoon meteorological conditions. Generally good dispersion assuming fuels are mostly consumed in this dispersion window, before night, with minimal smoldering of larger surface (1000-Hr) or ground fuels.
21 – 40	**Fair**	Characterized by persistent low wind speeds which facilitate poor air movement and can cause reduced roadway visibility. At this ADI level any residual smoke is likely to result in problems if surface wind speed is less than three mph. If nearby roadways are impacted at this ADI level, the Roadway Response Plan (RRP) [a] or mitigation actions will likely need to be implemented. For example, the Minimum Acceptable Visibility (MAV)[b] methodology for paved roads may indicate drivers should reduce vehicle speed due to low visibility. Some states, when solely using ADI, do not permit prescribed burning with ADI values ≤ 30.
13 –20	**Generally Poor**	Nearby roadways are very likely to be impacted at this ADI level, the RRP or mitigation actions will likely need to be implemented. If ADI is the sole criteria, risk for smoke impacts is high. Other criteria are recommended to support decisions such as dispersion models, air monitors, or other metrics (light fuels, small acreage, burn within day dispersion window, etc.).
7 –12	**Poor**	Nearby roadways are highly likely to be impacted at this ADI level. The RRP or mitigation actions will need to be implemented. If ADI is sole criteria, risk for smoke impacts is very high. Prescribed fires are permissible under certain circumstances if other criteria are used to support decisions. Other criteria could include dispersion models, air monitors, or other metrics (i.e. light fuels, small acreage, burn within day dispersion window, etc.).
1-6	**Very Poor**	Visibility will be reduced on nearby roadways at this ADI level. The RRP or mitigation actions will need to be implemented. If ADI is sole criteria, risk for smoke impacts is extremely high.

[a] The Roadway Response Plan (RRP) outlines when and how to respond to smoke visibility impacts on roadways.

[b] The MAV methodology for paved roads was adapted from California Highway Patrol and has been referenced in the past by the National Park Service (NPS 1991). The MAV is estimated for a range of speed limits given typical driver reaction times and the total distance a vehicle will travel once breaks are applied under ideal conditions.

5.2.6. Night ADI is based on the work of Lavdas 1986, Lavdas and Achtemeier 1995, and Wade and Mobley 2007. This table has been developed for use for prescribed fire involving fuels that are less than one inch in diameter, typical of the southeast. These index values can also be extended to wildfire, or prescribed fire involving larger fuels with longer combustion periods but should be used with additional metrics as described in this chapter. If roadway impacts appear likely, take mitigation actions or consult the Roadway Response Plan (RRP) description in the *Smoke and Roadway Safety Guide*, PMS 477. The approaches below reflect the fact that nighttime Minimum Acceptable Visibility (MAV) for paved roads is doubled compared to the daytime.

Night ADI	Smoke Dispersion Description	Interpretation Table - Sunset to Sunrise conditions
13 – 20	**Good**	At this ADI level night smoke dispersion is "GOOD", surface wind speed > 12 mph. Roadway visibility is only likely to be impacted due to dense surface smoke crossing the roadway, take mitigation actions or consult the Roadway Response Plan (RRP)[a].
8 – 12	**Fair**	At this ADI level night smoke dispersion is "FAIR" with surface wind speed eight to 12 mph (Lavdas and Achtemeier 1995). Roadway visibility may be impacted due to dense surface smoke. If there is dense surface smoke it may require adjusting vehicle speed to existing conditions, take mitigation actions or consult the RRP.
5-7	**Poor**	At this ADI level night smoke dispersion is "POOR" with surface wind speeds five to seven mph (Paul *et al.* 1987). Roadway visibility is likely to be reduced. RRP or mitigation actions will likely need to be implemented. Traffic control beyond reduced speed may be required, for example the use of an unoccupied lighted law enforcement vehicle.
1 – 4	**Very Poor**	At this ADI level night smoke dispersion is "VERY POOR" with surface wind speeds less than five mph (Lavdas 1997). Roadway visibility will be reduced due to smoke, smoke induced fog, or natural fog. RRP or mitigation actions will need to be implemented. Minimum acceptable visibility (MAV) [b] for paved roads needs to be used and traffic control is very likely required. With surface wind speeds less than two mph (Princevac *et al.* 2013), night smoke dispersion is "STAGNANT". Roadway visibility will be seriously reduced and road closure should be considered. RRP or mitigation actions will be needed.

[a] The Roadway Response Plan (RRP) outlines when and how to respond to smoke visibility impacts on roadways.

[b] The MAV methodology for paved roads was adapted from California Highway Patrol and has been referenced in the past by the National Park Service (NPS 1991). The MAV is estimated for a range of speed limits given typical driver reaction times and the total distance a vehicle will travel once breaks are applied under ideal conditions.

Calculating ADI in the field

The ADI may be available through the local NWS office; if not, it can be estimated using figure 5.2.2, in conjunction with tables 5.2.2 and 5.2.7 if mixing height, stability class, and transport wind speed are known. If Turner stability class is known, use the appropriate numeric stability class from table 5.2.2 to determine ADI with figure 5.2.2.

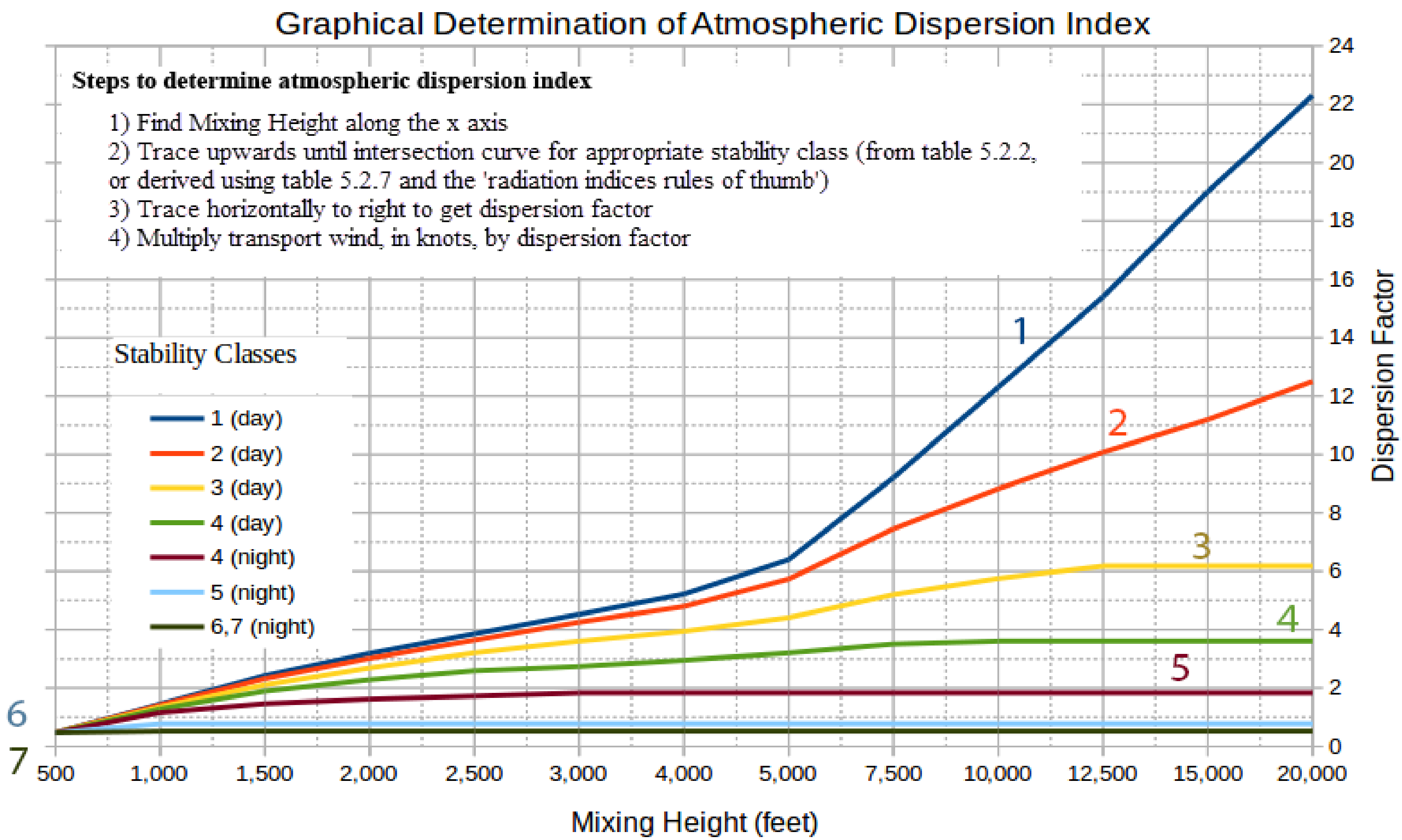

Figure 5.2.2. Atmospheric dispersion index (ADI) can be calculated manually if mixing height, stability class, and transport wind speed are known. The graphic provides a dispersion factor which is then multiplied by wind speed in knots to determine ADI. Adapted with content from Lavdas 1986.

Calculating Stability with Radiation Indices

If the Turner stability class is not available, stability can be determined using table 5.2.7 along with information in the "radiation index rules of thumb" subsection. Use the result with figure 5.2.2 to determine ADI.

Table 5.2.7. Stability class as a function of net radiation index and surface wind speed. Obtain net radiation from the "Rules of Thumb" below this table (Table modified from Turner 1964).

	Net Radiation Index						
Wind Speed (knots)	**4**	**3**	**2**	**1**	**0**	**-1**	**-2**
0-1	1	1	2	3	4	6	7
2	1	2	2	3	4	6	7
3	1	2	2	3	4	6	7
4	1	2	3	4	4	5	6
5	1	2	3	4	4	5	6
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8	2	3	3	4	4	4	5
9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
≥12	3	4	4	4	4	4	4

"Rules of Thumb" for Calculating Radiation Index

These Radiation Index "rules of thumb" are adapted from Turner 1964, Lavdas 1986.

- Day or night: If the opaque cloud cover is total and the ceiling height is <7,000 feet, use a net radiation index of 0.
- Night (between sunset and sunrise): If total opaque cloud cover is less than 40%, use net radiation index equal to -2; if it is over 40%, use net radiation index equal to -1.
- Day: Determine the insolation class number as a function of solar elevation angle with table 5.2.8 and the information below.

Table 5.2.8. General solar elevation angles and insolation class numbers (Table adapted from Turner 1964).

Solar elevation angle (δ)	Insolation class number
$60° < \delta$	4
$35° < \delta < 60°$	3
$15° < \delta \leq 35°$	2
$\delta \leq 15°$	1

- o If the total opaque cloud cover is less than 50%, the net radiation index is equal to the insolation class number.

The NWS describes their cloud conditions as "sky condition". Should the forecast products not include percent cloud cover, it can be estimated using table 5.2.9. Note the current NWS convention is to represent cloud cover in eighths (table 5.2.9).

- o If the total opaque cloud cover is greater than 50%, modify the insolation class number by following these six steps:

1. Ceiling height less than 7,000 feet, subtract 2.
2. Ceiling height greater than or equal to 7,000 feet but less than 16,000 feet, subtract 1.
3. Total opaque cloud cover is 100%, subtract 1. (This will only apply to ceilings greater than or equal to 7,000 feet because cases with 100% coverage with ceiling less than 7,000 feet are determined by step 1, above.)
4. If neither steps 1 and 2 nor 3 are applicable, assume that the modified insolation class number is equal to the insolation class number.
5. If the modified insolation class number is less than 1, let it equal 1.
6. Set the net radiation index equal to the modified insolation class number.

Table 5.2.9. National Weather Service terminology and predominant sky conditions (National Weather Service 2015a).

Term	Predominant or average sky condition
Cloudy	7/8ths or more of the sky is covered by clouds.
Mostly cloudy or considerable cloudiness	6/8th to 7/8ths of the sky is covered by with opaque (not transparent) clouds.
Partly cloudy or partly sunny	Between 3/8 and 5/8 of the sky is covered by clouds.
Mostly clear or mostly sunny	1/8th to 2/8ths of the sky is covered by with opaque (not transparent) clouds.
Clear or sunny	0/8 opaque cloud cover.
Fair	Less than 40% opaque cloud cover, no precipitation and no extremes of temperature, visibility, or wind.

Atmospheric dispersion index strengths

- Fairly simple to understand, yet more comprehensive than VI.
- Suitable for prediction using high-resolution weather modeling, which can produce better precision and accuracy.
- Tracks well with general weather, but also accounts for variations in stability class that can be very localized.
- Can be useful for evaluating nighttime dispersion potential.

Atmospheric dispersion index weaknesses

- Wind direction is not considered, so determining where the smoke will go requires further information unless direction is provided with the transport wind information.
- Is quite sensitive to cloud cover and ceiling height, which can be highly variable and difficult to forecast.
- The following are weaknesses only if they are not well captured by high-resolution weather models that may be used to forecast ADI:
    - Does not account well for situations when local wind systems have a strong influence on transport winds.
    - Does not account for variability in mixing depths caused by complex terrain.

- Does not account for fires that significantly alter the local mixing depth.

Atmospheric dispersion index tips for use

- Use 1 to 3 days before ignition, especially in conjunction with high resolution weather modeling, to assess the combination of general and local weather factors affecting dispersion.
- Be wary of potential inaccuracies due to variable cloud amount and/or height.
- Try to validate the extent to which ADI forecasts are capturing localized conditions at a particular burn location, as this should bolster overall confidence in the applicability and accuracy of the ADI. Consult a meteorologist as necessary.

Low Visibility Occurrence Risk Index (LVORI)

The low visibility occurrence risk index (LVORI) (Lavdas and Achtemeier 1995) combines ADI with relative humidity (RH) and relates it to the proportion of historic traffic accidents reported due to reduced visibility caused by smoke and/or fog. The LVORI categories range from 1 to 10, with values increasing as ADI decreases and RH increases (table 5.2.10). Assuming smoke is present, elevated LVORI values indicate a relatively high probability of traffic accidents due to reduced visibility from a combination of smoke and fog (sometimes referred to as 'superfog').

Low visibility occurrence risk index strengths

- An easy to interpret, and fairly comprehensive, index tied statistically to a very undesirable effect of wildland fire (poor visibility related traffic accidents).
- All the strengths associated with the ADI.
- A valuable tool to assess the nighttime probability and risk of residual smoke reducing visibility.

Low visibility occurrence risk index weaknesses

- All the weaknesses associated with the ADI.
- Addition of relative humidity provides another source of complexity and potential error.
- Does not account for variance in concentration or amount of smoke emitted.

Low visibility occurrence risk index tips for use

- Use along with other indicators before a planned ignition to assess the risk for reduced visibility due to smoke, especially the night/early morning following the burn.
- Use caution when burning near wildland urban interface (WUI) or high traffic areas if the nighttime forecasted LVORI values are 7 or 8 and, unless extensive mop-up measures are taken, avoid burning when values are 9 or 10.

Table 5.2.10. Low visibility risk occurrence index categories and their interpretation (Lavdas and Achtemeier 1995). The table colors aid in quickly matching LVORI values to the LVORI interpretation below.

Atmospheric Dispersion Index

Relative Humidity	1	2	3-4	5-6	7-8	9-10	11-12	13-16	17-25	26-30	31-40	>40
<55	2	2	2	2	2	2	2	2	2	2	1	1
55-59	3	3	3	3	3	2	2	2	2	2	1	1
60-64	3	3	3	3	3	3	2	2	2	2	1	1
65-69	4	3	3	3	3	3	3	3	3	3	3	1
70-74	4	3	3	3	3	3	3	3	3	3	3	3
75-79	4	4	4	4	4	4	4	4	3	3	3	3
80-82	6	5	5	4	4	4	4	4	3	3	3	3
83-85	6	5	5	5	4	4	4	4	4	4	4	4
86-89	6	6	6	5	5	5	5	4	4	4	4	4
89-91	7	7	6	6	5	5	5	5	4	4	4	4
92-94	8	7	6	6	6	6	5	5	5	4	4	4
95-97	9	8	8	7	6	6	6	5	5	4	4	4
>97	10	10	9	9	8	8	7	5	5	4	4	4

LVORI Interpretation

1: Lowest proportion of accidents with smoke and/or fog reported (130 of 127,604 accidents or just over 0.0010 accidents).
2: Physical or statistical reasons for not including in category 1, but proportion of accidents not significantly higher.
3: Higher proportion of accidents than category 1, by about 30% to 50%, but of marginal significance (1%-5%).
4: Significantly higher than category 1, by a factor of 2.
5: Significantly higher than category 1, by a factor of 3 to 10.
6: Significantly higher than category 1, by a factor of 10 to 20.
7: Significantly higher than category 1, by a factor of 20 to 40.
8: Significantly higher than category 1, by a factor of 40 to 75.
9: Significantly higher than category 1, by a factor of 75 to 125.
10: Significantly higher than category 1, by a factor of 150.

HYSPLIT Model Trajectories

The HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model (Draxler and Hess 1997, Draxler and Rolph 2015) computes simple air parcel trajectories and complex dispersion, and simulates deposition. The discussion here focuses on only the trajectory application of HYSPLIT because using the model for other applications is quite complex. With trajectory modeling, HYSPLIT provides the user with the ability to examine potential smoke plume travel in both the horizontal and vertical directions which can help indicate the direction and extent of travel of prescribed fire plumes. It's important to remember that HYSPLIT trajectories represent the movement of air parcels thus it may or may not represent the movement of a heat-influenced smoke plume.

Assessing ignition and smoke emission timing

Figure 5.2.3 is an example of using HYSPLIT to assess the potential variations in smoke plume trajectories from a point-source ignition throughout a daytime burning period for a specific starting plume height (500 m AGL). Each of the colored lines represents a forecast trajectory from the same location, but for a different starting hour during the afternoon.

The tight clustering of lines and similarity of line length in the top portion of figure 5.2.3 indicates that the time of ignition will have little effect on the horizontal spread of smoke. The lines on the bottom portion of the figure indicate that smoke emitted earlier in the afternoon is more likely to loft and remain elevated (red, blue, and green lines) while smoke emitted later in the day is more likely to return to the surface (aqua, pink, and yellow lines). The lines do not represent the horizontal width of the plume downwind or the vertical thickness of the plume but rather the vertical and horizontal trajectory of the parcel of air that will likely carry the smoke.

The result in figure 5.2.3 could indicate to a fire manager that ceasing ignition earlier in the afternoon was advisable to keep smoke elevated above sensitive downwind receptors. Or it may indicate that burning should take place on another day with more favorable conditions if ignition was to occur late in the day and sensitive receptors were found in the direction of the trajectories.

Assessing the effect of fire intensity on plume direction

The HYSPLIT output in figure 5.2.4 shows the potentially variable nature of smoke trajectories from an ignition assuming different levels of fire intensity that could push smoke higher into the atmosphere. Each of the colored lines indicates the forecast trajectory from the same location emitted into the atmosphere at the same starting time (unlike the previous example), but starting from 500m, 1000m, and 1500m AGL.

Rough interpretation of the example in figure 5.2.4 is that a more intense fire that results in a higher plume will cause the smoke to travel further away and remain elevated for a longer time, especially if the plume height is above 1000m AGL. However for all plume heights, the smoke will subside and affect the ground downwind, with some release heights taking longer than others. Note also that with a low plume height (500m), common for low intensity burns, the direction the smoke is likely to travel is a different direction than higher plumes (1000m and 1500m) and would affect the ground quite quickly increasing the likelihood of smoke effects if sensitive receptors were present.

With many prescribed fires, there may not be an opportunity to alter fire intensity enough to significantly alter the height of the convection column. In this example, smoke is forecast to affect the Snake River Valley in Idaho if it’s not pushed above 500m AGL.

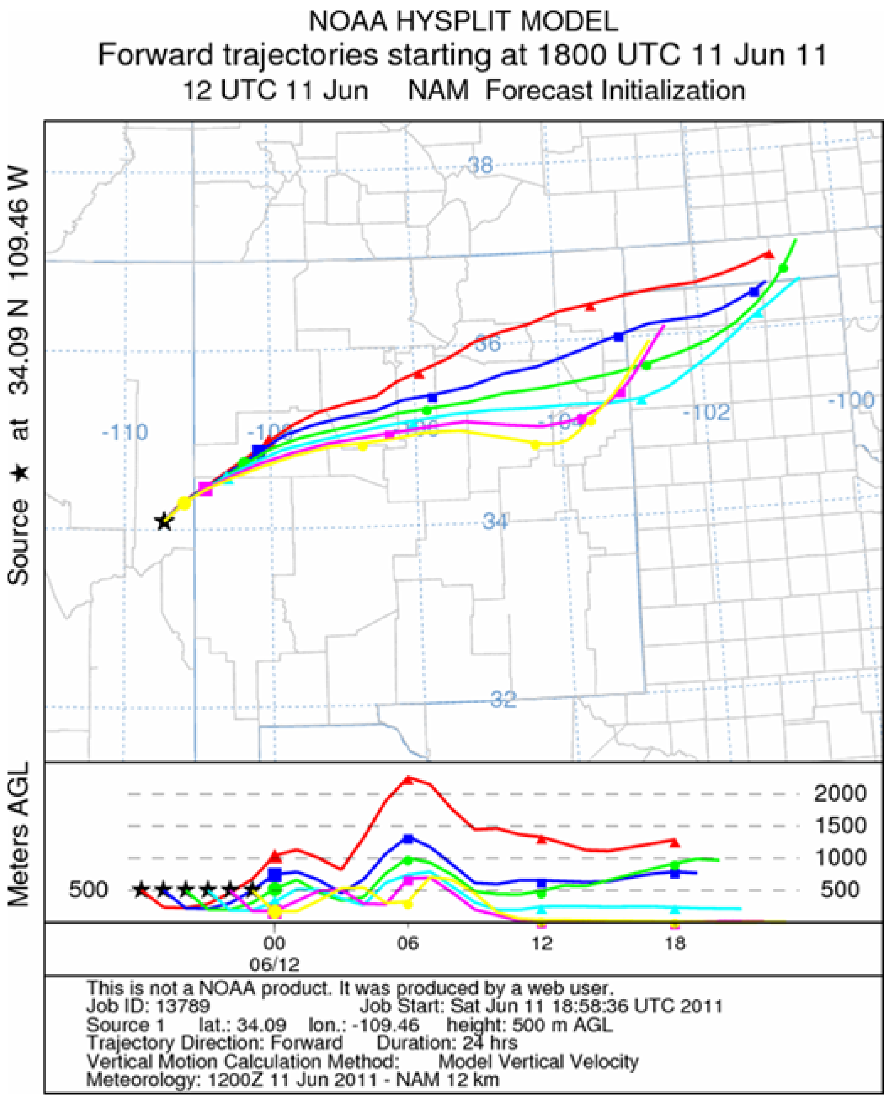

Figure 5.2.3. Plume rise varies by ignition time: A HYSPLIT model results example assessing the varying nature of smoke trajectories from point-source ignition during a daytime burn.

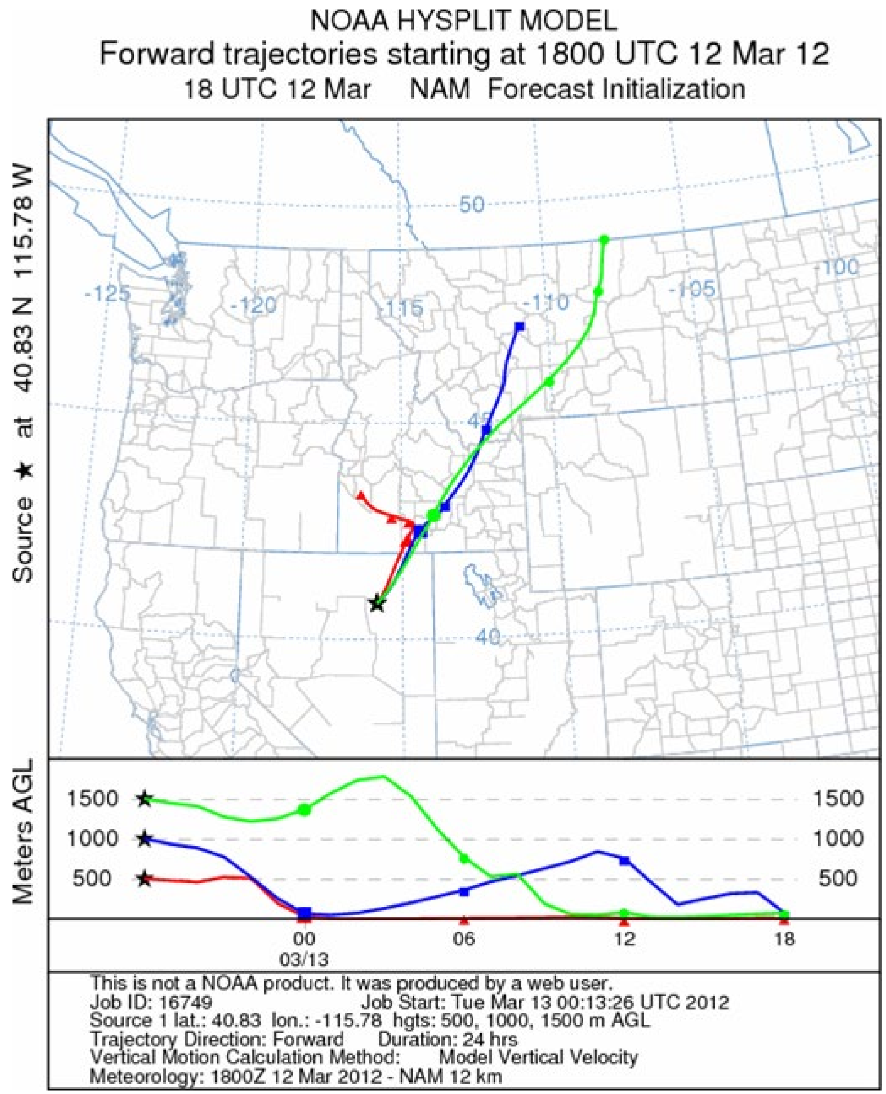

Figure 5.2.4. Plume rise varies by fire intensity: HYSPLIT model results assessing the potential variability of smoke plume trajectory from different fire intensities.

HYSPLIT strengths

- Robust, reproducible, scientific, graphical results.
- Flexible and fairly easy to access, with some basic assistance or training.
- Allows variability of user inputs which can help guide timing of ignition and simulate intensity of burning which will influence smoke trajectories.
- Capability to utilize archived meteorological forecast data for post burn assessment.
- Available online at: http://ready.arl.noaa.gov/HYSPLIT_traj.php or http://smoke.airfire.org/trajectories/.
- A HYSPLIT-trajectory run can be requested by a burner or fire manager as part of the NWS Spot Weather Forecast request submittal.

HYSPLIT weaknesses

- Somewhat complex to interpret and apply. Requires some expert assistance and/or training for most prescribed fire specialists.
- HYSPLIT-trajectory does not predict the severity of smoke effects at the surface.
- Relies on moderately high resolution (12km grid) weather models, which have varying accuracy and different strengths and weaknesses themselves.
- Decreased accuracy when general winds are light and variable, and/or winds are strongly influenced by local winds (slope/valley/sea breeze) or in complex terrain.
- Predicted trajectories are based on modeled weather only. Fire intensity, fire/atmosphere interactions, and heat driven plume rise are not factored in automatically.

HYSPLIT tips for use

- Consult the following resource for information regarding the HYSPLIT information available with NWS spot forecasts and a list of subject matter experts (SMEs) to assist with interpretation[1]:
- Do not attempt to use HYSPLIT online without subject matter expertise or training and experience.
- Use the day before or the day of planned ignition to assess potential smoke trajectories, in consultation with the SMEs identified in the document at the link above or other knowledgeable experts.
- Best used when winds are moderate to strong and NOT strongly influenced by local wind systems. Nighttime use is not generally recommended.
- Assess the characteristics of forecast trajectories to consider modifying the timing or intensity of prescribed fire.

[1] http://www.weather.gov/media/fire/HYSPLIT_one_page.pdf

Estimated Smoldering Potential (ESP)

Organic soils, or mineral soils with thick organic horizons, cover significant areas of Alaska and the Southern, Gulf and Northern Lakes States regions of the United States (figure 5.2.5). The consumption of these organic soils is a serious concern during wildland fire. Suppression techniques that are normally effective in controlling flaming combustion in surface fuels are often ineffective when used on smoldering combustion in organic soils.

Figure 5.2.5. Root mat soil horizon. This example was taken from an area where the root mat was between 12 and 18 inches (30 to 45 cm) thick. Photo: Jim Reardon, Forest Service.

Combustion of organic soil is by smoldering which can extend the burn duration to days, weeks, or months with minimal plume loft. This can be due to meteorological conditions, the effect of the diurnal cycle and the minor convective lift that results from the smoldering combustion process itself. Smoldering combustion tends to produce emissions that can last for an extended period of time and total as much as 19 times the total emissions produced by surface fuels alone. These emissions have been linked to health concerns (Rappold *et al.* 2011) and increased potential for highway vehicle accidents due to reduced visibility and superfog events (Achtemeier 2003).

The estimated smoldering potential (ESP) model (sometimes called estimated smoldering probability) is a predictive tool developed to assist managers in evaluating the risk of smoldering combustion of organic soils in the pocosin/pond pine vegetation communities on the North Carolina coastal plain (Reardon *et al.* 2007). ESP uses soil properties and soil moisture to reflect the chance of continued smoldering after a successful ground ignition. At low ESPs continued smoldering is unlikely and control may require minimal resources, while at high ESPs there is the likelihood that most ignitions will result in sustained smoldering and control will be more difficult.

Separate ESP models were developed for the root mat and muck soil horizons. The root mat is comprised of a concentration of roots and highly decomposed material of granular structure and can be up to 30 cm thick. Below the root mat layer is the highly decomposed muck (or sapric) layer. In North Carolina, the average thickness of the muck layer is 4.6 feet (1.4 meters) with depths ranging from 1 to 15 feet (0.3 to 4.6 meters).

Terms to Know

Root mat soil horizon: the upper organic soil horizon composed of small roots and moderately decomposed organic soil.

Muck soil horizon: the lower organic soil horizon composed of highly decomposed sapric soils.

ESP, specifically for root mat soil, is a function of soil moisture content and mineral content. Field and laboratory validation of this model demonstrated that using a default mineral content of 5% gave good results on a range of NC coastal plain sites.

The probability that root mat soils will smolder can be estimated for moisture contents between 0 and 200% (figure 5.2.6). At a default mineral content of 5%, the ESP of root mat soil with moisture contents less than 68% ranges from 79 to 100%. Between 68% and 128% soil moisture content, the predicted ESP probability is most sensitive to moisture content and decreases rapidly from 79% to 22%. Above that moisture content range the likelihood of smoldering diminishes further and by 170% moisture the ESP is less than 5%. During the testing of this model a moisture content of 170% was used as a Go/No-Go decision threshold for operational prescribed fire. The overriding concern in the selection of this threshold was a reduction in the ground fire risk to less than 5%.

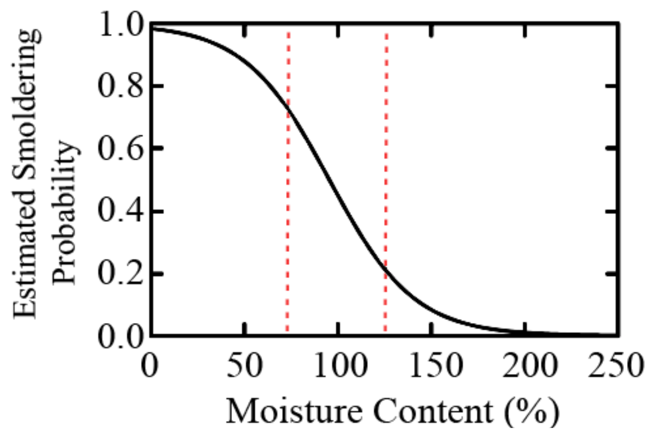

Figure 5.2.6. The ESP root mat model response assuming 5% mineral content. Dashed lines at 68% and 128% indicate where ESP is most sensitive to soil moisture content change.

The probability that muck soil will smolder is modeled over a wider moisture content range than root mat soil, 0 to 300% (figure 5.2.7). ESP from the muck soil model is greater than 50% at moisture contents up to 200%. Between 166% and 236% soil moisture, predicted ESP decreases rapidly from 79% to 21% and at 270% moisture the ESP is less than 7%. This moisture content has been used as a Go/No-Go decision threshold for operational prescribed fire.

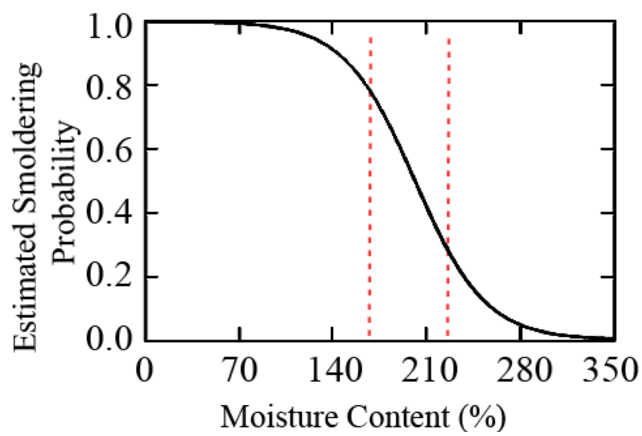

Figure 5.2.7. Moisture content of muck soil can be used to estimate the smoldering potential. Dashed lines at 166% and 236% indicate where ESP is most sensitive to soil moisture content changes.

Estimated smoldering potential strengths

- A simple model of organic soil potential to sustain smoldering combustion expressed as a probability.
- Has been shown to possess a good ability to discriminate between smoldering and non-smoldering conditions in both laboratory and prescribed fire scenarios.
- Applicable to fuel complexes in the southeast that are comprised of similar organic soils or mineral soils with thick organic horizons similar to those in North Carolina.
- Reliability to assess the availability of organic soils to sustain smoldering combustion. It has confidently supported prescribed fire practitioners in Go/ No-Go decisions or wildfire suppression crews to determine if suppression or mop-up action will be required.
- Supports insight on organic soil availability so can help prevent costly budget overruns by increasing the likelihood of informed decisions.

Estimated smoldering potential weaknesses

- Application of the ESP model is limited by the lack of an efficient means to monitor changing soil moisture conditions in the field with the spatial and temporal resolution needed.

- In determining ESP, standard laboratory drying procedures and field sampling are often impractical due to time and equipment requirements. However, drying time of samples can be substantially reduced by using a developed microwave oven drying technique (Reardon and Curcio 2014). Alternatively, automated data collection methods which can provide continuous data from a limited number of sites, are becoming an increasingly attractive alternative due to decreasing costs and advances in cell phone technology. Remote sensing technology of soil moisture is improving; thus, providing data at larger scales than is available from either field sampling or automated sampling at fixed points. Unfortunately, the spatial resolution of the data is limited.

Estimated smoldering potential tips for use

- The use and interpretation of the ESP values is dependent on the determination of soil moisture. This value reflects the smoldering potential of the soil to the sampled depth.
- In addition to its use in establishing a burn/no-burn decision threshold for prescribed fire or fire danger, ESP can be used to estimate smoldering contribution to total emissions.
- Use 1-7 days before prescribed fire ignition and anytime for wildfires.
- Sampling moisture at multiple depths can be used to estimate depth of consumption and more intensive sampling can be used to estimate the spatial variability of organic soil consumption.

Superfog Potential Table (SFP)

Superfog is an extremely dense fog created by the mixing of two masses of air (the smoke plume and the ambient air) of widely differing temperatures. Neither air mass need be saturated (relative humidity equal to 100 percent) at the time of mixing. Superfog must form at the site of combustion where the plume is still warm. It is in the physics of formation that sets superfog apart from other visibility-reducing events that involve mixing of dense smoke with dense fog.

Superfog is capable of reducing visibility to less than 3 m (10 feet) and on occasion can reduce visibility to less than 1 m (3 feet–cannot see fingers on an outstretched arm). Superfog will not form over open flaming because plume temperatures are too high and relative humidity is too low. Superfog formation is most favored during smoldering combustion in moist fuels over wet ground and when ambient air is cool and humid–the latter condition being favored during predawn hours late at night.

Once formed at the combustion site, superfog drifts with the ambient wind. It persists until mixing with unsaturated ambient air evaporates the fog. Thus, depending on mixing and relative humidity of ambient air, superfog may last for a few seconds or a few hours. Superfog may not last long enough to leave a burn site or it may travel several kilometers (miles) to cross a roadway.

Superfog Potential table 5.2.11 was determined from measured observations collected from prescribed fires. Fuel availability and fire danger were within acceptable levels to conduct prescribed fires. The table shows the probability when smoke mixes with ambient air and facilitates a supersaturated condition producing superfog. Visibility is reduced to less than 3 meters. Air conditions are calm and stable. As wind speed rises, it increases mixing and helps to dissipate superfog.

Built on observations from smoldering prescribed fires, the table’s application to wildfires burning under more severe conditions comes with uncertainty. It is emphasized that it addresses only the smoldering combustion phase. Flaming combustion generates more buoyant conditions and supports smoke lofting. If flaming combustion is intense, it can facilitate smoke rise through the nighttime surface inversion that usually is present. Smoke from flaming combustion can still severely reduce roadway visibility making driving unsafe without superfog forming.

Table 5.2.11. Superfog Potential table for smoldering combustion on prescribed fires.

Relative Humidity (%)	Temperature (°F)										
	30	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0
45	10	0	0	0	0	0	0	0	0	0	0
50	20	0	0	0	0	0	0	0	0	0	0
55	30	10	0	0	0	0	0	0	0	0	0
60	40	10	0	0	0	0	0	0	0	0	0
65	50	20	10	0	0	0	0	0	0	0	0
70	60	40	10	0	0	0	0	0	0	0	0
75	80	50	30	10	0	0	0	0	0	0	0
80	80	70	40	20	10	0	0	0	0	0	0
85	90	80	70	40	10	10	0	0	0	0	0
90	100	90	80	70	40	20	10	0	0	0	0
95	100	100	90	90	70	50	40	10	0	0	0
100	100	100	100	100	100	90	70	50	40	20	10

SFP strengths

- A simple model to address superfog forming from smoldering fires expressed as a probability.
- Applicable to smoldering fires in all fuels anywhere where the merging of two air masses (smoldering fire and ambient air) creates an overly saturated air mass and facilitates transport of superfog from the fire site.
- Supports insight as to the risk of superfog and provides the opportunity to implement effective mitigation measures.

SFP weaknesses

- Model has been constructed on limited data.
- The model only pertains to smoldering combustion. Flaming combustion and its smoke can cause reduced visibility but inhibits superfog formation.
- Assumes calm wind speeds. As wind speed increase mixing is facilitated making superfog formation not possible.
- Assumes air mass traits, liquid water content and water droplet size are conducive for superfog forming.

SFP tips for use

- Use on smoldering combustion only.
- Use within 1 to 3 days before prescribed fire ignition and daily for wildfires.
- Likely environmental conditions that support the formation of superfog include calm surface winds (≤ 2.2 mph), air temperature range > 40º F and < 70º F, and relative humidity > 80%. Wind speeds supporting natural fog usually initiate at ≤ 4 mph.

Planned Burn-Piedmont (PBP)

PBP is a land surface model developed as a tool to evaluate low-level transport / dispersion of smoke. Built for nighttime smoke from prescribed fires, it also has potential use for wildfire smoke under similar meteorological conditions. The premise of the model is to determine the state and activity of nighttime surface drainage flow that occur over moderate and steep terrain at night when meteorological forcing is weak. The variables used for the model include wind speeds (at 10 meters height above ground level), relative humidity, temperature (measured at 2 meters), and mean sea level pressure. Local drainage patterns become established usually starting around sunset. Smoke movement is extremely poor at the surface and under moist conditions smoke's hydroscopic particles produced from smoldering combustion may initiate or augment fog formation. Smoke or the combination of smoke and fog can create visibility hazards for roadways. Currently the model can be found at the url: https://cefa-new.dri.edu/PB_Piedmont/

PBP strengths

- In conducting prescribed fires or managing wildfires that are coupled with weak meteorological forcing, PBP may be used to evaluate where nighttime surface smoke particles from smoldering combustion are likely to be transported and/or settle in or around nearby drainages within close proximity to the fire area.
- It provides information with regards to superfog forming at the fire's location and its surface transport from the fire's location.
- It also can indicate if transported surface smoke coupled with supportive downwind weather conditions facilitates smoke induced fog formation.
- PBP allows timely modeling to evaluate the potential location of reduced roadway visibility impacts before they occur. Thus mitigating measures can be implemented well before hazard.

PBP weaknesses

- With strong large scale meteorological forcing (winds that can override natural diurnal flows) the model should not be used. Smoke dispersion at night may still reduce visibility but fog formation is highly unlikely.
- It is highly dependent on smoldering combustion. Presence of flaming combustion can create on-site turbulence and influence smoke transport vertically and horizontally.
- Currently uses the 5km North America Mesoscale (NAM) meteorology. This may not be reliable in very steep topography as elevation change in short horizontal distances may not be adequately captured / modeled.
- PBP has just been operationally made available for field validation in late fall / winter 2017-18.

PBP tips for use

- PBP model runs need to be started at 15:00 local time, the same day ignition occurs, with a run time of 18 to 20 hours (from 3pm to 8am or 10am the next day). This is required to capture potential fog formation that can setup from midnight to 2 hours after sunrise.
- Weather elements being used include 2 m temperature and dew point temperature and 10 m wind along with surface pressure, terrain height and column averaged cloud water.

Outputs are individual hours of smoke particle transport (yellow) and where condensation and fog formation are taking place (red). Special Note: If particle transport at the fire's origin is red, then this is highly probable for the occurrence of superfog (figure 5.2.8).

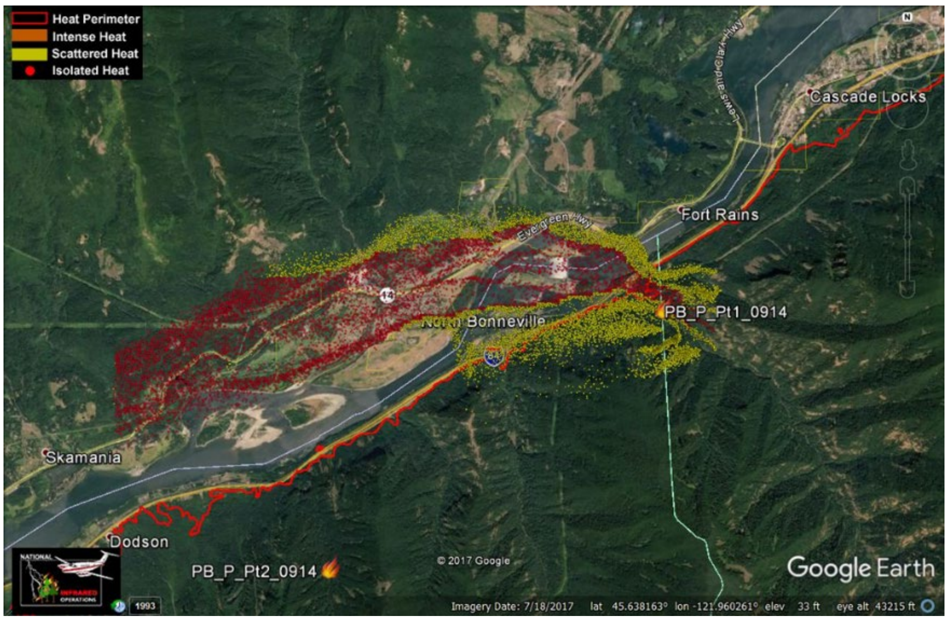

Figure 5.2.8. PBP run overlay for September 15, 2017 at 0730 am from Projection Point 1 created on September 14. Yellow dots display smoke drift while red dots display area of smoke and fog. Knowing the presence, location, and timing of smoke and smoke and fog combinations can facilitate the timely implementation of mitigation measures.

Accessing Smoke Prediction Tool Forecasts

The tools described in this chapter would be of little value if the forecasts they relied upon were not routinely available in time frames and formats suitable for prescribed fire planning and implementation. Fortunately, aside from the more intensive HYSPLIT trajectories, forecast values for these tools are routinely available on a national, regional or local basis from the NWS. Forecasts from some high-resolution weather models that include smoke prediction tools or indices are appropriate for augmenting the decision process as well.

The recommended first stop for forecast information pertinent to wildland fire and smoke is the NWS Fire Weather Portal at https://www.weather.gov/fire/. At this website, the user can retrieve the pertinent

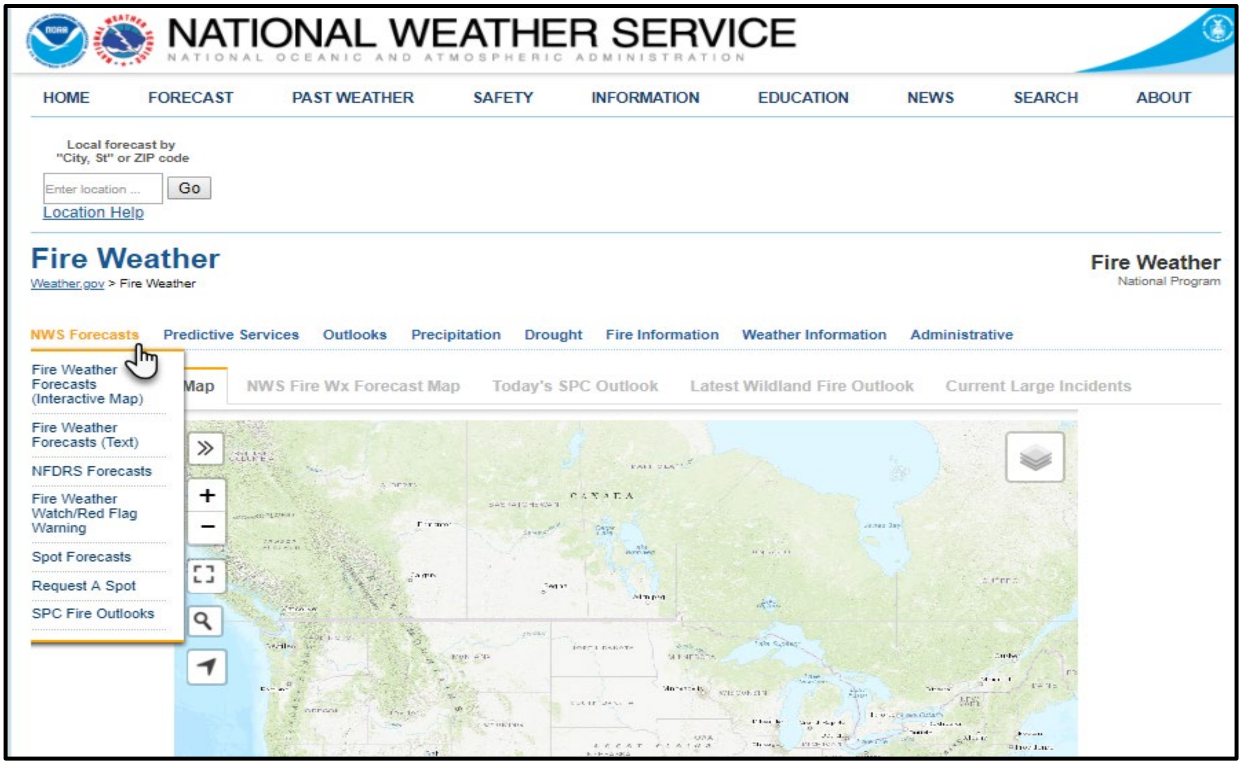

Figure 5.2.9. Screenshot of the NWS fire weather portal.

Fire Weather Forecast, review or request Spot Forecasts and review Special Fire Outlooks (figure 5.2.9). For more specific point fire weather information that can be locally enhanced for assessing smoke dispersion, individual local weather forecasting office (WFO) websites are a valuable resource.

The fire weather planning forecasts (FWF) in WFOs will contain information for how smoke will disperse in the selected location out 48 hours. VI is provided nationwide. ADI and LVORI are common across parts of the east and south. Additional general forecast information is provided 3 to 7 days out.

Also at local NWS WFO fire weather pages, users can access the Hourly Weather Graph product, Weather Activity Planner, links to request a spot forecast for the selected location, and information from nearby weather stations and their surface observations which is another important resource. The Fire Weather Point Forecast (PFW) matrix (figure 5.2.10) provides information that is customized to fire and smoke management needs at the station of specific interest. Note that individual WFOs may vary in the products offered, and where they are accessed.

The NWS PFW matrix, such as the example from the southeastern U.S. in figure 5.2.10, is a pseudo-standardized forecast for specific locations that is produced locally by NWS offices. The format is standard in that date/time increases from left to right and forecast elements for the various time frames extend down the page. The key is that various smoke prediction tools, highlighted in yellow, can be added to the matrix at the request of local fire/smoke management personnel. The result is a site-specific, customized product that allows for assessment of a variety of smoke prediction tools and weather parameters simultaneously. Specific information regarding PFWs, their content, and issuance locations should be available on the fire weather web page of the providing NWS WFO.

FIRE WEATHER POINT FORECAST FOR GUION FARM

DATE		WED 10/24/12								THU 10/25/12								FRI 10/26/12				
UTC 3HRLY	09	12	15	18	21	00	03	06	09	12	15	18	21	00	03	06	09	12	15	18	21	00
EDT 3HRLY	05	08	11	14	17	20	23	02	05	08	11	14	17	20	23	02	05	08	11	14	17	20
MAX/MIN						74				52				70				48				69
TEMP					71	62	57	55	53	53	64	69	68	60	55	51	49	50	62	67	67	59
DEWPT					45	47	47	43	41	42	47	49	48	48	48	49	48	49	50	50	52	53
MIN/MAX RH						38				71				41				100				54
RH					39	58	67	65	64	65	53	48	49	65	78	90	95	96	65	54	59	80
WIND DIR					SE	S	S	SW	SW	S	W	SE	SE	SE	E	S	SW	N	N	N	NE	NE
WIND DIR DEG					15	16	20	22	22	20	27	15	15	12	10	20	23	00	00	02	04	04
WIND SPD					5	3	2	2	2	2	1	5	5	5	3	1	1	3	5	5	4	3
CLOUDS					CL	CL	CL	CL	CL	FW	FW	FW	FW	FW	SC	SC	SC	SC	SC	SC	SC	SC
CLOUDS(%)					0	0	0	0	0	6	14	16	13	20	33	45	39	33	37	40	44	47
VSBY					9	9	9	9	9	9	9	9										
POP 12HR						0				0				5				10				10
QPF 12HR						0				0				0				0				0
LAL						1		1		1		1		1		1		1		1		1
HAINES						4		5		5		4		4		3		4		4		4
DSI						1								2								1
MIX HGT						5100		1000		300		4200		4200		1000		300		4500		4400
T WIND DIR						SE		W		NW		SW		S		E		NW		NE		E
T WIND SPD						5		2		3		6		9		3		4		3		3
ADI						27		2		4		35		35		3		6		14		13
MAX LVORI						3		4		3		3		3		7		9		4		5
STABILITY						B		G		F		B		B		G		F		B		B
CEILING						NONE		NONE		NONE		NONE		NONE		NONE		NONE		NONE		NONE
STA PRES						27.82		27.82		27.81		27.80		27.79		27.76		27.73		27.70		27.66

Figure 5.2.10. Example of an NWS fire weather point forecast matrix. Customized products for the local area are highlighted at the bottom of the graphic. (National Weather Service 2015b).

Meteorological Rules of Thumb for Smoke Management

Meteorological rules of thumb for smoke management can be characterized through examination of general atmospheric dispersion features and the reaction of the various tools for predicting smoke and smoke effects during the evolution of a large scale low pressure system as it moves east across the country. During many times of the year, one of the map features shown in figure 5.2.11 will apply to a location (relative to the large scale general weather pattern) where prescribed fire activity may be being planned.

The labeled regions on the map in figure 5.2.11 depict: A, an area north of a warm front; B, an initial ridge breakdown; C, pre-cold front; D, post-cold front; and E, an area beneath a ridge, respectively. General characteristics for these meteorological events and the corresponding potential value ranges using the indices discussed earlier in this chapter are described in table 5.2.12.

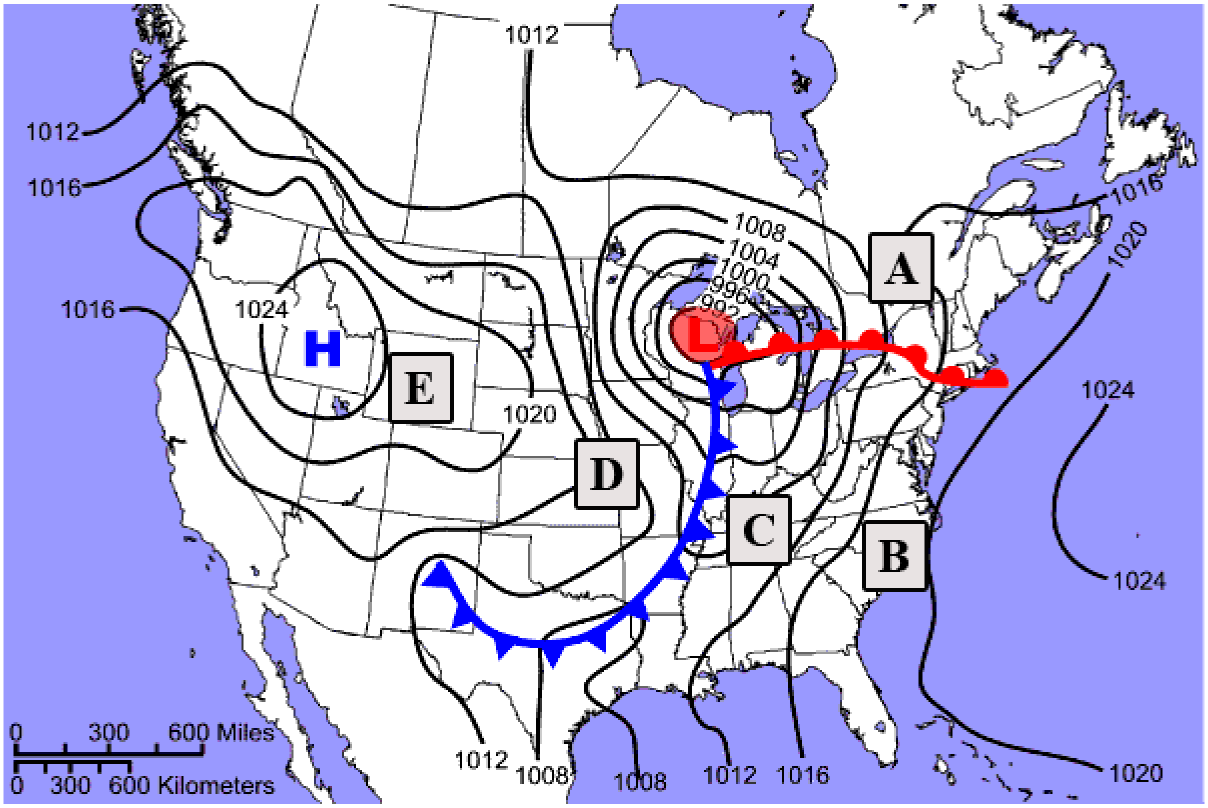

Figure 5.2.11. Map of the U.S. showing several meteorological events which can affect smoke conditions. The regions of the map depict an area north of a warm front (A), an initial ridge breakdown (B), pre-cold front (C), post-cold front (D), and area beneath a ridge (E). These are described in detail in table 5.2.12.

Table 5.2.12. General meteorological characteristics and indices corresponding to the map points in figure 5.2.11.

Map point	**General characteristics**	**Ventilation** (daytime)	**ADI** (daytime)	**LVORI** (nighttime)	**HYSPLIT-trajectory**
A—North of warm front	Moist, stable, low mixing heights, low-moderate transport winds, minimal influence from local wind systems.	Poor/Fair	< 30	8 +	Short, steady, towards W/NW
B—Initial ridge breakdown	Varying moisture (tending moist in eastern U.S.), increasingly unstable, moderate mixing heights and transport winds, strong influence from local wind systems.	Fair/Good	50-80	4-8 (Higher SE U.S.)	Moderate length, steady or rising, towards N
C—Pre-cold frontal	Varying moisture (tending dry western U.S. and moister east), most unstable, high mixing heights and transport winds, minimal influence from local wind systems, beginning of clearing event.	Excellent	80-100+	1	Long, rising, towards NE
D—Post-cold frontal	Dry, initially unstable – but stabilizing fairly rapidly, moderate to high mixing heights and transport winds (but both lowering over time), minimal influence from local wind systems, second part of clearing event.	Good/ Excellent	60-90	1-4	Long (but shortening over time), steady or sinking, towards E/SE
E—Beneath ridge	Varying moisture (tending dry western U.S. and moister east), generally stable – but with often significant surface based instability, relatively low mixing heights and transport winds, local wind systems dominant, relative stagnation.	Poor/Fair	20-50	4-8+ (Higher SE U.S.)	Short, often spiraling and complex mix of rising & sinking

Importance of Local Winds

Kevin Hiers

Using local winds is one of the easiest and more practical means of avoiding impacts. Whether from larger scale local winds like sea breeze circulations or more discrete phenomena, like canopy openings and wind eddies, the smoke impacts related to local winds on burn units are often underappreciated. Despite the widespread knowledge of the effects of seas breezes, they still frequently catch burners off guard and accounts for dozens of smoke management mishaps. Anytime there is a temperature differential between land and sea, a circulation may be established and needs to be considered.

In January on a warm sunny day, temperature 72° F, a prescribed fire was ignited between a state highway and the Choctawhatchee Bay. Just after noon, a 180-degree wind shift shutting down a state highway and took smoke inland for a mile lofting to 2000 feet AGL. A little while later the upper level smoke returned it overhead in the predicted wind direction. While the surface wind shift was not predicted (and it certainly was not in the forecast), the vigilance and experience of the burn boss to the possibility allowed for quick reactions to the traffic issues on the roadway.

On a smaller scale, knowledge of local winds can mitigate, or avoid impacts. When burning against a road frontage, maintaining a simple 50-100 foot buffer (outside of the right of way or beyond power lines often parallel to roadways) can avoid the temporary effects of wind eddies and local circulation around vegetation openings which can lead to obscured visibility. Use the predictability of seas breeze to "turn" smoke plumes inward away from populated coastal areas which can, despite predicted transport wind, reduce the potential for impacts. Simply knowing if a lake is large enough to affect wind direction, or which directions sea breezes come from on a portion of your forest or property is invaluable. Again, this local smoke management experience is critical to learn and to later share.

Smoke Management Situations that Shout "Watch Out"

In addition to the meteorological "rules of thumb", the following list of smoke management watch-out situations are listed to raise awareness for fire and smoke managers. These situations warrant special care to mitigate inherent risks. Below are ten of these watch-out situations, and measures to mitigate them:

1. **Burning on a long-term forecast (multiple burn periods):** The reliance on a forecast more than 12 hours from the start of ignition should always raise concern. For prescribed fires of multiple periods, there should be significant on-site weather observations. Frequent acquisition of updated forecasts and trigger points should be used to prepare for unexpected conditions.
2. **Burning on a red-flag day:** Red flag conditions issued by the National Weather Service are customized to the region of the country and represent the potential for rapid fire spread. In simplest terms, a burn plan and prescription should justify why red flag conditions are necessary and appropriate. These conditions typically correspond to higher winds which can help move smoke from the burn site but can also limit long range dispersion.
3. **Burning in activity fuels (logging or thinning slash, post-herbicide), storm damaged forests, or long unburned stands with duff smoldering potential:** Long duration smoldering potential is the cause for concern in this situation. Mitigation measures include burning under moist conditions to reduce the fuel available to long-duration smoldering, reduce unit size, or burning only isolated areas if less than ideal smoke dispersion is forecast.
4. **Burning in dry wetland features or areas of peat and organic soil:** This is one of the most common fuel types that result in residual smoke effects from burning in the Southeast. Not only

do the fuels often smolder, but they are in topographically low areas that tend to pool smoke. Mitigation includes looking for LVORI values of less than six or consistent nighttime winds away from roadways.

5. **Predicted land/sea breeze:** Differential heating between land and large bodies of water create diurnal air pressure changes that result in a sea breeze, where winds move from the water towards the land during the day; and a land breeze, where air flows from the land to the water body at night. Confer with local experts on the timing of the sea/land breeze reversal to avoid smoke effects to coastal residents. Mitigation can include early ignition and extensive mop-up, and burning in seasons when sea/land breezes are less likely.
6. **Burning next to any major transportation corridor:** Transportation smoke safety is critical any time there is a planned ignition. Obviously avoidance is critical, but to effectively burn adjacent to roadways, planning for unforeseen effects is critical. Posting lookouts for evening and early morning hours is critical as most smoke related accidents occur between 4 and 6 AM.
7. **Multiple large burns in vicinity:** Multiple fires—particularly aerial ignitions—have been observed to entrain one another at great distances (miles apart) and modify local wind fields at the burns, or plumes have merged downwind to create intense smoke effects. Communicating with other land managers in the area or coordinating multiple ignitions on your property is critical to avoid unexpected effects.
8. **Uncertain Forecasts:** When reading forecast discussions, any divergence of models used to generate the fire weather forecast provide indications that conditions are uncertain. If smoke management objectives require specific winds, nighttime dispersion, or humidities consult a meteorologist.
9. **Large unit with no cutoffs:** These burn units require high forecast certainty and strict adherence to very narrow dispersion windows. Large units (>1000 ac) have the ability to affect smoke sensitive areas 50-100 miles away.
10. **Mountainous Terrain:** Down slope, down-valley winds and inversions should be carefully monitored to avoid local smoke effects. Initial nighttime ignitions on ridgelines mean that thermal belts are not as great a concern for initial burn periods. Consider use of lookouts or smoke observers monitor smoke transport.

Summary

Burn bosses have always managed smoke, but increasingly, they are becoming emissions managers. While the information in this chapter is by no means exhaustive, it provides real world examples of smoke management tools, techniques, and situations that will improve the ability of fire managers to manage smoke and emissions effects. Each of the tools described in the chapter is summarized in table 5.2.13.

When using these tools throughout the planning process it is important to document lessons learned about what worked and what didn’t at specific locations, this is critical expert knowledge for future burners. It is also critical to provide input back to those developing smoke management forecasts so they can further refine and improve their prediction capabilities. Documenting lessons learned and providing input back to smoke forecasters will help improve smoke management thus maintaining public trust and avoiding unnecessary conflict between air quality concerns and natural resource benefits of prescribed fire.

Table 5.2.13. Summary of the tools presented in this chapter.

Tool	Usage	Brief description	Tips for use	Tool access
Ventilation index (VI)	1 to 7 days before day of ignition	Simple metric of smoke dispersion potential. Higher values indicate better potential dispersion.	- Use to assess adequate daytime dispersion windows one week in advance, and to assess specifics and variability within a few days of ignition. - Augment with observations, especially where local weather influence is expected.	Point forecast via National Weather Service (NWS) Fire Weather Portal; local fire weather forecast (FWF) or point forecast matrix (PFM); by request in spot forecasts.
Lavdas atmospheric dispersion index (ADI)	1 to 3 days before day of ignition	More complex metric of dispersion potential than VI. Incorporates transport wind speed, mixing height and stability class to find an index value from 1 to over 100. Higher ADI values mean better potential dispersion.	- Use before ignition, along with high-resolution weather modeling to assess the combined effects of general and local weather factors on dispersion potential. - Be aware of potential inaccuracies due particularly to varying cloud height/amount. - Validate how well ADI captures conditions at a burn location before using for decision making.	Local FWF or PFW, sometimes upon request in spot forecasts.
Low visibility occurrence risk index (LVORI)	Prior to ignition	Combines ADI with relative humidity in relation to traffic accidents from reduced visibility caused by smoke and fog. Higher values indicate increasing risk for traffic accidents.	- Use along with other indicators to assess the risk of reduced visibility due to smoke and high humidity; especially during the night and early morning following a burn. - Use caution when burning near WUI or high traffic areas if nighttime LVORI is 7 or 8; avoid burning when values are 9 or 10 unless extensive mop-up is planned.	Local FWF or PFW, sometimes upon request in spot forecasts.
HYSPLIT-trajectory	No more than 48 hours before ignition	Three-dimensional forecast of air parcel trajectory, useful for assessing the downwind travel of smoke.	- Use in consultation with a subject matter expert (SME) to assess potential smoke trajectories and locations of effects. - Best used when winds are moderate to strong and not overly influenced by local wind systems. - Nighttime use not generally recommended. - Assess the characteristics of forecast trajectories to consider modifying burn timing and/or intensity.	Air Resources Laboratory HYSPLIT website (with SME assistance) via NWS spot forecast request by adding the term "HYSPLIT" and an e-mail address in the remarks section.
Estimated smoldering potential (ESP)	Usually 1-7 days before prescribed fire ignition and anytime for wildfires	- Models potential sustained smoldering of organic soil. - Relies on knowledge of soil properties and soil moisture.	- Values are dependent on soil moisture and mineral content. - Use to establish a burn/no-burn decision threshold. - Can be used to estimate parameters important to emission prediction.	See figures. 5.2.6 and 5.2.7.
Superfog Potential (SFP) table	Usually within 1 to 3 days before prescribed fire ignition and daily for wildfires	Projects the probability of superfog events from smoldering fires. Visibility is < 10 feet.	Consider the environmental caveats; air temp > 40º F but < 70º F, RH > 80%, wind. speed ≤ 4 mph.	Table. 5.2.11
Planned Burn-Piedmont (PBP)	Usually within 24 hours or less when information is needed	Shows possible location of surface smoke plume and fog formation as a result of smoldering combustion.	Be sure to start model run 3 pm the prior afternoon. The model run needs to include the cooling down period from the afternoon to nighttime. This reinforces the model's ability to predict surface smoke transport.	Found at CEFA website https://cefa-new.dri.edu/PB_Piedmont/

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5.3. Smoke Prediction Models

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Over the past decade, major advances have occurred in the science of predicting smoke impacts from wildland fire. These advances can be attributed to faster, more sophisticated wildland fire emissions and smoke plume modeling systems, enhanced databases of on-the-ground fuels, and the use of new technologies that allow for direct user interaction and input with smoke prediction tools via computer applications and the web. The result is a proliferation of tools that are now available to fire practitioners. These tools range from very simple indices that characterize the condition of the atmosphere to complex full chemistry models that simulate chemical transformations and are necessary for understanding ozone formation and regional haze. While these tools have placed more information in the hands of decision makers, the underlying assumptions, limitations, and applicability considerations of these tools can be confusing and daunting when trying to determine how best to apply the information to the decision-making process.

Within this chapter we distinguish between tool and model as follows: a *tool* – a system designed to supply information into a decision process – and a *model* – the numeric engine that can be operated in many settings, and can form the core scientific basis for a decision support tool. In short, the tool supports the decision process and the model supports the tool. Smoke prediction tools range from simple two-dimensional mapping systems to complex interactive websites. They are supported by models that perform complex calculations behind the scenes. Information requested by the webpage or model (as input to be supplied by the user of the smoke prediction tool) ranges from no information at all—when simple tools can operate entirely on defaults—to the multiple custom inputs and observations of on-the-ground meteorological and fuel conditions, needed by more complex models. This range of complexity and input requirements allows a user to select a modeling approach that balances their need for accuracy and precision with the time and effort available for the analysis.

Important terms used in this chapter:

TOOL: A system designed to supply information into a decision process.

MODEL: The engine that forms the scientific basis for the tool.

So, the *tool* supports the decision process and the *model* supports the tool.

The science of predicting and understanding wildland fire emissions and smoke concentrations is complex. Many different components of the fire must be modeled to predict smoke plume pollution concentrations at the surface. These include fire spread and consumption of fuels, fire emissions production, vertical placement of the emissions (plume heights) and, finally, smoke plume transport, spread and in-plume chemistry. To predict downwind smoke concentrations each of these components must be calculated; different types of models have been developed to assist with these estimates. Each model has its own set of assumptions, sources of uncertainty, and error. This chapter reviews the types of models used in the smoke plume transport, spread, and in-plume chemistry component of the smoke plume prediction process. It also presents examples of tools currently available along with key elements and considerations needed to best apply them to real-world smoke applications.

Although the discussion here endeavors to be comprehensive, it is necessarily incomplete, and in complex situations managers are advised to seek the advice of trained smoke modelers. In addition, because the science and application of smoke models is rapidly evolving, managers or modelers interested in the details of specific smoke models are directed to trained smoke modelers for more specific advice. It is important to remember that model predictions are only a tool to assist with the decision process; they are not definitive and they may miss a smoke impact problem or predict a smoke impact when none occurs. It is possible that meteorological and dispersion conditions at a burn site may not match what has been predicted by a model. Therefore, it is important to check the meteorology and air quality conditions at the burn site and, if possible, at the potential smoke sensitive receptors before ignition. Models may tend to be more or less accurate in some geographic areas so it is helpful to determine if local knowledge on smoke behavior is available from other fire practitioners.

How and When to Use a Smoke Prediction Tool

Using smoke prediction tools during prescribed fire planning or wildfire operations makes it possible to include smoke production and potential air quality effects in the decision-making process. There are two terms that are commonly used when describing smoke predictions and effects: *source* and *receptor*. The *source* is where the emissions are generated, so in our case the fire itself, whether it is flaming or smoldering. The *receptor* is the entity affected by the smoke. The receptor can be a person, fire camp, community, hospital, or Class I Area, to name a few examples.

Often, regulations (federal, state, local, or tribal) or state or agency procedures require fire practitioners to consider potential smoke effects on receptors when contemplating decisions surrounding ignition of prescribed fires. When contemplating locations where the smoke may affect a receptor, it is helpful to remember that smoke may be an issue:

- Very near the fire (e.g., affecting fireline personnel and aircraft operations)
- Near the fire (e.g., affecting fire camps, secondary fire personnel, and nearby roads and towns)
- Far downwind (e.g., affecting roads, airports, hospitals, towns, and visibility for many tens to hundreds of miles)

Determining where the smoke from a fire will go depends on a great many factors including: the amount of emissions, how high they are lofted, where the emissions are transported, and how the emissions mix and change chemically with the non-smoky part of the atmosphere during their transport. In general, the hotter the fire (often associated with larger fires), the higher the plume rise, and the higher plume can place emissions in a portion of the atmosphere where winds can transport the emissions tens to hundreds of miles downwind. Even smoke from smaller, cooler fires can become an issue because of:

- Drainage of smoke down valleys and canyons (e.g., low lying smoke can enter into the nocturnal downslope winds, remain concentrated, and affect a nearby roadway or distant town).
- Other burning in the region (e.g., local smoke mixing with smoke from other regional fires).
- Residual smoldering.
- Proximity to smoke sensitive areas.

When choosing and using smoke prediction tools, it is helpful to bear in mind:

- The local geographic situation; for example, distance to sensitive receptors, nocturnal downslope drainages, and potential for pooling of smoke in low lying areas that may result in formation of white-out conditions, informally called “superfog.”
- The size of the fire. What were the smoke impacts of similarly sized burns in this region? Are only very nearby smoke impacts expected? Close proximity impacts? Far downwind impacts?

- The regional situation. How many other fires are burning in the region? Have there been public complaints? Has public awareness been heightened due to smoke from these or past fires?

Types of Smoke Models Used in Smoke Prediction Tools

One of the first things to consider before using a smoke prediction tool is the type of smoke model that is most appropriate for your situation and whether or not the prediction tool you wish to use includes that model type. The types of models used "behind the scenes" by smoke prediction tools differ greatly in their complexity and appropriate range of use. There are many different model types used by smoke prediction tools in the smoke plume transport, spread, and chemistry component of the smoke plume prediction process. These model types include, in approximate order of increasing complexity, simple approximation models, plume models, trajectory models, puff models, particle models, and "one-atmosphere" (full photochemistry) grid models (figure 5.3.1). Each model type represents a distinct method for estimating smoke concentrations, with its own advantages and drawbacks.

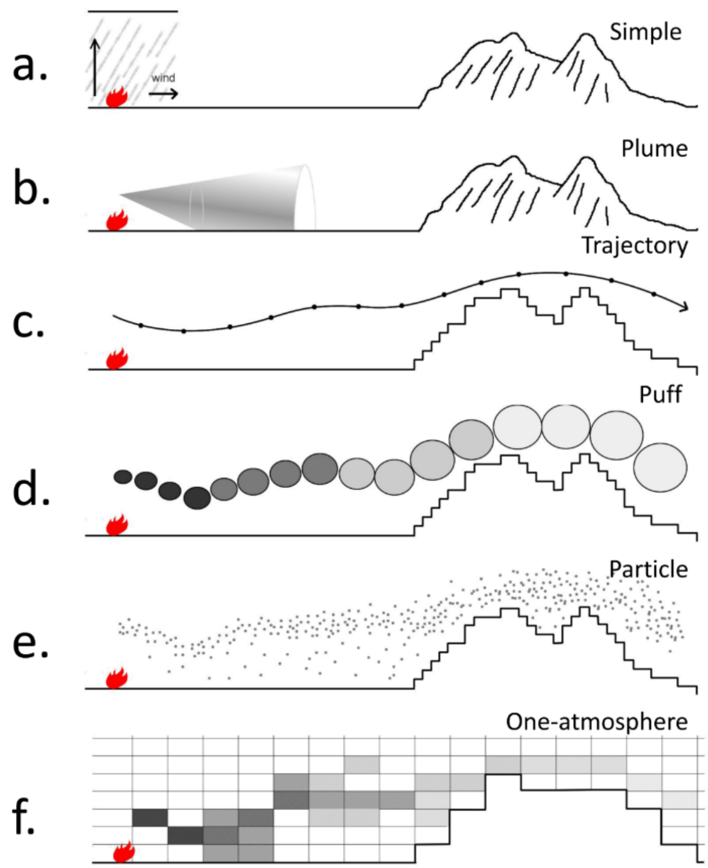

Figure 5.3.1. Conceptual illustration of how each of the model types treats the smoke plume and trajectory. Where 'Simple' is short for Simple Approximation Method.

Information needed by smoke models

All smoke model types require information about the source of emissions, which is the fire, and the meteorology. The bare minimum information needed is fire location and size. The minimum meteorological information needed is wind speed and direction. More complex model types, such as plume, puff, particle and one-atmosphere, require an estimate of hourly emissions from the source of the smoke (the fire). To calculate emissions by the hour, estimates of fire spread and fuel consumption rate (hence fuel type and moisture) are required. This detailed information is necessary because different fuel types are associated with different consumption efficiencies and different quantities of emissions of gases and particles (see Chapter 4.1). Four-dimensional (three spatial dimensions and time) predictions of meteorology are also required by some of the more complex smoke plume model types. Figure 5.3.2 illustrates the type of information needed to model smoke. Note that not all of the required information listed necessarily has to come from the user; when used as part of a smoke prediction tool, smoke models are often combined with other models (consumption, emissions, weather) that can provide this information.

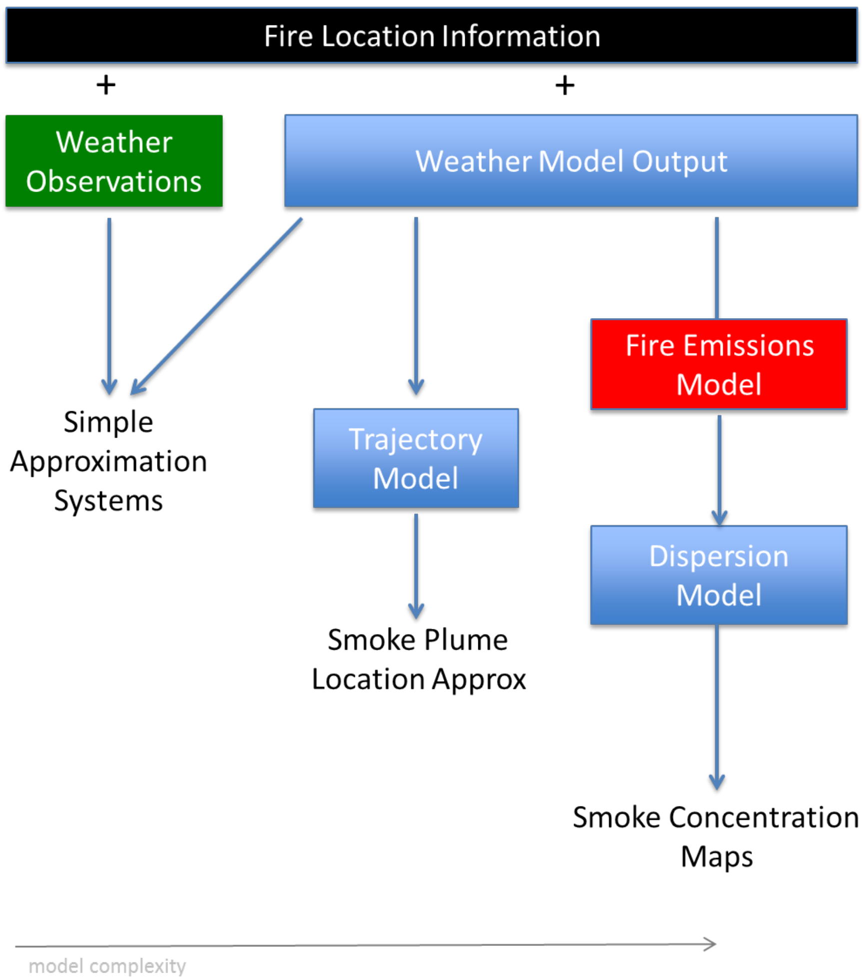

Figure 5.3.2. Information typically needed by smoke prediction models. Simpler model types require less information (left side) while more complex model types require additional information (right side).

Simple versus complex model types

In general, the simpler model type has more basic assumptions built into its system. For example, a simple model may assume the winds are steady while a more complex model will use the changes in wind predicted by meteorological models. Figure 5.3.3 shows a top-down view of what the output from a particular model type may look like. Note that the smoke plume becomes less simplified with the complex models. All model types have limitations that correspond to their built-in assumptions; thus, if the model type is applied beyond the scope of its design large errors in the smoke predictions will result.

For example, fast and simple plume models developed for use with steady-state winds over a flat landscape may not produce valid predicted smoke concentrations for complex terrain.

For more complex model types (e.g., trajectory, puff and particle, and “one atmosphere”), representing

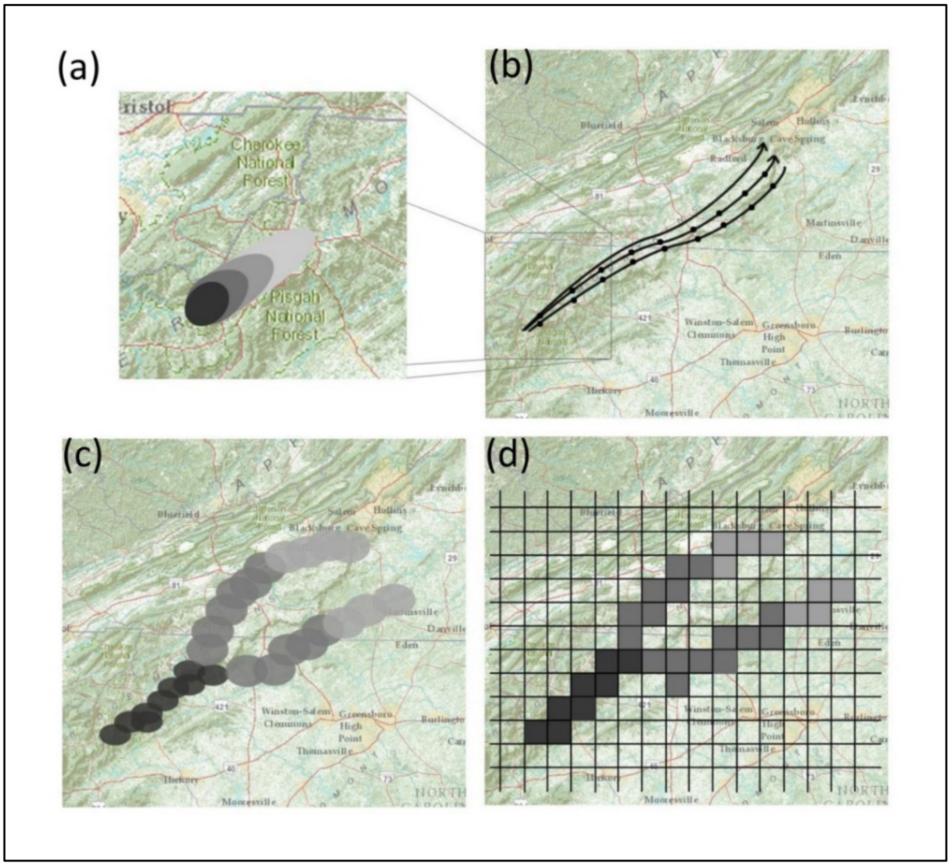

Figure 5.3.3. Top down view of (a) plume, (b) trajectory, (c) puff, and (d) one-atmosphere models conceptually compute smoke concentrations and what the output may look like. NOTE: plume output is located near the fire source compared to the other models. The resolution of the one-atmosphere plume is highly dependent on grid size, the larger the grid the more ‘smeared’ the plume becomes.

meteorology in complex terrain is of critical importance. In order to model winds and temperature shifts that result due to terrain, a fine meteorological grid is required; for the grid size of the meteorological model determines the level to which local topographical features affect wind flow. Standard meteorological forecast models from the National Weather Service are sufficient for general smoke forecasting; however, in cases where nocturnal drainage of smoke down-valley systems is of concern, a smaller (higher grid resolution) grid spacing is important. There are regional modeling centers that use models with higher grid resolutions and make the output smoke predictions available online.

The following discussion walks through the smoke model types starting with the simplest and progressing towards complex model types. Always remember the model results can only be as good as the data entered into that model.

A Summary of Current Models and Methods

Mark Fitch, Smoke Management Specialist, NPS, and Janice Peterson, Air Resource Specialist, USFS

Below is a list of current models used to predict atmospheric dispersion and smoke concentrations, and a brief explanation of each.

Simple

- Ventilation Index
- Atmospheric Dispersion Index (ADI)
- Low Visibility Occurrence Risk Index (LVORI)

Used to approximate the dispersion conditions of the atmosphere. Many state smoke programs use the ventilation index for go/no go decisions for prescribed fires. Many National Weather Service fire weather forecasts include the ventilation index in their discussions. (See chapter 5.2 for more information.)

Plume

- V-Smoke
- SASEM

An increase in data is needed for these models. They use Gaussian equations to approximate plume dispersion with the highest emission concentrations in the center of the distribution. Plume models are best suited for flat or gently rolling terrain.

Trajectory

- HYSPLIT-trajectory

A trajectory model uses modeled meteorological output to reflect the movement of the centerline of a parcel of air in the horizontal and vertical. The user provides a starting height of the air parcel–the model does not estimate the buoyancy of the parcel of air. Thus, the starting height represents the height where smoke is released. Trajectory models do not require fire emissions, so output does not show smoke concentrations, just where the centerline of the smoke plume will travel.

Puff and Particle

- CALPUFF
- HYSPLIT-dispersion
- FLEXPART

These sophisticated models require more information to run including 4D meteorological data and emissions from the fire. Their benefits over the simple, plume or trajectory models is that they are useful in complex terrain. These models transport and disperse smoke plumes downwind and estimate surface pollution concentrations. While there are differences in the way each model emits the smoke emissions—think balloons vs. confetti—both models provide a forecast of surface concentrations given emissions from a fire.

One Atmosphere

- WRF-Chem
- CMEX
- CMAQ
- GEM-MACH

One atmosphere models use relatively the same 4-dimensional weather data as puff and particle models, however, they require a more complex emission profile to run. They are regularly used to understand atmospheric chemistry, including secondary aerosol transformation and ozone formation. They are generally not used for operational forecasting of go/no-go fire decisions. These models require large amounts of computing power and output storage. Their complexity puts them outside the realm of daily forecasting of wildland fires.

Simple approximation methods

Simple approximation models are among the most straight forward method of estimating smoke effects.

The Ventilation Index (VI), discussed in Chapter 5.2, is a simple approximation model that uses a simple calculation (often, the mixing height multiplied by wind speed) to predict the potential for the atmosphere to dilute and mix the smoke. This index is sometimes referred to as the clearing index. The VI is calculated slightly differently (different height definitions and different wind speeds) in different regions of the country and therefore it is beneficial to ask how the VI is calculated and used at your location. In some regions of the country the VI is used in some smoke management programs as part of the go, no-go decision process for a prescribed fire. The VI does not estimate emissions or smoke dispersion so it cannot be used to determine if smoke concentrations will be high at a specific receptor.

Simple screening methods

Another simple approach for estimating smoke impacts is to use a screening method model. Most screening models are straight forward to run and can help determine if smoke is likely to affect sensitive receptors. Screening gives a rough estimate of where the smoke may go and alerts the user to sensitive receptors that may be impacted. Although screening is extremely useful, caution is advised when using this method because it does not account for terrain, atmospheric stability nor nighttime slope flows. The results must be considered only as an approximate guide.

The basic steps involved in screening are: (1) determine fire size, fuel loading, and fuel moisture, (2) calculate fuel consumption and smoke emissions (see Chapter 4.1), (3) map the direction smoke will travel using wind direction, (4) identify smoke sensitive receptors such as areas out of compliance for fine particulate matter ($PM_{2.5}$) and ozone, hospitals, schools, airports, highways, and areas subject to visibility protection, and (5) minimize the risk of smoke effects by changing the burn timing, ignition type, weather conditions, or day of burn.

A rough estimate of the direction a smoke plume may travel during the day can be estimated by considering the size of the fire and assuming smoke plume dispersion of 30° on either side of the centerline trajectory (Mobley 1976). This tool can be used either on the day of the burn with actual winds or as a planning tool by using forecasted winds. Mobley suggest the size of the smoke plume dispersion cone should be enlarged to 45° when using forecasted winds. This approach provides a rough estimate of smoke impact and does not account for terrain features or stability of the atmosphere. To minimize risk, consideration of mixing height, transport wind speed, background visibility, dispersion index, and various methods of altering ignition and mop-up patterns are needed. This tool is excellent for initially assessing impacts and determining if further work is required to better understand smoke transport and dispersion and downwind surface concentrations.

Screening methods are a quick and simple way to gain a rough understanding of where smoke may go and whether it will affect a sensitive receptor. They are a useful first step for understanding smoke transport and may be used in the initial burn planning process to determine if more complex model types are needed. More complex model types must be used to understand smoke effects, particularly in moderate to complex terrain, during nocturnal slope-flows and valley drainages, and when the atmosphere is unstable, or, if you want, to predict ground level pollutant concentrations.

Guides that describe how to use screening model types include: *Introduction to Prescribed Fire in Southern Ecosystems* (Waldrop and Goodrick 2012), *Managing Smoke at the Wildland Urban Interface* (Wade and Mobley 2007), *A Guide for Prescribed Fire in Southern Forests* (Wade 1989), *Southern Forestry Smoke Management Guidebook* (Mobley 1976).

Plume models

Plume-type models are designed to simulate a more realistic plume-like conical shape that starts at the fire location and continues downwind (figures 5.3.1b and 5.3.3a). This model type adds a layer of complexity in its calculation. The major assumption with this type of model is that the smoke travels in the primary wind direction and that both the winds (speed and direction) and the emissions are steady-state; that is, they do not change with time. The modeled result is a triangular area that represents the conical shape of the plume. The plume-type model handles wind direction changes and turbulence by increasing the conical area. Concentrations within the cone are dispersed in a bell-shape (Gaussian) distribution pattern with highest concentrations in the center of the cone.

Plume-type models are most commonly applied where the terrain is flat or gently rolling. They do not require detailed weather inputs and are useful when meteorological information is scarce. Approximations used in plume-type models become invalid when smoke extends beyond a distance that is reasonable for steady-state wind assumptions (typically up to about 30 miles or 50 km). When terrain or water bodies interact with the plume, steady-state wind assumptions become difficult to justify no matter how close to the source (the fire), and plume-type model results are no longer reliable. This type of model would not be useful for predicting superfog formation.

Trajectory models

Trajectory-type models are also conceptually simple, like plume models, but include another level of complexity because they allow for changes in the plume's trajectory as a result of the changing winds and atmospheric turbulence. Instead of treating smoke as a plume that spreads out with constant emissions winds, trajectory models simply keep track of the path a specific air parcel takes as it is transported downwind. The downwind path is typically shown as a line on a map (figures 5.3.1c and 5.3.3b). The path may meander and go up and down. Individual trajectories are often labeled with the time they were released from the source location. Most trajectory-type models use the four-dimensional meteorological data from weather models as their input. This allows the trajectories to change with changing winds, mixing heights, and other meteorological conditions that vary in time.

There are two significant hurdles to recognize when using trajectory models. The first is that, because a trajectory leaves the source at a given starting height above the ground with no additional buoyancy (e.g., from the heat from a fire), this starting height should represent the height of the smoke plume or it will be in the wrong layer of the atmosphere. The layers of the atmosphere dictate the strength of the wind speed and wind direction and, hence, plume transport. Therefore, some prior knowledge or educated guess as to the correct starting height at which to release the trajectory must be assumed or computed. For example, a low intensity prescribed fire may have a plume top height of 1000 feet, whereas a high intensity prescribed fire plume top may reach 3,000 feet. One technique that can be applied in the absence of additional information is to use several trajectories with heights varying from near the surface up to a few miles above the ground.

The second hurdle is in interpretation. Although the trajectory-type model provides a path along which smoke will go, and therefore a geographic line over which smoke will pass, it does not reflect the dispersal (outward spread) of the smoke or the concentrations of pollutants within the smoke plume. Because the trajectory usually represents the centerline of the plume, the smoke effects area can be interpreted as spreading out on either side of the trajectory path. Another interpretation of the data can be made by looking at the vertical height of the trajectory path downwind from the fire, for example, to see if it moves closer to the ground. This could indicate higher smoke concentrations. Both interpretations can be used to form a working mental picture of expected smoke effects near the ground, but neither is exactly correct. Unfortunately, interactions with wind shear, variable and complex terrain, and other factors mean that the actual smoke effects, including the location of the maximum ground level smoke concentration, can differ from the predicted trajectory path.

Ultimately the trajectory represents how the air will move, regardless of whether there is smoke or not. Thus, although trajectories provide a simple and often useful picture of the potential smoke plume path, one must exercise caution and not assume that they represent the full picture.

Puff models and particle models

Puff (figure 5.3.1d) and particle (figure 5.3.1e) models have advantages over the simpler screening and plume models because they include fewer assumptions, are applicable over complex terrain and water bodies, and provide a means to describe a source (fire that emits pollutants at a variable rate). They also attempt to directly model smoke concentration, eliminating the major drawback of trajectory models. Both the puff- and particle-type models provide a method to transport and disperse (spread) smoke plumes downwind. The advantage of these model types is that they can model fires that vary over time and are subject to changing winds and complex terrain.

The particle model type is named so because of the method it uses to simulate the plume, it can be used to describe dispersion of all types of pollutants, including gases.

Puff and particle model types differ in how they treat smoke. In both model types, fire emissions (smoke) are emitted at discreet time steps and then transported downwind by the inputted wind data. In a puff-type model, smoke is treated as a three-dimensional circular “puff” of mass (figure 5.3.3c). The puff volume grows and moves every time step to simulate dispersion (spread and dilution) of the smoke. In a particle-type model, many thousands of particles are sent out at each time step. The number of particles used is related to the total mass of pollutants emitted from the fire. Each particle responds to atmospheric turbulence differently and their direction of motion is tracked and smoke plume dispersion (spread) and concentrations calculated. Both model types are a better selection for use during changeable weather conditions and around complex terrain compared to the simpler plume-type model.

Puff- and particle-type models assume that neither emissions nor meteorological conditions change during the model time step (e.g., one hour). Therefore, for both model types, the shorter the time step the better the results because each time step can use new emissions and meteorological conditions. Most national-scale tools use one hour time steps due to the amount of computational time these models take to produce results. With faster computers becoming available, these time steps should start to decrease.

Sometimes the puff- and particle-type models can be combined and used as a hybrid. Typically, the particle-type is used to describe vertical smoke movement where dispersion is more sensitive to quick changes in atmospheric turbulence, and the puff-type is used to model the spread of the plume in the horizontal plane. This allows for a faster calculation and model run time.

It is important to note that puff and particle model results are often placed on a grid for display. This is a function of processing the results of the model, not of how the model internally represents the smoke.

One-atmosphere (full chemistry) models

“One-atmosphere”-type models explicitly handle the pollutant (gas and particle) chemistry that occurs within the atmosphere. The advantage of modeling smoke with this model type is that it includes consideration of emissions from industry, vehicles, and urban centers, and therefore simulates the mixing of the fire-produced smoke plume with all other urban plumes. This provides a more realistic estimation of how smoke from the fire affects pollution levels relative to other pollution sources. This model type is very useful for evaluating the effect of smoke on regional haze and ozone concentrations.

One-atmosphere-type models compute a range of atmospheric gas and particle phenomena including interactions, transformations, and deposition out of the atmosphere. Sometimes called "air quality models" they are the most complex model types of any described herein. Due to this complexity, they are rarely used in the go/no-go decision making process. This model type requires a super-computer and model results, predictions of smoke concentrations, are only available via the internet. Managers may need to use results from this type of model if ozone is a pollutant of concern, or if regional visibility modeling at Class I areas is needed. This model type is designed to evaluate all potential air quality effects from all known sources in combination with the regional background air quality. The one-atmosphere type of model does not follow individual plumes; rather, it computes concentrations of pollutants within each grid cell (figure 5.3.1f, 5.3.3d). The assumption is that the grid cells are small enough in volume to appropriately represent the mixing and chemistry of the pollutants in the atmosphere.

Which Smoke Model Type and or Tool Is Best?

Given all of the model types and their inherent complexities, the question naturally arises: which model type is right for my management need? The key consideration for choosing a modeling approach is in the question you wish to answer. The modeling type should fit the question. For questions surrounding ozone and regional haze (visibility impacts), the choice is simple–only the one-atmosphere (full chemistry) type of model is appropriate. This is because ozone is formed through chemical reactions, and regional haze is affected by chemical reactions. For other questions, generally a combination of the distance downwind to sensitive receptors and the complexity of the terrain dictate the type of model that should be chosen. Results from one-atmosphere models are made available on the internet through many regional and national organizations.

Beyond the matching of question and model type, a skill that is learned with experience, the choice of model type is usually also a matter of access to required input data, available modeling tools, comfort level of using that tool, history, and past model and/or tool performance. It is important to note that different tools, even ones that use the same model types, may markedly differ in their performance depending on how they were set up (with input information and modeling options).

The advent of web-based interfaces and fast servers has increased the utility and availability of many smoke prediction tools, each using a variety of model types. For example, there are tools online that use screening or plume type models to determine areas likely to be affected by smoke. An example of this is the U.S. Forest Service (USFS) Simple Smoke Screening tool developed for the Southeastern U.S. There are also tools that allow users to perform puff and particle modeling in real-time with results returned after a short wait. These tools allow the user to customize the input to their specific needs and to experiment with different options, leading to understanding inherent model type sensitivities and uncertainties. A current example is the HYSPLIT tool, made available by the National Oceanic and Atmospheric Administration. Customized modeling is often a good choice when the user has specific local knowledge of fire conditions such as fuel loadings or expected consumption.

The advent of integrated smoke modeling frameworks has allowed users to easily switch between different model types and model assumptions. Pathways through the framework are selected by the user and vary in complexity. Frameworks allow the user to choose between different sources of input information and a range of assumptions used by the models to quantify downwind smoke effects. These frameworks have web-based user interfaces, which make them valuable tools for learning how different input and model selection affects the results. As of this writing, the USFS BlueSky Smoke Modeling Framework (Larkin *et al.*, 2010), a modular framework combining fire and weather information with fuels, consumption, emissions, plume rise, and models such as the trajectory and puff, particle, and one-atmosphere dispersion models is available online through the USFS BlueSky Playground tool. By going through such systems and changing options and parameters, users can investigate and learn about modeling sensitivities as they apply to their real-world fires. Such “game-playing” is intrinsically useful in building up your intuition on smoke effects and smoke prediction tools.

Additional Considerations

Complex smoke models are capable of modeling smoke from multiple fires in a region simultaneously. Results include cumulative smoke effects given as hour-by-hour ground concentration maps. It should be noted that, often, smoke plumes from small prescribed fires are not included in these results because of difficulties in detecting these types of fires from a satellite platform and in logging and reporting them before they occur.

Overall, complex smoke models are good at predicting smoke plume trends, overall pattern of smoke impacts, expected maximum level of concentrations, and the general location of the highest ground concentrations. The models do not do well at predicting the exact (hour-by-hour) timing of smoke concentrations. This does not mean that they are valueless. Their predictions of overall daily concentrations or the maximum concentrations have proven very useful for determining smoke effects in sensitive areas. Some systems routinely do better mid- to far-field (few to hundreds of miles) from the fire, and within a time frame of current to a few days. Knowing the spatial and temporal scale the model used to quantify the smoke concentrations will assist your understanding of the likelihood for prediction error. Also, a trained smoke forecaster, familiar with the modeling system under consideration, can often correct for biases and errors in the modeled results, dramatically increasing its usability.

Meteorological Inputs

The grid resolution (size of the grid the predictions are made on) of the meteorological information used, typically from a numerical weather forecast model, is critical to most model types presented here. Winds from the meteorological model are used to compute the transport and dilution of the smoke plume. Therefore, it is important to know the grid size of the meteorological input because the larger the grid size, the more the modeled winds are averaged or ‘smeared’ over the grid cell. For a plume-type model to simulate smoke plume movement around terrain features (e.g., mountain valleys and ridges), the meteorological model grid size must be smaller than the terrain feature.

West vs. East

Fires and their smoke effects differ depending on where they occur. Often, the fundamental questions and concerns that drive smoke management issues differ across the country. In the eastern U.S., generally higher population and road network densities have historically created a focus on smoke management issues that tend to occur near the fire. In the western U.S., far-field concerns such as smoke nuisance, regional haze, and regional air quality have historically received more attention.

There are specific challenges for each portion of the U.S. that influence the type of model or smoke prediction tool that best suits the decision making process. Western wildfires burning for many days in complex terrain will require a different smoke prediction tool than will numerous prescribed fires burning for a single day in the east. For example, many of the plume-type models work well to describe potential smoke effects in the southeast, but are not applicable in the mountainous west.

Similarly, consumption models— used in the modeling chain to predict the quantity of emissions from the source (fire) —can introduce error into the smoke predictions. For example, a consumption model developed for predominantly above ground dead fuels will not adequately represent the deep organic consumption that can occur in southeastern and north-central fuel types as well as in Alaska fuels. In humid regions such as the Southeastern U.S., an additional consideration is the potential for smoke to mix with a saturated air mass and form whiteout conditions, commonly referred to as “superfog.” This is an extremely dense mixture of smoke and fog that reduces visibility to near zero and has caused serious traffic accidents.

Uncertainty

All prediction systems include a level of uncertainty which may originate from the meteorological inputs, the fire characterization, emissions information, or from the assumptions used in the models that predicted the smoke plume movement or concentrations. Some systems use satellite-based fire detection data directly entered into smoke plume and trajectory models. A degree of uncertainty is associated with this type of data including information about the total size of the fire and the number of fires present. Prescribed fires can be too small for a satellite to detect and, therefore, would not be present in the fire information data. In addition, faster moving fires may be missed or their location misrepresented. Characterizing fire as a source of emissions is difficult; however, a recent study found plume rise and the rate of emissions or consumption to be the most uncertain components in characterizing emissions from fire (Larkin *et al.* 2012). Both of these are closely linked to fire spread and behavior. Because of the inherent complexity and variability in fire behavior, it is very difficult to accurately predict the number and vertical extent of the individual plumes that are generated by the fire. If the plume is modeled at a height that is too high, where the winds are strong, then the plume will be shown to quickly move away from the fire. If the plume is placed too low, in a layer where the winds are slower, the modeled smoke will appear to remain near the source.

The Future

How are smoke prediction tools expected to change? There are three important trends likely to affect the availability, usability, and accuracy of smoke prediction tools in the next decade.

The first is the increasing use of web-based technologies to create custom interfaces for resource managers to access, use, and customize smoke prediction information. Tools like the BlueSky Playground, Wildland Fire Decision Support System (WFDSS), Interagency Fuels Treatment Decision Support System (IFTDSS) and others are likely to become easier to integrate. In the near term, fire information in one system is likely to be transferrable to other systems. Efforts are also underway to make these smoke prediction tools available on mobile devices, “untethering” smoke managers from their computers.

The second is a growing recognition that improved smoke predictions require improved models of plume rise and a better understanding of plume chemistry. Plume rise is linked to fire growth and consumption modeling, and a better understanding of the fire itself is necessary for improving plume rise modeling. With efforts by the Joint Fire Science Program and the National Atmospheric and Space Administration (NASA) to push forward on creating better models through integrated field campaigns, ground-based confirmation of satellite information, and other activities, it is possible that more accurate smoke models may become available in the next 5 to 10 years. In-plume chemistry is complex and differs from regional airshed atmospheric chemistry. Researchers are currently working to understand how plume chemistry changes as the plume ages and moves away from the fire and the heat source. Observations translated to model algorithms over the next few years will help to improve the “one-atmosphere” models discussed above.

The third is the continuing advancement of computer technology. With faster computers, meteorological model results will be on finer grid cells, allowing for the predicted dispersion of smoke to be more greatly influenced by terrain. The faster computers will also allow the more complex one-atmosphere-type models to work on a smaller grid, which better represents the volume taken up by a smoke plume.

In this way, less sophisticated models with many inherent assumptions (such as no plume chemistry) are likely to be replaced by more advanced full chemistry models.

The advancement of computer technology will also help with the advancement of coupled fire-atmosphere models. These models are starting to move from the science world toward the application world. Coupled fire-atmosphere models simulate fire behavior and its influence on the atmosphere, providing a feedback loop between the two. Due to the heavy computation required by these types of models, they will likely be used only for extreme incidents during their initial operational application. Web tools need to be developed to display or download their results because the models are very complex and require large amounts of computer resources.

Summary

For many fire planning efforts, the use of results from a simple smoke approximation model to assess potential effects of fire on air quality is sufficient, and appropriate to the task compared to results from a more complex model type. Regulations, however, may require a more rigorous modeling effort. Other times, permit requirements, the General Conformity Rule, National Environmental Policy Act (NEPA), or community values, may mandate the level of effort needed to show compliance or assess alternatives. Regulations vary from state to state and from tribe to tribe, and expectations vary from burn to burn. There is no simple way to determine which model type or smoke tool is "best." Users are advised to try various approaches and, through experience, gain confidence and proficiency with a model or models that suits their needs.

Whatever the situation, screening, planning, regulating, or simply "game playing" to determine the best smoke management approach, it is helpful to remember the strengths and weaknesses of the model type used by the smoke tool that generates the results. The smoke modeling field is changing rapidly due to new field study programs and new modeling techniques. For this reason we recommend that smoke model users make an effort to stay up-to-date with the latest information and evolving science on smoke prediction tools.

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5.4. Smoke Monitoring

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Introduction

Fire managers should integrate the monitoring of smoke plumes, smoke movement, and accumulations of ground level smoke into burn planning and implementation to document any effects their management actions may have on air quality. There are many ways to monitor smoke, and the method selected should balance the need for information with available resources. Monitoring smoke can be as simple as standing on a ridge and watching and recording which way the plume goes (figure 5.4.1); or as complicated as purchasing, installing, and operating an expensive electronic particulate monitoring instrument complete with satellite data transfer capabilities.

Monitoring smoke can help a fire manager to:

- Evaluate and minimize impacts of smoke on communities,
- Demonstrate attention to, and consideration of community concerns,
- Have a record of what happened, and when, if a smoke impact is reported,
- Provide feedback to the public, regulators, smoke forecasters, and managers about smoke dispersal and accumulation,
- Verify assumptions and predictions about smoke effects in analysis documents,
- Avoid violations of air quality goals and standards,
- Assess visibility effects to Class I areas or other visually sensitive areas,
- Document and describe air quality impact tradeoffs between prescribed fire and wildfire,
- Establish approximate nuisance smoke thresholds,
- Distinguish individual impacts within the same airshed,
- Verify smoke dispersion model accuracy.

Figure 5.4.1. Watching and documenting plume transport and dispersion is a simple way to monitor smoke.

Monitoring Approaches

The monitoring approach appropriate for a particular fire project or program will be influenced by the air quality values of most concern, possible effects, and the time and money required to successfully conduct the monitoring. Is there concern about possible plume impacts to a highway, or of overnight smoke accumulations in low-lying areas? Will there be long-term tracking of air quality effects from a prescribed fire program, or documentation to distinguish effects from other burns or pollution sources? Or maybe there is interest in multiple objectives? Table 5.4.1 describes commonly used methods for monitoring and documenting smoke effects. A single method may be selected or multiple options chosen and used in combination.

Table 5.4.1. Summary of various approaches to monitoring smoke. Some states require monitoring. Be sure to check local regulations.

Monitoring method	Description	Relative cost
Viewpoints/ cameras/notes	Observation of smoke plume movement and accumulation plus documentation (with photographs or video) and notes should be done for nearly every prescribed fire unless the location is especially remote and/or the burn is very small.	$$
Existing or custom webcams	Existing webcams are abundant and may be a good way to visually track smoke if located in an area of interest. Consider purchase and installation of a custom webcam(s) to visually monitor a sensitive area. A custom webcam will generally take higher resolution images. Remotely-controlled webcams that can pan across an area of interest are also available.	$-$$
Existing particulate monitors	Most states have fairly extensive networks of particulate monitors and their data may be quite helpful in understanding and measuring air quality trends and smoke accumulation in communities. States typically place monitors in larger communities or in areas of particular concern, so rural areas near forest lands may not be monitored.	$
Temporary particulate monitors	Federal agencies have a cache of particulate monitors that can be requested through the National Interagency Fire Center (NIFC) for temporary use during a wildland fire. You could also consider purchasing a monitor to use as needed for projects of particular interest or concern.	$-$$$
Permanent monitoring network	Plans for extensive use of prescribed fire, combined with nearby sensitive communities that are not adequately monitored by the state, may justify purchase and use of permanent particulate instruments.	$$$-$$$$

Particulate Monitoring Instruments

Particulate monitoring instruments generally use one of three approaches to measure particulate concentrations: gravimetric, optical, or beta attenuation.

Gravimetric (or filter-based) instruments collect particulates on ventilated filters (figure 5.4.2). They have been used for many years when very accurate measurements of airborne particulate matter are needed. This approach to air sampling is labor intensive. Filters must be conditioned, weighed before sampling, installed and removed from the instrument, and reconditioned and weighed again at a special facility to determine the mass concentration of particulate collected. Results may not be available for days or weeks. Airflow rates and elapsed sampling time must be carefully tracked and recorded to ensure accurate results. Filter-based techniques

Figure 5.4.2. Gravimetric, or filter-based, monitors collect particulates on a filter that is weighed before and after the sampling period. This is the most accurate but also the most difficult way to monitor air quality.

integrate samples over a relatively long period of time, usually 24 hours, to obtain the required minimum mass for accurate analysis. Gravimetric monitoring is best for projects that require the measurements to be very accurate, and where the time delay in receiving the data is not a problem. State monitoring networks that detect exceedances of air quality standards rely largely on gravimetric monitors. Specific monitoring devices must be approved by the Environmental Protection Agency (EPA) for this task and are called Federal Reference Method (FRM) monitors. Fire managers typically do not directly use this type of instrument.

Optical monitors measure light-scattering (nephelometers) or light-absorbing (aethalometers) characteristics of the atmosphere (figure 5.4.3). The optical measurement unit from a nephelometer is called bscat (or back-scatter) which can be converted to an estimate of the concentration of airborne particulates. Optical monitors offer several advantages over gravimetric monitors including real-time readings, portability, low power consumption, ease of use, and relatively low cost. Optical monitors have the disadvantage of being generally less accurate than gravimetric monitors at measuring particulate concentration. Optical instruments are best for projects where real-time or near-real time data is needed, it doesn't need to be extremely accurate, and instrument portability and ruggedness are desirable. These are the types of monitors commonly used to estimate smoke concentrations.

Figure 5.4.3. Nephelometers, such as the MetOne E-Sampler and TSI DustTrak, measure how much light is scattered by suspended particles in the air.

Proper conversion of the light scattering measurements collected by a nephelometer to estimates of particle concentration ideally involves development of a customized conversion equation. Light scattering varies as a function of the relative proportions of fine particles (including smoke) and coarse particles (such as soil dust) which is a unique property of a specific location. As a result, optical instruments ideally should be calibrated against a collocated FRM in the same area and pollutant mix in which they will eventually operate. A custom equation is then developed to convert light scattering (in bscat) to particulate concentration (in $\mu g/m^3$). Optical instruments are generally preprogramed with a standard conversion equation that can be used when collocation study results are not realistic. Some examples of nephelometers that have been used for smoke monitoring include the E-Sampler, DataRAM, and DustTrak.

Figure 5.4.4. Beta attenuation monitors, like the rugged and portable E-BAM, are accurate and well-suited for smoke monitoring applications.

The third category of monitors is the beta attenuation monitor (BAM), and the more portable environmental beta attenuation monitor (E-BAM) that is housed in a rugged case (figure 5.4.4). The BAM and E-BAM collect particulate samples on a filter tape and estimate concentration through a process called beta ray attenuation. For this process, beta particles from a naturally occurring radioactive isotope are emitted through a clean filter tape and counted. Next, sampled air is passed through the exposed filter tape and particles are deposited. Finally, beta particles are emitted through the tape again and recounted. The second count will be lower than the first, because beta particles will have been absorbed by the deposited particulate. The instrument then uses a conversion formula to estimate the total mass of the deposited particulate. The estimated mass is divided by the volume of sampled air to calculate the average concentration in mass per unit volume. The exposed filter tape will advance automatically and begin a new collection after a user-specified time period or when the filter becomes clogged. In general, beta attenuation monitors are more accurate than optical monitors but less accurate than gravimetric monitors.

Next Generation Personal Air Monitoring

The expense and complexity of current air quality monitoring instruments limit their use. To increase the availability of air quality measurements for public health purposes, EPA, the commercial sensor industry, academic institutions, and others are developing, evaluating, and applying a variety of innovative technologies. The goal is to develop methods for people to monitor personal air quality including airborne particles and gases in their own backyard. Included in this development effort are small, inexpensive sensors; plus apps and web pages for accessing data and health advisories.

Smoke Monitoring Instrument Evaluations

The Forest Service's Technology and Development Program has evaluated real-time smoke particulate monitors in response to fire managers' interest in using appropriate monitoring technology for field measurements of smoke (figure 5.4.5).

Figure 5.4.5. Various air quality monitors have been tested by the National Technology and Development Program for their suitability to wildland fire application.

The most recent evaluation tested five instruments considered appropriate for smoke monitoring, including an E-BAM and four different nephelometers: the E-Sampler, the DustTrak, the DataRAM 4 and DataRAM 2000[1]. These monitors were set up side-by-side inside a smoke chamber and their results were compared to that from a very accurate filter-based FRM sampler[2] (Trent 2006). Features of each instrument (except the discontinued DataRAMs) are described in table 5.4.2.

[1] The DataRAM 4 and DataRAM 2000 are no longer available. Some units may still be in use in the field.
[2] BGI Inc. PQ-200.

Table 5.4.2. Some of the instruments suitable for smoke monitoring applications. E-BAMs and E-Samplers are available from Met One Instruments Inc. (www.metone.com). Dustraks are available from TSI (www.tsi.com).

Instrument	Approx. Cost (2012)	Description
E-BAM	$10,200	A continuous-reporting Beta Attenuation Monitor housed in an environmentally sealed aluminum enclosure. The instrument measures the mass of particulates in the air with filter tape.
E-Sampler	$5,300	A dual technology instrument. It combines a real-time optical scattering measurement with a gravimetric filter system using the same 47-millimeter filter as the FRM sampler. It is housed in an environmentally sealed aluminum enclosure.
DustTrak	$5,400	The TSI DustTrak is a portable desk top laser photometer with a built-in data logger. An environmental enclosure can be purchased separately for about $1,400. New models are available including the DustTrak II 8530 which costs about $5,400 and the DustTrak II 8533 which costs about $10,000.

The conclusion of the testing was that all five instruments overestimated smoke particulate concentration when compared to the FRM sampler. The E-BAM was closest to the FRM and overestimated smoke particulate concentrations by just 1 percent, whereas the DataRAM 4 overestimated the concentration by 144 percent. Table 5.4.3 presents correction factors and the overestimated percentages for each of the samplers evaluated. To improve accuracy, these adjustment factors should be applied to data retrieved from the instruments. Ideally, all optical instruments would be calibrated in the field to reflect the type of fire event, current meteorological conditions, and existing levels of ambient particles.

Table 5.4.3. Correction factors and the overestimation percentage for the real-time particulate samplers compared to a Federal Reference Method sampler (Trent 2006).

Real-time particulate monitor	Recommended correction factor	Percentage overestimated compared to FRM
E-BAM	1	1 %
E-Sampler	0.89	13 %
DustTrak	0.32	217 %
DataRAM 4	0.37	144 %
DataRAM 2000	[a]	15%

[a] Previous tests of the DataRAM 2000 indicate it normally overestimates concentration by more than 100 percent. It may be necessary to develop individual correction algorithms for DataRAM 2000s.

Deploy an electronic air quality monitor without purchasing an instrument.

Federal agencies can request monitors through their local fire dispatch office.

Instruments available at this time include E-Samplers and E-BAMs, plus satellite data transfer technology.

Accessing Data from Deployed Monitors

Some smoke monitors can be linked to a satellite modem which automatically transfers air quality measurements made in remote locations. The data is then hosted on a website and available over the internet. Monitoring instruments may be programmed to send 1-hour averages of particulate matter concentrations via satellite to a stored database to be viewed and retrieved through a website.

Currently, two satellite telemetry systems are available and can be used with smoke monitors described in table 5.4.2. The Iridium satellite system by Airsis has been custom suited for the E-Sampler and the E-BAM. Data from monitors using the Airsis telemetry system can be viewed online.[1]

The second satellite telemetry system is Forest Technology Systems add-on GOES transmitter for Met One's E-Sampler and E-BAM particulate monitors. Currently, the E-Sampler/GOES kit includes meteorology instruments that measure wind speed and direction, relative humidity, and ambient air temperature. Data from the E-Sampler/GOES kit can be viewed on the Fire Cache Smoke Monitor website.[2]

Recently, EPA has begun to display health-based Air Quality Index (AQI) values derived from temporary monitors deployed for fires alongside traditional state monitor AQI values on an AirNow web page designed especially for wildfires.[3]

Smoke Monitor Operating Basics

There are simple criteria to follow when operating a smoke monitor so the data collected is valid.

Locations & Siting

Samplers used to monitor smoke effects are usually placed in areas that are both of special sensitivity, and are likely to be affected by smoke. These sites may be near a school, community, city park, or anywhere smoke is of concern. The monitor should be placed in an open area away from obstructions such as trees or buildings, and away from nearby particulate pollution sources such as dirt roads, burn barrels, or woodstoves. The telemetry antenna must have a clear line- of sight to the sky to transmit data. Power availability, site security, and site access are often controlling considerations (CH2MHill 1997).

Sampling Schedule

The timing, duration, and frequency of sampling depend on the objective of the monitoring. Ideally, a particulate monitor will be up and operating for a few days or weeks before a prescribed fire. This allows the operator to become comfortable with its operation, ensure it is functioning properly, and collect background air quality measurements. Continuous, hourly data is often needed to monitor smoke effects from several days before burn ignition to a day or two after the event. In contrast, $PM_{2.5}$ NAAQS compliance monitoring using filter-based instruments is conducted once every six days in attainment areas.

[1] https://app.airsis.com/USFS/

[2] http://www.wrcc.dri.edu/cgi-bin/smoke.pl.

[3] http://airnow.gov/index.cfm?action=topics.smoke_wildfires

Quality Assurance

Data integrity is essential in any monitoring program. Table 5.4.4 is an overview of maintenance recommendations for two commonly used particulate monitoring instruments. Besides the maintenance and calibration measures outlined by the manufacturer of the instruments, quality assurance measures may be included in the plan if accuracy of the monitoring data is especially critical. Fire managers may wish to confer with their state or local air agency, or with an agency air resource specialist, to assure that monitoring results are valid.

Table 5.4.4. Recommended maintenance schedules for two commonly-used smoke monitors will give fire managers an idea of the commitment involved.

	E-Sampler[a]		**E-BAM[b]**	
Maintenance frequency	**Time required (approx.)**	**Maintenance tasks (cost)**	**Time required (approx.)**	**Maintenance tasks (cost)**
As needed	----	----	1 hour	Replace filter tape ($65) Clean beta detector assembly
Monthly	2 hours	Review alarm log Check for leaks Calibrate temperature sensor Calibrate pressure sensor Calibrate flow[c] Clean inlet	4 hours	Review alarm log Check for leaks Clean nozzle and tape vane Calibrate temperature sensor Calibrate pressure sensor Calibrate flow Span membrane test Set clock Clean PM_{10} inlet particle trap Clean $PM_{2.5}$ cyclone particle trap Download digital data log
2 months	1 hour	Check pump	2 hours	Test pump Clean inside of sample nozzle assembly
6 months	----	----	2 hours	Calibrate filter RH sensor Calibrate filter temperature sensor Check analog voltage output (if used with external datalogger) Replace pump muffler (external pump box version only)
12 months	1 hour	Pump and purge filter replacement ($35) Pump replacement (or as needed) ($650)	1 hour	Replace internal D.C. pump (or as needed) ($650)
24 months	1 hour	Return to factory for recalibration ($300)		Rebuild AC pump (external pump box version only, contact Met One)
60 months	1 hour	Replace memory battery ($25)		

[a] From Section 3.3.5 of E-Sampler Operation Manual, Rev H.
[b] From Section 8.4 of E-BAM Particulate Monitor Manual, Rev L.
[c] U.S. Forest Service field experience with the E-Sampler indicates flow calibration may be needed every two weeks, or even every week, until the stability of this metric for an individual instrument can be determined.

Monitoring Costs

Using an air quality monitor is expensive. Besides the capital cost of the instruments, costs for equipment installation, electrical, maintenance, calibration standards, supplies, shipping, data analysis, and reporting must also be considered. In the case of filter-based particulate sampling, laboratory costs for filter weighing and chemical analysis must be included. Annual operating costs for technician time to service the instruments are a major expense that often drives the monitoring system design.

Real-Time Training Aids

Intimidated by the thought of learning how to use a smoke monitor? Don't be. Some excellent training aids are available for the E-Sampler and E-BAM. These include "quick sheets" with concise instructions on navigating and setting up the instrument parameters for E-Samplers with the Airsis satellite telemetry system (https://app.airsis.com/USFS/Content/pdf/quicksheet_esampler.pdf) and the GOES satellite telemetry system (http://www.wrcc.dri.edu/smoke/documents/quick_sheet_goes.html). Flash media presentations provide in-depth visual instructions about the sampler components and set up instructions for the E-Sampler and E-BAM with the Airsis satellite telemetry systems (https://app.airsis.com/USFS/Content/flash/fla09252F01/index.html) and with the GOES system (http://www.wrcc.dri.edu/smoke/documents/SetupVideo.html).

Automatic Cameras for Monitoring Smoke

Sometimes smoke monitoring requires use of a high tech instrument that measures concentrations of smoke particles in the air, but at other times a simple view of the plume and smoke is all that's needed. Remote monitoring of wildfire or prescribed fire activity, smoke plume rise and dispersion direction, and ground level smoke accumulation can be done through the use of automated and portable high-resolution cameras. Remotely-placed cameras can be powered by solar panels and connected to the internet by mobile phone technology.

Figure 5.4.6. A solar-powered automatic camera that transfers images to a public or private web page can be useful for visually tracking plumes and smoke accumulations.

Remote monitoring cameras (figure 5.4.6) can be set up to view an area where prescribed fire is planned for tracking and documentation of smoke movement and accumulation. Cameras can be positioned to document a wildfire and help inform incident personnel, air quality regulators, and the public on trends in fire growth and behavior, as well as the severity of air quality effects. Images can be automatically uploaded and hosted on a website that is shared with cooperators or kept private.

Alternatives to Deploying Monitoring Equipment

If use of a monitoring instrument is not realistic due to cost or personnel availability, monitoring data may still be available. State air quality monitoring networks are extensive although generally focused on populated areas. EPA's AirData web page at https://www.epa.gov/outdoor-air-quality-data, has current information about state monitoring networks including—in some cases—access to data archives (figure 5.4.7). Also, many states provide direct web access to real-time monitoring data. A quick internet search may turn up monitoring data that is quite useful to fire managers. The Forest Service AirFire research team has developed an air monitoring data access and summary webpage available at: https://monitoring.airfire.org/monitoring/v3/.

A visual perspective on current smoke conditions in an area can be helpful at times. Web cameras are common around the country, and may show which way smoke is traveling and whether it is accumulating in a sensitive area.

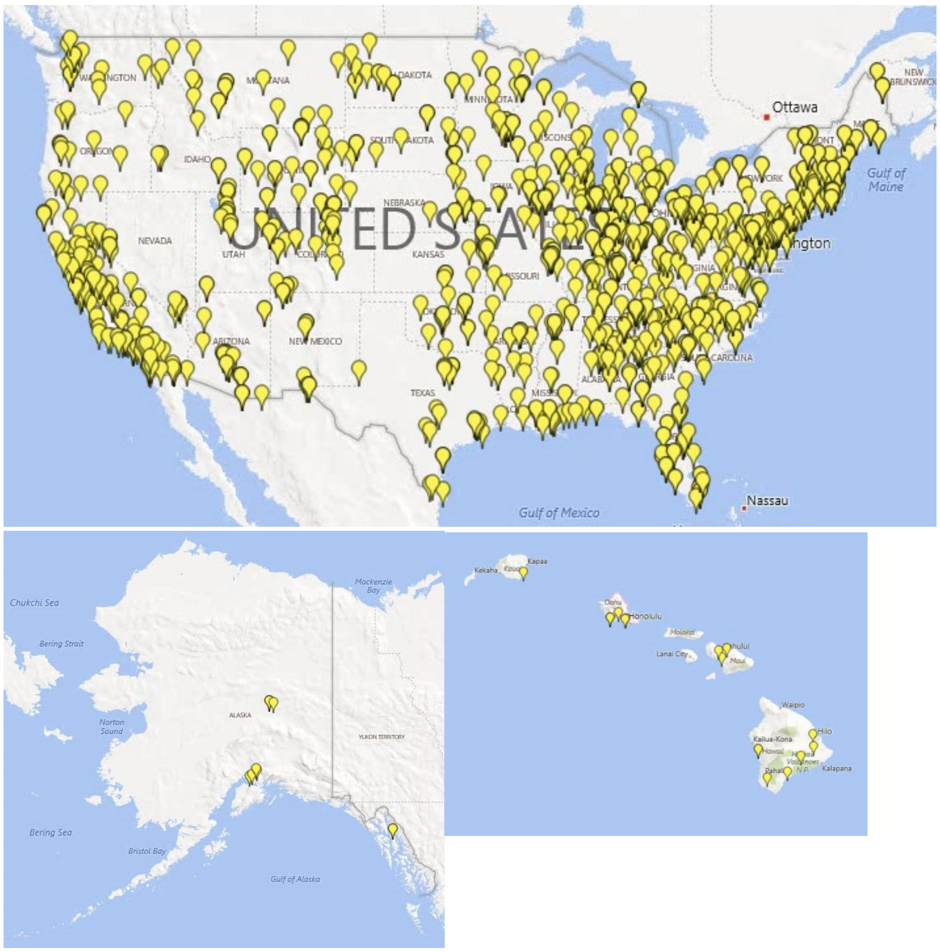

Figure 5.4.7. Official FRM/FEM $PM_{2.5}$ monitoring sites in the United States as of January 2016.

Documentation of Visual Smoke Observations

Stationing personnel at a high point or other appropriate lookout to observe and document smoke transport, dispersion, and accumulation may be sufficient for monitoring smoke. Notes and photographs can provide good documentation of smoke movement and may be especially important to have if something goes wrong. The notes below are from a burn on the Naches Ranger District in Washington State where the plume took an unexpected turn and smoke affected the nearby town of Yakima. This documentation was later used to prepare a litigation package; so accurate notes and other documentation may be very important and could be used in a court case.

"Ignition took place at 3,500' elevation and below. Smoke rose to a level of 2,000 – 4,000'+ AGL above the 6,000' ridge top (estimated by observation) moving to the N – NE from the burn location. Smoke passed over the 6,000' Bethel Ridge and was still rising. Smoke continued moving N – NE passing west of the Wenas Valley (this was noted by the Burn Bosses Supervisor per phone call at approximately 14:30 local time). At least two other phone calls were exchanged and noted the smoke carrying favorably to the north. At approximately 16:30, the supervisor called and noted that smoke was beginning to settle into the Wenas Valley). U.S. Forest Service personnel on the Cle Elum Ranger District had also noted the smoke plume heading "over the ridge top and straight at them".

Visual Range Estimates of Air Quality

Visual range (i.e. how far can you see) is sometimes used to obtain a snapshot estimate of particulate levels in the air in the absence of a monitor. Use of visual range techniques as a surrogate for monitors is advocated by some state and local agencies as a method for the public to use because the concept is easy to understand and implement, and electronic monitors can never be deployed everywhere they are needed. Note that different states may use different thresholds for visual range and impact messages than the technique below. During a serious smoke episode, a visual range estimate may be the only way members of the public can get some idea of the magnitude of air quality impairment they are experiencing at that moment. This method is not generally used during prescribed fires since it is not accurate or reproducible, especially at light smoke levels more typical of prescribed fire.

Basic method to determine visual range:

- Use only during daylight hours (avoid sunrise and sunset).
- Use only if relative humidity is less than 65%. (Particulate matter plus atmospheric moisture dramatically reduces visibility making this technique best suited to the western U.S. and far less likely to be useful in the eastern and southern U.S.)
- Focus on the darkest object you can see in the distance (e.g. black is better than green).
- Determine the limit of visual range by looking for targets at known distances (miles). The visible range is the point at which even high-contrast objects (e.g., a dark forested mountain viewed against the sky at noon) totally disappear.
- After determining visual range in miles, table 5.4.5 can be used to identify actions the public can be advised to take to reduce exposure.

Table 5.4.5. Visual range and actions for the public to take to reduce smoke exposure (Lipsett *et al.* 2016).

Distance you can see	You are:		OR	You have:
	A healthy adult, teenager, or older child	Age 65 and over, pregnant, or a young child		Asthma, respiratory illness, lung or heart disease
> 10 miles	Watch for changing conditions and moderate outdoor activity based on personal sensitivity			
5-10 miles	Moderate outdoor activity	Minimize or avoid outdoor activity		
< 5 miles	Minimize or avoid outdoor activity	Stay inside or in a location with good air quality		

It is often difficult to assess the point at which even high-contrast objects totally disappear. It may be more useful to use known landmarks at a given distance to assess possible visual range. For example, if target A is 2 miles away and visible, but target B which is 4 miles away is not visible, then the visual range can be assumed to be somewhere between 2 and 4 miles.

This effect is most pronounced at lower particulate concentrations and if hygroscopic types of particulate (such as sulfates and nitrates) are mixing with particulates from wildland fire. For a given particulate concentration, visibility decreases substantially when RH is above 65%, therefore visual range should not be used to estimate particulate concentrations under conditions of high humidity.

Another uncertainty in estimating particulate concentration from visual range is the effect of human error. The visual range technique relies on human estimation of when dark objects at known distance from the observer have just disappeared from view due to haze from air pollution (smoke). An analysis investigating the possible errors of estimating particulate concentration with human-sighted visual range (Malm and Schichtel 2013) modeled an overall factor of two uncertainty due to difficulties such as: sighting on distant features that were not dark objects (e.g. green forested landmarks, snow-covered peaks), difficulty judging when an object is just barely visible, absence of an appropriate target at an exact visual range, non-homogenous atmosphere across the line of sight, and extrapolating from an instantaneous assessment to a time average $PM_{2.5}$ concentration. Figure 5.4.8 shows the relationship of visual range to short term average (1-3 hours) $PM_{2.5}$ concentration. The vertical dashed lines indicate the

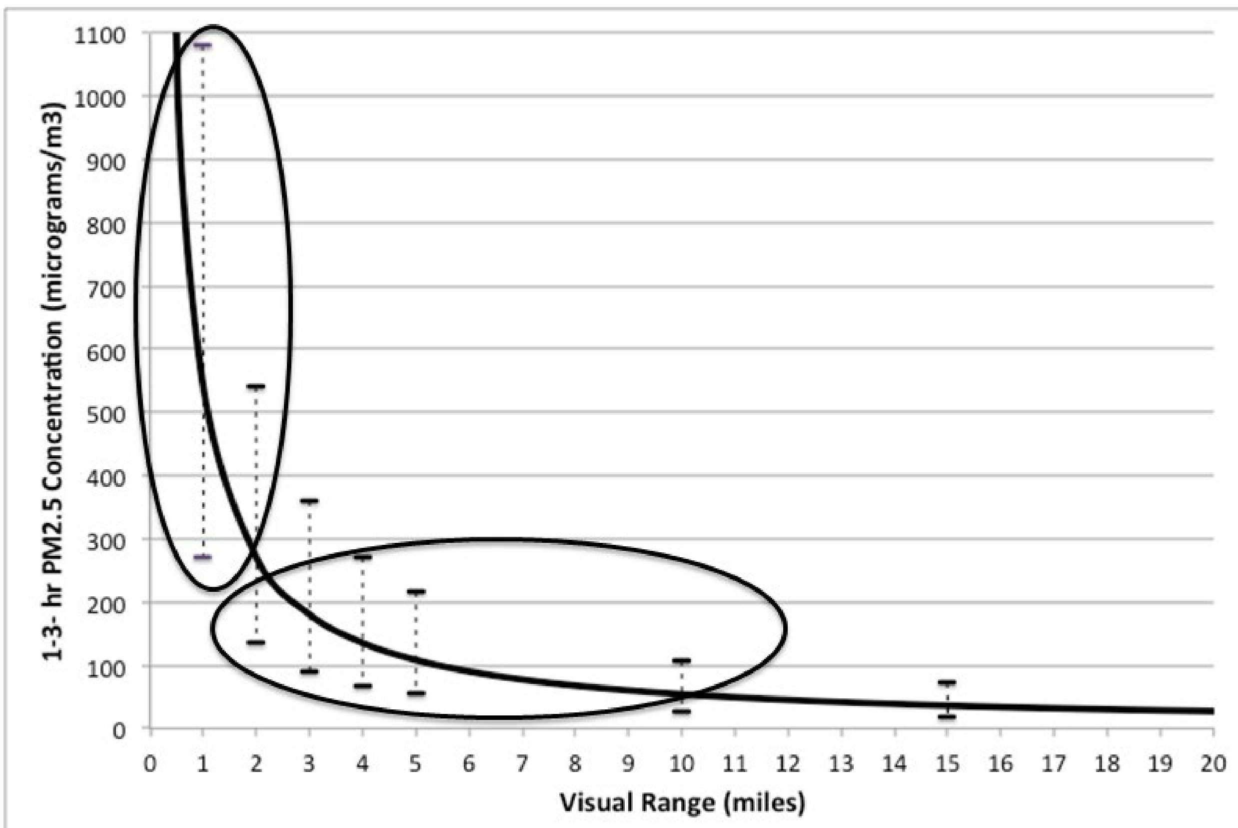

Figure 5.4.8. Relationship of visual range to $PM_{2.5}$ concentration (adapted from Malm and Schichtel 2013). Vertical lines indicate uncertainty is especially significant when visual range is low and $PM_{2.5}$ concentration is high. Ovals indicate broad categories of visual range such as very smoky and moderately smoky.

amount of uncertainty in the relationship for various visual ranges. At the low end of visual range when air quality is very impaired, the uncertainty in estimating $PM_{2.5}$ is quite large. For example, at a human-estimated visual range of 1 mile, the $PM_{2.5}$ concentration estimate could potentially be any value from 270 µg/m^3 to almost 1,100 µg/m^3.

Support for, and approaches to, the use of visual range to estimate particulate air quality impacts from smoke vary widely across the U.S. and Canada and fire managers are encouraged to be aware of local methods.

In summary, visual range should not be used to estimate particulate concentrations if RH is greater than 65%, and users should always take into consideration the large errors that can result from this technique, especially when particle concentrations are high.

Using Monitoring Data—Analysis Examples

Following are some examples of when smoke monitoring data were used to analyze and communicate information about fire affects to air quality. Most monitors collect and report 1-hour average concentrations of particulate matter although this short term average does not coincide with federal NAAQS regulations which are 24-hour averages. Short term averages can be of use to show the magnitude and duration of a smoke impact and a 3-hour average is best for revealing both the short-term impact while damping out some of the spikes seen in a 1-hour average.

Wildfire Air Effects

In 2006, the Tripod Complex fire in northcentral Washington State burned over 175,000 acres and sent smoke into local communities for months. Particulate concentrations collected by two nearby monitors (Radiance Research Nephelometers) were plotted against the EPA's Air Quality Index (AQI) warning values as evidence of the severity and duration of the effects from the wildfire (figure 5.4.9). This

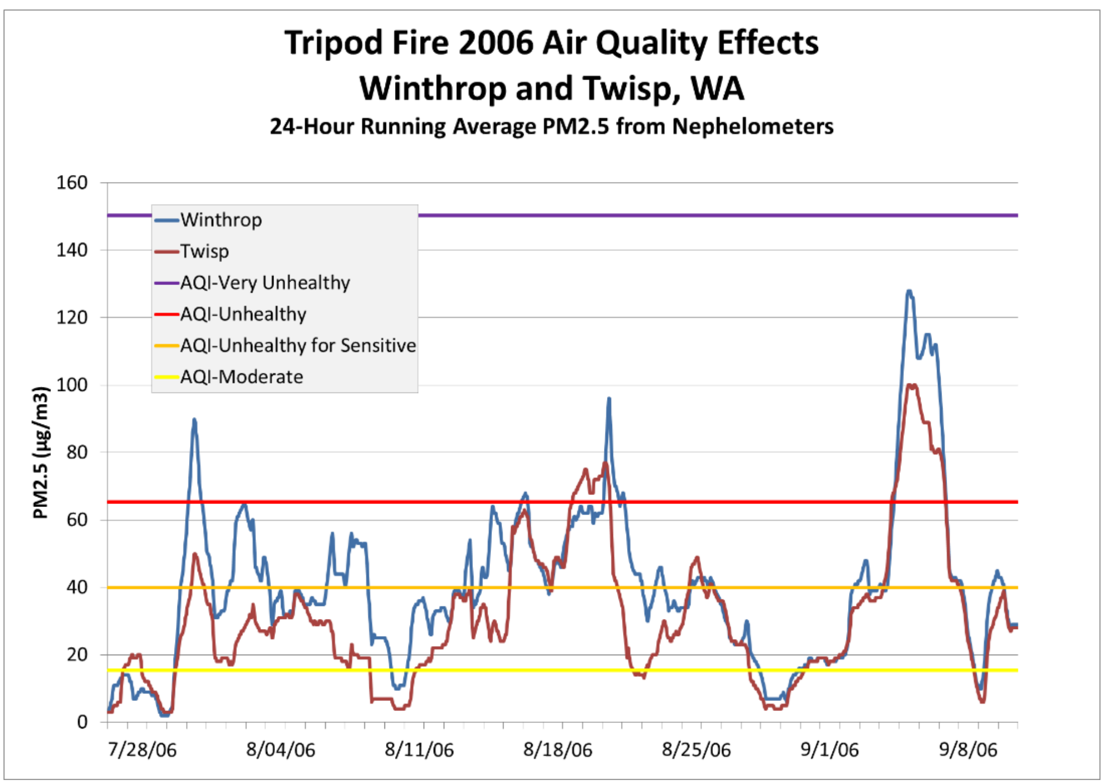

Figure 5.4.9. Air quality effects on two nearby communities during the 2006 Tripod Complex wildfire in northcentral Washington State (note the AQI breakpoints shown were valid in 2003 but have since been updated).

information was used to help inform the public of the severity of the health risk from the smoke and develop some recommended actions they could take to protect themselves.

This sort of wildfire monitoring information can also be used after the fire is over to compare and contrast effects from prescribed fires in the same area to help fire managers, communities, and air regulatory agencies understand the tradeoffs between how wildfire versus prescribed fire can affect air quality.

Prescribed Fire Air Impacts

A report documenting the air quality effects of the 2015 wildfires in Washington and Oregon (Forest Service Region 6) compared smoke intrusions from prescribed fires with air quality effects from other sources (Graw *et al.*, 2016). Prescribed fires caused smoke intrusions into three communities in Oregon in 2015. This display was used to compare air quality impacts from different sources of fine particulate matter and to help put the prescribed fire impacts in context with other threats to community air quality (Figure 5.4.10).

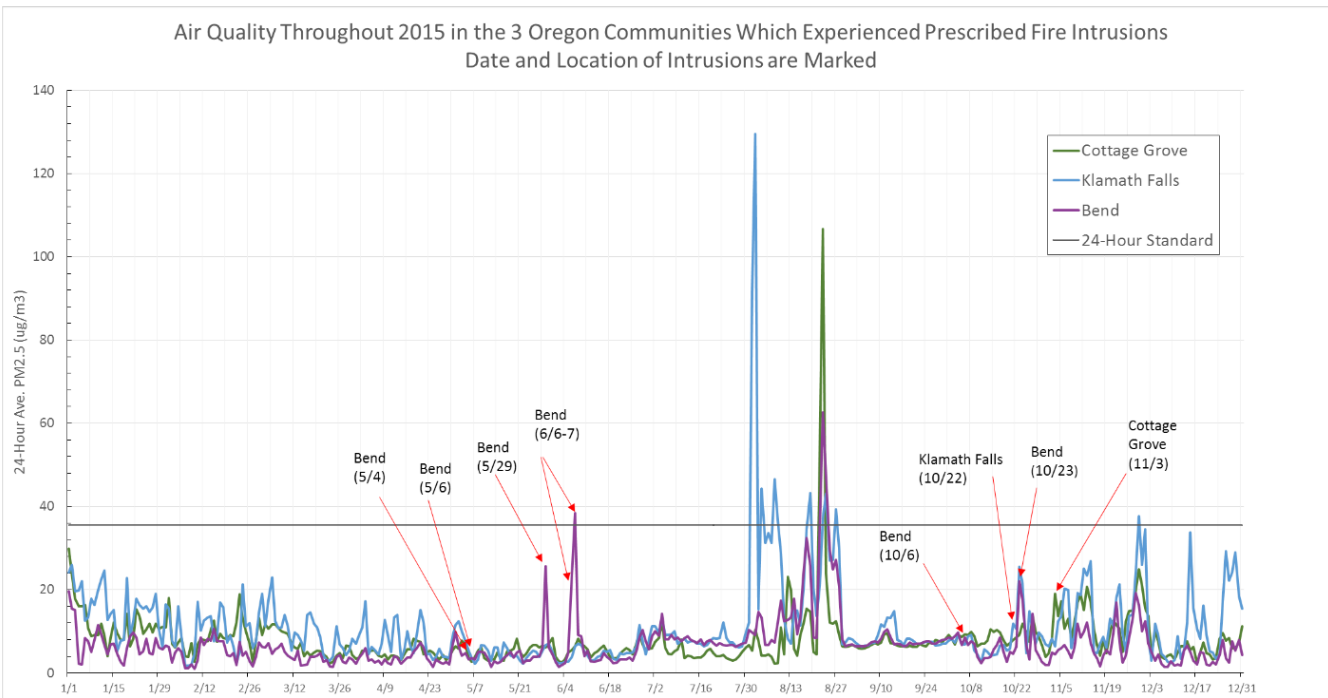

Figure 5.4.10. Three communities in Oregon experienced intrusions of smoke from prescribed fire in Oregon during 2015 for a total of 9 events. High $PM_{2.5}$ values seen from late July through August are from wildfires. Elevated values during winter months are likely due to home heating.

In 2003, smoke from a U.S. Forest Service prescribed fire affected local communities and resulted in a Notice of Violation (NOV) from the state regulatory agency. To help the Forest Service and the air regulatory agency understand what had happened, 1-hour, 4-hour, and 24-hour average $PM_{2.5}$ concentrations from a nearby smoke monitor were displayed (figure 5.4.11). The blue horizontal line marks the 24-hour NAAQS standard for $PM_{2.5}$ and shows that the monitored 24-hour average (yellow line) did not exceed the standard in the nearby community of Twisp, WA. The number of acres burned on each of the districts' spring burning projects is indicated inside the rectangles and the approximate duration of the burning is shown in red horizontal lines. In this way, the issue of the severity of effects could be described numerically rather than through speculation. The air regulatory agency could be reassured that it was unlikely the standards were exceeded, and the Forest Service could better understand that, even though standards were not exceeded, smoke levels were quite high for a number of hours because of a prescribed fire.

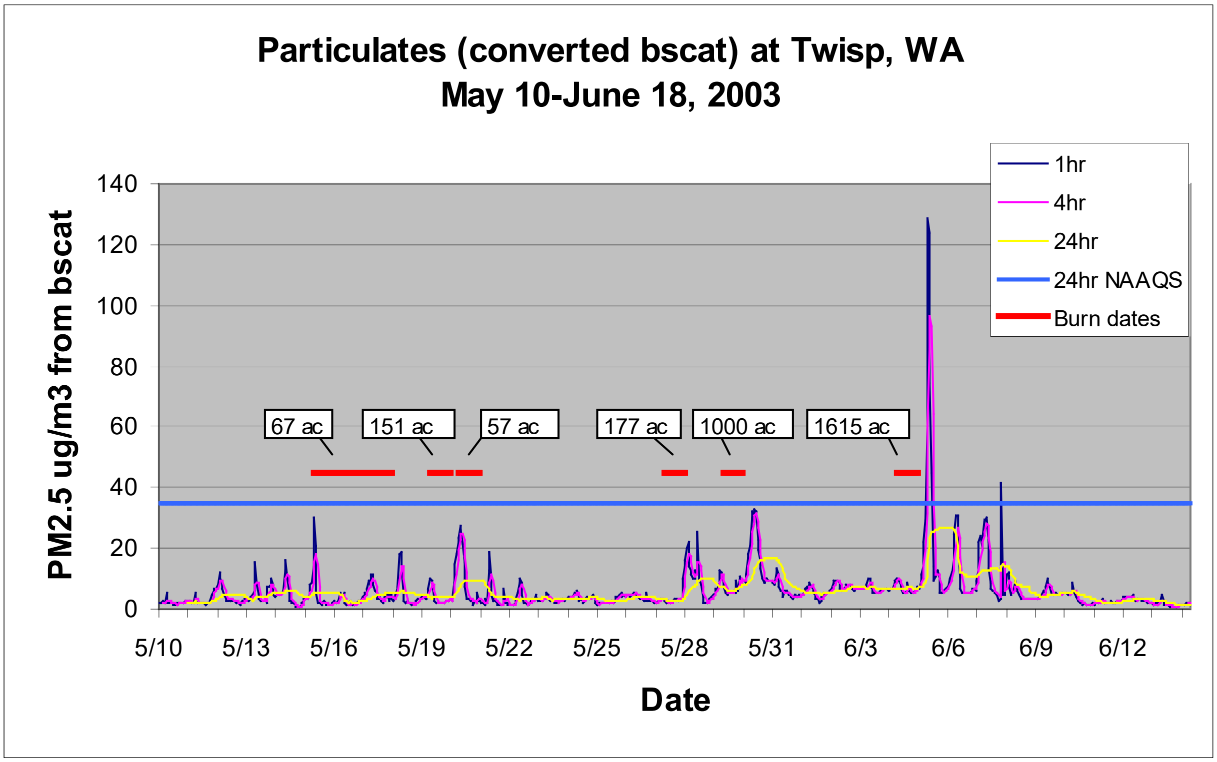

Figure 5.4.11. Air quality effects from various prescribed fires compared to the 24-hour $PM_{2.5}$ national ambient air quality standard (NAAQS).

A special project with the Naches Ranger District on the Okanogan–Wenatchee National Forest in Washington, and various state regulatory agencies led to a customized air quality monitoring set-up during the spring of 2007. Monitoring data from four strategically-placed E-BAMs was used to improve daily burning decisions. At the end of the spring burning case study, monitoring data was plotted against daily burning accomplishments to show how air quality was protected even while many acres were burned (figure 5.4.12).

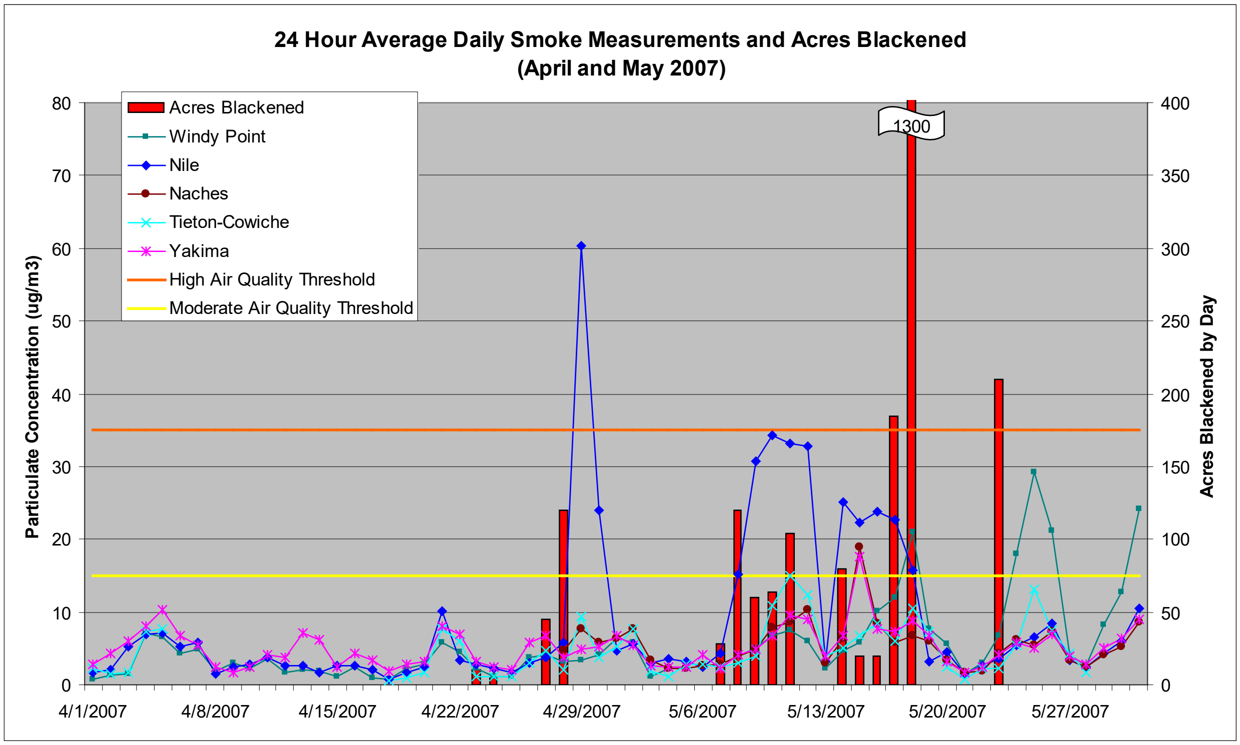

Figure 5.4.12. Four air quality monitors were deployed in surrounding communities in support of a special prescribed fire project to improve daily go-no go decisions.

Summary

Monitoring smoke movement and smoke impacts can take various forms, from complicated and expensive (such as when using an electronic air quality monitor) to simple and relatively inexpensive (as when using a human observer with a camera and notepad). It's important to select the monitoring approach that will be successful within the constraints of time and budget. Nearly every prescribed fire with any possibility of affecting public air quality should be monitored in some way. Monitoring results can provide evidence of successful burning with little to no effect on air quality, or monitoring results can help document and understand what happened if something goes wrong.

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CHAPTER 6 – COMMUNICATIONS AND PUBLIC PERCEPTIONS

6.1. Smoke Management Communication

Dennis Haddow

Introduction

A foundation for the success of a long term prescribed fire program depends on strong relationships with the communities that may be affected by smoke; and the air regulatory agencies who protect the public through enforcement of air quality rules and regulations. It's almost inevitable that at some point the public will be impacted by smoke from a prescribed fire. How will they respond? What if it becomes necessary to expand the boundaries of current smoke management rules to accomplish a unique or evolving fire program goal? Will air regulatory agencies be willing to negotiate? The ability to expand a prescribed fire program, or rebuild trust and recover from a smoke incident without incurring extra restrictions, will depend in large part on public and air regulatory understanding and support for fire program goals and trust in the professionalism of those responsible for their implementation.

Good working relationships with the public and air quality regulators are critical to meeting both prescribed fire objectives and the land management objectives they support. These relationships do not happen overnight but are developed through years of investment in sustained and targeted interaction and communication.

Developing a Communication Strategy

This chapter describes the development of a communication strategy that addresses smoke issues. It describes how to address public concerns in both the planning and implementation stages of a prescribed fire. It also describes how to communicate with the public, air regulatory agencies, and media if air quality problems arise. If problems do arise, your agency may have specific protocols and responses established which should be known and followed. Your agency public affairs staff or public information officer can assist with this. Communication about prescribed fire and smoke management programs should be a proactive and ongoing effort. Increasingly, both air quality and prescribed fire issues intersect and are often complex. Air quality standards are becoming more stringent, fuel loadings are increasing in many areas, fire in the wildland urban interface (WUI) is more common, and there may be a need to increase the size of individual fuel treatments—putting up more smoke for longer periods of time. One of the best ways to meet these social and political challenges is to develop and implement a good communication plan.

Public Perceptions of Smoke

It is important to understand local perceptions and the level of tolerance for smoke to develop effective local communication strategies (see Chapter 6.2 on public perceptions of smoke). People view smoke effects differently depending on where they live, their understanding of the role of fire in the ecosystem, their understanding of how prescribed fire can reduce the effects of wildfire, impacts of smoke on local economic activity such as tourism, their experiences with fire in general, and their individual health and sensitivity to smoke.

Studies suggest that there is a relationship between the public's understanding of the role of fire in ecosystems and their tolerance of wildland fire smoke. Public support for using prescribed fire as a land management tool often depends on whether people believe that the fire and smoke can be effectively controlled, and whether fuels management tools will reduce the risks and consequences to their values (e.g., homes, property, health, and wildlife.). Local communication strategies need to support this public understanding. Public acceptance of fuel treatment approaches that involve smoke is often related to the degree to which people trust the land manager. On the other hand, less personal experience and knowledge about prescribed fire has been linked to beliefs about negative outcomes, such as escaped fires. Trust has long been understood as an important component of land management. In any aspect of life, trust is difficult to establish, easy to lose, and very hard to regain. Usually, what people don't understand, they don't like. What they do not like they do not support.

The public's lack of understanding about the ecological role of fire has the potential to result in more public complaints about smoke which could lead to more stringent smoke management requirements. The public, including most air quality regulators, understand the need for good air quality much better than they understand the role of fire in ecosystems. Few are aware that many natural ecosystems exist because of periodic fire rather than in spite of it. Few understand the relation of fire to wildlife habitat and populations, forest diseases, protection of rare and endangered species, management of national parks and wilderness, ecological succession, and biological diversity. Today’s fire manager needs to assess local understanding of biological processes and ecology before developing a communications plan.

Population and land development in much of the country is increasing at the same time as the ecological need for the use of prescribed fire is increasing. However, given a finite atmosphere and a need to control air pollutants, the public must determine which pollutant sources will be allocated shares of this valuable air resource. Public decisions on the allocation of the air resource will be based to some degree on the public's knowledge about the role of fire as a land management tool. Where the public is uninformed, there is a greater potential for unnecessary restrictions on the use of prescribed fire. Land managers must effectively inform the public and regulatory agencies of the changes to ecosystem viability and productivity that may result from withholding fire from a fire-dependent ecosystem, along with the need to reduce fuels.

Local Situation Analysis

Relative to smoke management for individual prescribed fires, the need for and level of communication is influenced by many factors. It is prudent to conduct a “situational analysis” for the general area as part of the burn planning process to determine the level of effort necessary to communicate with people who could potentially be affected by smoke from the burn. For example:

- Is the proposed burn within a non-attainment area? If so, is the burn planned during a time of year or under meteorological conditions that are not conducive to exceedances of air quality standards?
- Have there been adverse effects from smoke during previous prescribed fires? Have there been complaints about prescribed fires in the past and, if so, what were the complaints about?
- Is the prescribed fire near a smoke-sensitive area?
- Does the local public understand the goals of prescribed fire (hazard reduction, ecological, wildlife, threatened and endangered species)? Is the public supportive of those goals?
- Does the land manager conducting the burn regularly communicate the need for prescribed fire? Can those same messages be used in a local communication strategy?
- Is this prescribed fire different from previous prescribed fires in terms of size, duration, proximity to smoke sensitive areas, etc.?
- Are there public notification requirements as part of the local smoke management program?

- Has there been a large wildfire in the area lately?
- Are there public affairs or visitor services staff or volunteers able to help with public contacts?

Special circumstances may require extra outreach and communication efforts.

Audience

It may also be necessary to determine who the audience is relative to a specific prescribed fire. Examples include:

- Persons in areas that may be affected by smoke, especially those with known health issues or smoke sensitivities.
- Daycare centers, nursing homes, and hospitals.
- Recreation and tourism businesses.
- Local media.
- Air quality regulators.
- State forestry agencies.
- Others that use prescribed fire.
- Local health and elected officials.
- Public interest groups.
- People who have been adversely affected or have complained in the past.

Messages

Messages to the above audiences need to be tailored to meet the needs of the local situation and specific burn. The general messages agencies have developed on a previous prescribed fire may or may not be appropriate. Information given to the public a year ago about a different burn may have been forgotten. Often, public communication materials are developed for a homogenous audience. However, people's beliefs and values differ within and between communities. Messages need to be developed to address these diverse local beliefs and values to gain public support for wildland fire management activities. The messages that may need to be conveyed include answers to questions such as:

- Why burning is being planned, where the burn will be located, how large an area will be burned, and how long will the fire last?
- What steps are being taken to ensure that the burn stays within the planned area? What contingency plans are in place in case the burn escapes beyond the planned area?
- What are the management alternatives to burning?
- What are the risks and/or ecological effects if there is no burning?
- What are the benefits for fire hazard reduction, wildlife and watersheds?
- What are the tradeoffs between wildfire and prescribed fire including air quality tradeoffs?
- What are the best timing and conditions under which to burn, and why?
- What smoke effects can be expected in the best and worst cases?

- How long there will likely be visible smoke in the area?
- How will the burn meet air quality requirements?
- How will the fire be managed to minimize the amount and/or effects of smoke?
- How the top priority of protecting public and firefighter safety fits into fire and smoke decision making?
- Who should the public contact if the burn is causing smoke problems?

Often, the best place to communicate prescribed fire and smoke management messages is in the field, rather than in offices or meeting rooms (figure 6.1.1). When trying to talk about the need to manage vegetation for fire hazards, or other reasons, it is much easier to show those needs on the ground.

Continuous public messaging is often necessary because fire management issues change and people may move in and out of the area. Consider the demographics of your audience and whether messages need to be conveyed in multiple languages.

Figure 6.1.1. Fire personnel communicating with the public at the site of a prescribed fire.

Planning

Communications about smoke need to be part of standard operating procedures, preplanned as part of burn planning. In addition, various contingency plans should be in place for communications, just as they are for the burn. An action matrix should be developed identifying specific audiences, contact information, concerns to be addressed, key messages, how communication will take place, when the contact will be made, who will make the contact, and documentation that it was done (table 6.1.1).

Table 6.1.1. Burn communications action matrix (for a specific burn).

Contact	Info	Concern	Message	Vehicle	Timing	Who	Done?
Local public	Community or subdivision	Burn locations	Burn map, phone #	Mail boxes, social media	ASAP after approval of plans	Fire/Public Affairs staff	______
Local public	Community or subdivision	When burn will occur	When burn will occur and how long it should last	Notice on door day before burn, social media	ASAP after a date has been selected	Fire/Public Affairs staff	______
Local facilities	School, nursing home, and others	Where and when smoke could be expected in their area	Notice of burns, projected smoke effects	Hand delivery with offer of on-site meeting	Weeks to days before burn	Fire/Public Affairs staff	______
State air quality	Problem smoke	Excess smoke	Status of smoke problem	Personal phone call	When aware of problem	Burn Boss	______

Other methods for contacting the public about a prescribed fire may include news releases to local newspapers, television stations, and radio stations, inserts in water bills, phone trees, and presentations at other public meetings (e.g., city council, local service organizations) (figure 6.1.2).

Figure 6.1.2. A door-hanger with information on a planned prescribed fire is a helpful method to communicate with nearby members of the public who may see or smell smoke.

Coordination with Fire Management and Public Affairs Staffs

It is important to coordinate communication strategies with fire management and public affairs staff as well as any agency-specific requirements. This will help ensure that smoke management messages are coordinated within and between agencies. It will also help ensure that smoke management issues are adequately addressed in project planning, including the National Environmental Policy Act process and associated public meetings or any meetings held on fire prevention or Firewise programs. They can also help coordinate presentations to schools, public service organizations, and city councils where the message can be given on why there is a need to burn and what can be done to mitigate the amount and effect of smoke produced. They can also help determine how to work with concerned individuals or groups.

Communication Challenges

What to do if Smoke Has a Significant Impact

Prescribed fires do not always go as planned. Actual weather conditions may differ from forecasts, fuel conditions may be different than assumed, and fire behavior may not be what was predicted. As a result, smoke may cause problems for both the public and the people conducting the prescribed fire. From a communication standpoint, it is important to learn how to effectively manage those problems.

A communication challenge is any situation that threatens the integrity or reputation of the land manager, usually brought on by adverse or negative regulatory, public, or media attention. It can also be a situation where, in the eyes of the media, air regulator, or general public, the land manager did not appropriately react to a smoke problem. In addressing such a situation, it is critical to follow the respective agency protocols if they exist and/or seek guidance from public affairs or possibly legal counsel to insure the appropriate response. Following the burn plan which should have contingency measures is very important. If a significant amount of smoke impacts a sizable community for an extended period of time, a public information operation may need to be set up on a temporary basis similar to a large wildfire

A smoke management communication challenge, as defined above, may include putting smoke across a single residence to creating haze at a community scale; affecting nearby facilities with clients having sensitive respiratory needs (e.g., day care centers, nursing homes, schools, and hospitals), causing driving difficulties and motor vehicle accidents, significantly impacting local economic activity, or causing an exceedance of air quality standards. More prescribed fire regulations have been developed because of public complaints than from smoke violating air quality standards, so it is essential to anticipate and respond to any predicted or actual effects on the public. Keep in mind, receiving only a few direct complaints is not necessarily a measure of insignificant effects or public acceptance of the smoke.

Suppose you are the burn boss on a prescribed fire that unexpectedly put significant smoke into a community and you are not sure why it is happening. What do you do first? Who do you contact? When do you contact them? What do you say? What do you try to convey? What can you do through appropriate communication to minimize the immediate and long term effects of this incident on your prescribed fire management program? All of this needs to be planned. The burn boss may be the first point of contact for addressing the smoke incident and must be prepared to represent the agency or land manager in a credible and professional manner.

Strictly from a communications standpoint, it is important to first address any immediate public safety or health concerns and act in a manner that maintains the integrity and reputation of the land manager. Use of prescribed fire is a long term endeavor and one does not want to let an unplanned impact negatively affect the ability to use this important natural resource management tool.

How can Communication Build Important Relationships and Minimize Impacts?

How well do you know your local air regulatory staff, media, and people who live where you are burning? Agencies and programs can withstand unplanned impacts better if they have established sound, long-term relationships with stakeholders—the people and organizations who are at risk from the land management actions. Do local air regulatory agencies and the public understand why you are burning (see Chapter 6.2 on public perceptions of smoke)? If they do not understand why you are burning, they will likely not support your program when there are effects to them and they will be less likely to accept any smoke problems you cause. Being proactive and credible are crucial.

When a Problem Occurs

Along with your supervisor and any other positions as directed by agency guidance, such as public affairs staff and public information officers, the air regulatory or permitting agency should hear about any smoke management problem from you before there are significant effects on the public and, most importantly, before they receive any complaints. It is wise to notify the air agency immediately when you become aware of a problem, even if you are not certain of the cause. Air agencies do not like surprises. Convey to them that the immediate focus is on identifying factors that are causing the problem so that smoke effects can be minimized, contingency plans can be implemented, and the likelihood of it happening again can be reduced. Also, if you believe the public is affected by the smoke in terms of driving, possible health issues, and even general inconvenience and concern caused by haze, the air agency may be able to assist in explaining to the public what happened. It is important to stay in communication with the air agency as you find out more information about what caused the smoke problem and how long it will last. Usually, the main questions they and the public have are how long will there be a smoke problem and how bad will it get. This will require good communication with the National Weather Service and fire managers on the ground. If it is determined that a smoke problem has been caused by your burn, or even that the burn contributed to the problem, the best course of action is to acknowledge the situation, take responsibility by telling the truth, express concern for the public affected, and let them know the steps you are taking or will be taking to correct the problem. Some people are concerned that expressing regret will leave them exposed to possible legal action. Legal action may be taken regardless of whether regret is expressed or not. There is no legal liability incurred by apologizing for the effects of an obvious problem, and aggrieved people will be much more forgiving than if a stiff, legalistic, or delayed response is given and this may actually prevent legal action. However, it is important to follow policy on what should be said by whom if problems do arise.

Never lie, deny or hide involvement. If you ignore the situation, it will only get worse and you will be blamed in any case. It is always best, when a mistake has been made, or when things haven't gone as planned, to admit it up front and begin corrective measures to re-establish credibility and confidence with internal and external audiences.

If You are Contacted by the Media while at the Fire

The media may unexpectedly show up on a prescribed fire when they become aware of a smoke problem. If they ask you questions about why you are burning, why your fire is causing a problem and what you are doing about it, you need to be able to respond with an answer other than "talk to our public affairs staff" or "no comment." Work with your agency public affairs staff or public information officer to determine the appropriate response and ensure that agency news media protocols and procedures are followed if this scenario occurs. In most cases, you will likely be able to obtain advance approval to speak with the media if this scenario occurs as long as you stay within agreed upon topics of discussion and talking points. If you defer a response, your agency may be perceived as inept, at best, and negligent, at worst. You are not expected to be a public affairs expert or be able to speak as an agency spokesperson. However, this may be the only opportunity to get your side of the story across to the public. Express concern about any negative effects that they may be experiencing. Tell what you know, but do not comment on anything beyond your area of responsibility or authority or speculate about a situation where all the facts aren't yet clear (stick to confirmed facts). Acknowledge uncertainty. It's always best to say, "I don't know," or "we're still looking into that," rather than to improvise. Be sure to indicate that managing and responding to smoke issues are integral parts of the burn plan. Be truthful, honesty is the best policy from both an ethical point of view, and from a practical standpoint. People quickly find out about partial truths or cover ups–and they will resent you for it and make up their own conclusions, usually not in your favor (people forgive mistakes, not lies). Never talk off the record. With the media, assume there is no "off the record." Don't get emotional or take the interview or questions personally.

You should make no comment on the question of legal responsibility for the incident. That is best left to the proper investigating authorities, and you should acknowledge if any investigation is planned or underway. Contact your agency public affairs staff or public information officer and notify them about your media interaction as soon as possible so that they can notify others in your organization as needed and so that they can conduct any necessary follow up with the reporter.

Document Your Communications

Finally, establish a log to record all telephone calls to or from the media or other parties inquiring about the event. Let your public affairs staff, supervisor, and air agency know as soon as you have talked to the media. They don’t like surprises either.

General Communications with Air Regulatory Agencies

A major problem that land management agencies must overcome is that air quality agency staff often do not understand the need for, and uses of, prescribed fire. While air quality agency staff have an excellent understanding of control equipment for stationary pollution sources, they may have little understanding of biological processes and the natural role of fire in driving those processes. As a result, it is possible that air quality regulations will be proposed and air quality agency staff do not fully understand the consequences.

Land managers need to communicate with air regulatory agencies on the uses of, and needs for, prescribed fire. This communication can be done in meetings initiated by the land manager or, preferably, on field trips and actual involvement in prescribed fires. One day in the field is usually worth ten days of meetings. However, it is important that meetings and field trips take place before the air regulatory agency proposes regulations.

Land managers also need to communicate with air regulatory agencies on the smoke management techniques that are available and how various smoke management techniques relate to specific fire prescriptions. It is important that air regulatory staff understand that the smoke management technique selected must fit the specific fire prescription. Equally important is the need for fire managers to educate themselves about the air quality regulator’s roles and concerns to protect human health.

It is also critical that land managers establish credibility with the air regulatory agency staff before regulations are proposed. It is much more difficult to develop credibility with any type of regulatory agency after the regulatory process has begun. In most cases, air regulatory agencies view land managers the same way that they view any other polluter. These same air regulatory agencies have heard many excuses about why specific polluters should be exempt from regulations, why it is too expensive to comply, or why the polluter doesn't really cause any problem. Land managers will develop credibility with air regulatory agencies if they can demonstrate that they take air quality issues seriously and that they are doing the best possible job of minimizing both the amount and effect of the smoke they emit into the air.

The key for effective involvement in the regulatory development process is to be both proactive and credible. This takes time and effort. However, if land managers want to continue to use prescribed fire as a management tool, taking the time and making the effort is an absolute necessity.

Summary

Good communication with the public and other interested parties is critical to maintaining an active prescribed fire program. Communications help to develop relationships and trust and establish the professionalism and concern that fire managers have not only for the responsible use of fire but also for protection of air quality. To accomplish these goals the fire manager, in consultation with line officers and agency administrators, should develop and implement a communication and outreach strategy to:

- Identify the local public's perception of smoke and prescribed fire so messaging can be targeted in a way to best increase their knowledge and allay fears or misconceptions.
- Identify key audiences and develop smoke management and prescribed fire messages that are customized for them.
- Identify how to address communications if smoke management problems arise.
- Include a plan for regular communications even when all is going well.
- Include coordination with agency administrators, line officers, fire management and public affairs staff.
- Proactively establish and maintain the credibility and professionalism of the fire managers and land management agency.

6.2. Public Perceptions of Smoke from Wildland Fire

Jarod Blades, Troy Hall, & Sarah McCaffrey

Introduction

Land managers and public officials need to understand the diverse public opinions toward smoke from wildland fires (prescribed fire and wildfire); however, a very limited amount of research has been conducted on this topic. Hence, land and fire managers are largely uncertain about society's willingness to tolerate short-term effects of smoke in return for long-term natural resource benefits. They need effective ways to describe the likely consequences of smoke generated by each fire management program (e.g., prescribed fire treatments vs. suppression) and why these programs serve the public interest (Potter *et al.* 2007). Information about public values, attitudes, and beliefs can be used to inform land management decisions and tailor public communication strategies to align with local and regional perspectives. This chapter provides a brief overview of research on public perceptions of smoke.

It is difficult to disentangle public perceptions and tolerance of smoke from tolerance of wildland fire—the source of the smoke. This chapter reviews literature on complex factors that influence public tolerance of smoke (figure 6.2.1); much of it focused on wildland fire, where smoke was a smaller and secondary focus. It addresses: (1) public knowledge, beliefs, and attitudes about smoke from wildland fires; (2) agency trust and public outreach; and (3) selected individual and community characteristics (e.g., past experience with smoke, preparedness, and sociodemographic characteristics).

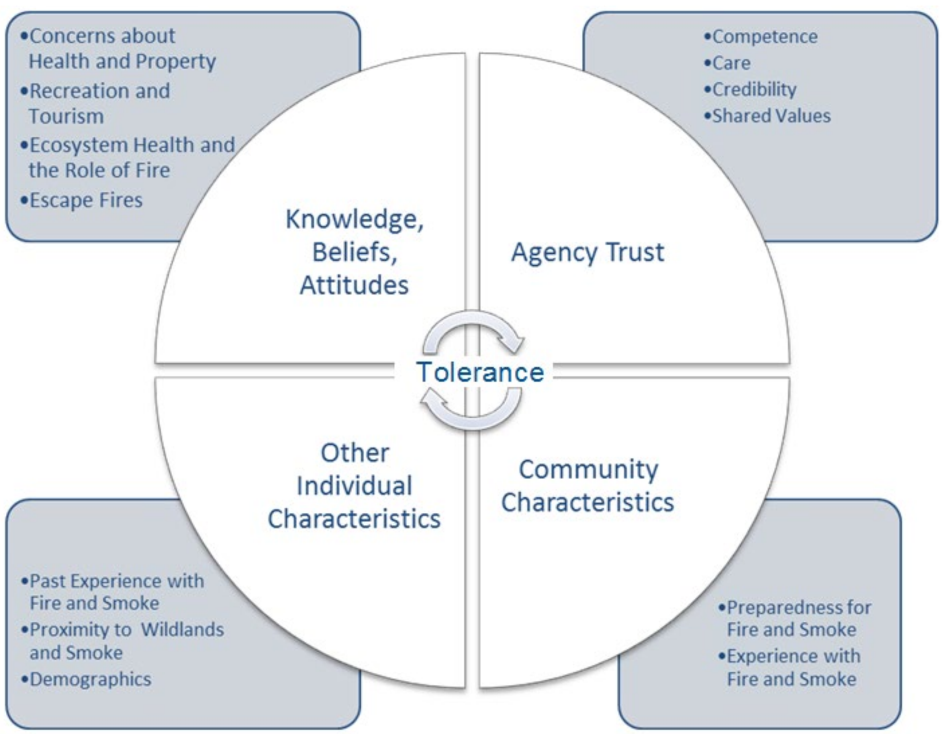

Figure 6.2.1. A framework for public tolerance of smoke from wildland fires.

Public Knowledge, Beliefs, and Attitudes About Smoke from Wildland Fire

Differing levels of knowledge, beliefs, and understanding of current fire and smoke issues can influence the public's tolerance of smoke and support for fire management. Higher tolerance is associated with levels of knowledge about the necessity of the fire producing the smoke; the positive effects of fire (e.g., improved forest health, reduction of wildfire risk, and improved better wildlife habitat) and steps fire managers have taken to minimize smoke impacts on communities (Blades and Hall 2012; Jacobson *et al.* 2001; Ryan and Wamsley 2008; Shindler and Toman 2003; Winter *et al.* 2004, 2006). However, greater knowledge does not always lead to a higher degree of tolerance because other factors may be more important, as explored below.

Concerns about Personal Health and Property

KEY POINT: A small percentage of the U.S. population considers smoke from wildland fires to be a serious issue. These individuals often have an existing health condition and can be the most vocal about health concerns—which can affect current and future land management activities.

Smoke from wildland fires can affect community residents in a variety of ways—through health effects, ash deposition (soiling of materials), public nuisance, impaired visibility, and economic impacts (see Chapters 2.1-2.4). For most people, smoke from wildland fires does not noticeably affect health; however, certain segments of the population and people are at greater risk of exposure to smoke (Fowler 2003). Individuals, households, and communities that have existing health problems are more aware of smoke's health impacts and are typically less tolerant of smoke from wildland fires. Fears about public safety and apprehension about increased levels of smoke can be a primary concern surrounding wildland fire (Brunson and Shindler 2004; Kneeshaw *et al.* others 2004); however, general population surveys show that most residents do not consider smoke to be a serious issue (Blades and Hall 2012; Brunson and Evans 2005; Jacobson *et al.* 2001; Loomis *et al.* 2001; McCaffrey *et al.* 2008; McCaffrey and Olsen 2012; Ryan and Wamsley 2008). Nevertheless, smoke from wildland fires is highly salient for people with existing respiratory health issues— approximately 30% of households (McCaffrey and Olsen 2012). These individuals are often more vocal about concerns, although some people with health issues have accepted smoke as a reality of where they live (Weisshaupt *et al.* 2005). Given rising asthma rates and an aging U.S. population, the issue of health impacts from wildland fire smoke is an increasing concern.

Concerns about Recreation and Tourism

KEY POINT: Community concerns about the impacts of smoke on recreation, tourism, and outdoor activities can be greater than other concerns.

People travel to national forests and protected areas to enjoy solitude and scenery—which can be affected by fire and smoke. The wildfire season often coincides with the peak tourism and recreation season, increasing the likelihood of smoke impacts to outdoor-related businesses. Smoke is sometimes perceived to have a negative effect on aesthetic quality and recreation, and can result in substantial revenue losses if visitation declines (Brunson and Shindler 2004; Ross 1988; Sandberg *et al.* 2002; Thapa *et al.* 2004; Winter *et al.* 2002). Recent research in the U.S. northern Rocky Mountains found that the public perceives the likelihood of smoke impacts on outdoor recreation, scenery, and school recess to be greater than the likelihood of impacts to personal health, and people from rural areas are more concerned about such impacts than people from urban areas (Blades and Hall 2012). Given that many rural communities, notably in the western United States, are shifting from commodity to amenity-based economies (Winkler *et al.* 2007), effects on recreation, tourism, or other amenity-based lifestyles are an increasing concern.

Ecosystem Health and the Role of Fire

> **KEY POINT:** The public is more tolerant of smoke when they have an accurate understanding of the positive effects of wildland fire, such as improving forest health and wildlife habitat.

Many people value natural landscapes and agree that ecosystem health is important. However, there are divergent opinions about what defines a healthy ecosystem, the appropriate role of fire, and whether smoke is an inevitable consequence of living near wildlands.

Some people are more concerned about prescribed fire's impacts on fish and wildlife than they are about the health effects of smoke or the cost of conducting the treatment (Bowker *et al.* 2008; Jacobson *et al.* 2001). Reinforcing and improving public understanding about the role of fire in improving ecosystem health and reducing community wildfire risk should be a focal point of public communication aimed at increasing public tolerance of smoke.

Public Trust in Land Management Agencies

Trust has long been established as an important component of public land management. In any aspect of life, trust is difficult to establish, easy to lose, and very hard to regain. Expectations of land managers are higher now than in the past because fire and smoke management activities have more direct impacts on citizens living in rural wildland urban interface (WUI) communities, largely due to population growth and more opportunities for people to experience wildland fire effects.

Public acceptance of fuel treatments that involve smoke is often related to the degree to which people trust the implementing agencies (Vogt *et al.* 2003). Several dimensions of trust related to land and fire management have emerged as being most salient to the public, notably competence, credibility, care, and shared values (Absher *et al.* 2009; Winter *et al.* 2004, 2006). Care and credibility are established through agency efforts to communicate with the public about current and future agency actions, especially about the risks associated with wildland fire and smoke. Providing the public with advance warning about smoke offers an opportunity for citizens to ask questions early, conduct personal and community preparations, and maintain relationships with fire management professionals (see the Local Situation Analysis section of Chapter 6.1). Advanced warning was identified in one regional study as the most important aspect of public tolerance of smoke from wildland fire (Blades *et al.* 2012). Further, a personal phone call from an agency representative who provided advance warning about potential smoke impacts was considered preferable to a radio, television, or newspaper public service announcement. Credibility and competency increase public trust and acceptance of forest treatment activities, resulting in a belief that the agency is able to manage the burn safely (Winter *et al.* 2002). Social trust is enhanced when people perceive that they share similar goals, thoughts, values, and opinions with the agency (Absher *et al.* 2009; Winter *et al.* 2004). Feelings of involvement, ownership, and shared responsibility have also been found to be key components of trust (Blanchard and Ryan 2007).

The Controllability of Fire and Escaped Prescribed Fires

As stated at the beginning of this chapter, it is often difficult to separate perceptions of smoke from perceptions of fire—where beliefs about wildland fire are intertwined with beliefs about the resulting smoke. Public support for wildland fire and smoke management activities is often dependent on whether people believe that the fire and smoke can be effectively controlled. Does the public believe that prescribed fire will reduce the likelihood of an extreme wildfire and subsequent risks to ecosystems, human health, and property? People from various parts of the United States have been found willing to trade-off the negative aspects of smoke from prescribed fires conducted now for the benefits of less smoke and reduced threat of extreme wildfires in the future (Blades and Hall 2012; Weisshaupt *et al.* 2005; Winter *et al.* 2006). Overall, people are more tolerant of smoke from prescribed fires if they believe that it ensures greater control over present or future fires, benefits the ecosystem, and reduces risks to personal health and property.

On the other hand, sometimes the threat of an escaped prescribed fire and widespread smoke is perceived to be greater than the potential benefits of burning. Stated another way, the cure is perceived to be worse than the disease. People who have concerns about the possibility of a prescribed fire escaping have a lower tolerance for its use (Absher *et al.* 2009; Blanchard and Ryan 2007; Brunson and Evans 2005; Fried *et al.* 2006; Weisshaupt *et al.* 2005).

KEY POINTS: Trust has long been established as an important factor of effective land and fire management, and the same holds true for smoke management. Advance warning about potential smoke impacts is one of the most important aspects of public tolerance of smoke from wildland fires.

People are often willing to trade-off the negative short-term consequences of smoke from prescribed fires if they **believe that it could reduce the threat of extreme wildfire and smoke events in the future, and trust that the likelihood of an escaped prescribed fire is low.**

To address public concerns, it is important to clearly communicate all trade-offs associated with fuel treatments because vague or incomplete discussion of smoke risks could jeopardize public trust and support. Face-to-face contact helps to promote trust. Communications should clearly reflect land managers' understanding of public concerns and a long-term commitment to a public-management relationship (Shindler 2004). Building and maintaining trust between land managers and stakeholders is not a new concept; however, a stronger focus on advance warning, personal communications about potential smoke impacts and smoke mitigation strategies could enhance public trust surrounding smoke management.

Other Individual and Community Characteristics Related to Tolerance of Wildland Fire Smoke

Past Experience with Fire and Smoke

The past experiences of an individual, community, and region with wildland fire and smoke have been suggested as driving differences in support for prescribed fire practices (Loomis *et al.* 2001), and the same is likely true for tolerance of smoke. Individuals or communities with more exposure to wildland fire activities, and those individuals who have worked in natural resource-related fields, are more accepting of fuel treatments (Blanchard and Ryan 2007; Winter *et al.* 2006). Moreover, people who have experienced recent and severe wildfire smoke may believe that prescribed fire is an effective technique for reducing wildfire and smoke risks (Weisshaupt *et al.* 2005). On the other hand, limited personal experience with wildland fire and smoke has been linked to beliefs about negative outcomes of prescribed fire, such as escaped prescribed fires, and lower support for forest treatments (Winter *et al.* 2006). This is an important consideration because the lack of wildland fire could actually increase the risk of severe wildfire and smoke in the future, as well as the need for fuel treatments. Therefore, understanding the types of individual and community past experiences with wildland fire and smoke (e.g., good or bad experience, short- or long-term impacts) is important to understanding public tolerance of smoke and level of support for management actions involving smoke.

Community Type and Proximity to Wildlands

How does the location of a person's home (urban to rural) and proximity to wildlands influence perception and tolerance of smoke from wildland fires? A public preference for perceived lower-risk treatments (e.g., mechanical thinning) near developed areas and perceived higher-risk treatments (e.g., prescribed fire) in remote rural areas has been documented in some instances (Bright and Newman 2006; Weisshaupt *et al.* 2005). Recent research in the northern U.S. Rocky Mountains found that residents of both rural and urban communities understood the benefits of prescribed fire, trusted management agencies, were somewhat tolerant of smoke from wildland fires, and supported prescribed fire management activities; however, rural communities were less tolerant in all of these categories than urban communities (Blades and Hall 2012). It is not surprising to find a difference between urban and rural residents, but it is encouraging that beliefs and attitudes generally trend in the same direction, and that a consistent communication strategy could be effective regardless of location and proximity to wildlands.

Community Preparedness for Fire and Smoke

KEY POINT: The amount and type of experience with fire and smoke can influence beliefs and attitudes about fire management and smoke.

There are important relationships among space, community, and culture that define a WUI community and its level of adaptability to fire, preparedness for wildfire and smoke (Bowker *et al.* 2008; Jakes *et al.* 1998, 2007; Lee 1991; Paveglio *et al.* 2009). Does a community's level of preparedness for wildfire (e.g., completed a Community Wildfire Protection Plan and followed through with recommended actions, coordination between structural and wildland firefighters, or formation of a WUI committee) change levels of tolerance for smoke from wildland fires? Recent research (Blades and Hall 2012) has shown that communities that are more prepared for wildland fire are significantly more tolerant of smoke than less-prepared communities, and more supportive of fuels management involving smoke (i.e., prescribed fire). This is likely related to the positive association, discussed earlier, between knowledge levels and support for prescribed fire.

Sociodemographic Characteristics

Demographic characteristics have rarely been documented as having a strong relationship to the level of public of support for fire management activities or policies (Absher *et al.* 2009; Blades and Hall 2012; Fried *et al.* 2006; McCaffrey and Olsen 2012; Shindler and Toman 2003). This is not altogether surprising because issues of smoke and fire are often complex and affected by geographic, social, and other contextual factors, as this chapter has established. Nevertheless, some studies have indicated that women (notably African-American and Hispanic women) are more concerned than men about the environment in general, and certainly more concerned about the potential adverse effects of prescribed fire and smoke (Bowker *et al.* 2008; Lim *et al.* 2009; Ryan and Wamsley 2008).

Summary and Conclusions

This chapter focused on the complex factors that influence public perceptions and tolerance of smoke from wildland fires. The studies reviewed here suggest that public perceptions and tolerance of smoke may be similar at regional levels for some aspects (e.g., support for the use of prescribed fire, awareness of prescribed fire benefits, general tolerance of smoke from wildland fires, moderate trust of public land and fire managers), but also vary significantly among different types of communities and individuals. Public communication materials are often developed for a homogenous audience, yet these studies are a useful reminder of the variability that exists within communities and regions, and that locally tailored messages may be more effective for developing public tolerance or acceptance of smoke from wildland fire management. In summary, wildland fire smoke management programs and plans should take into account some key points about public perceptions and tolerance of smoke:

1. **Public beliefs and attitudes about the benefits or detriments of wildland fire directly influence tolerance of smoke**—The strength of different beliefs and attitudes about the consequences of fire and smoke influence tolerance of smoke and support for management strategies that produce smoke. Public concern about health impacts appears to be the main issue for wildland fire smoke. However, where concerns are present they can be substantial; to date, this appears to be a concern for around one-third of households. Health issues related to smoke are anticipated to increase in the future, so an early and ongoing relationship with individuals who have existing health conditions is advisable to mitigate their concerns. Community concerns about the effects of smoke on recreation, tourism, and outdoor activities can be greater than other concerns. The public is generally more tolerant of smoke when there is an understanding of the positive effects of wildland fire, such as improving forest health and wildlife habitat.
2. **Build and maintain trust, and validate concerns about controlling fire and smoke—** Development of trust, and maintenance of relationships with the public have always been important aspects of effective land and fire management, and the same holds true for smoke management. Advance warning about potential smoke impacts is one of the most important contributors to public tolerance of smoke from wildland fires and agency trust. People are often willing to accept negative short-term consequences of smoke from prescribed fires if they believe that this will reduce the threat of extreme wildfire and smoke events in the future, and if they trust that the likelihood of an escaped prescribed fire is low. Fire managers should clearly communicate all trade-offs surrounding wildland fire smoke because vague, untimely, incomplete or glossed-over representations of smoke effects, exaggerated expectations of safety, could jeopardize public trust and support (see Chapter 6.1).
3. **The devil is in the details, so understanding each audience is important**—Of course, this is not a new suggestion, but individual and community characteristics such as experience, community preparedness, and individual characteristics influence perceptions and tolerance of smoke in complex ways. Because there is a mosaic of varying interests and lifestyles that are intermixed, often without clearly delineated boundaries, it is important to delve into the details of each community to understand contextual and spatial differences that could influence perceptions and tolerance of smoke.

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CHAPTER 7 – WILDLAND FIRE AND CLIMATE CHANGE

7.1 Wildland Fire and Climate Change

Janice L. Peterson

Introduction

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." (IPCC 2013)

The greenhouse effect is a natural phenomenon that makes the earth habitable by enabling our atmosphere to capture and hold heat from the sun. Specifically, solar radiation at the frequency of visible light passes through the atmosphere and warms the surface of the earth. The earth then re-emits this energy at the lower frequency of infrared thermal radiation. Some of the thermal energy is absorbed by greenhouse gases which, in turn, re-radiate much of it to the surface of the earth and the lower atmosphere, warming the planet (figure 7.1.1). Without this effect, the earth would be too cold to support life as we know it. Human activities have increased the concentration of the gases and particles most effective at capturing heat—especially carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and black carbon (BC). Therefore, the atmosphere is becoming more effective at capturing heat and the earth is warming as a result.

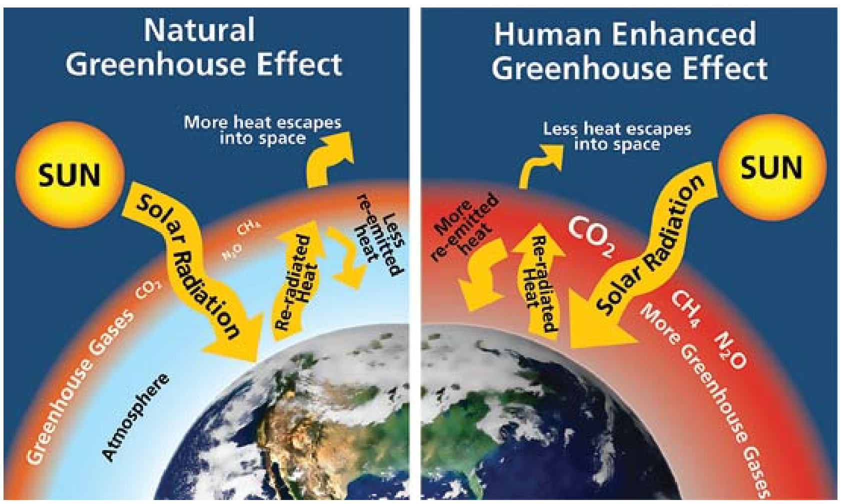

Figure 7.1.1. The accumulation of greenhouse gases in Earth's atmosphere results in increased capture of heat and warms the planet. (USDI NPS 2015)

How will a warming climate affect wildland fire? And how will efforts to slow and adapt to climate change affect use and management of wildland fire? This chapter is a brief overview of some concepts of a very complex and evolving issue relating climate change to wildland fire.

What Effect Does Wildland Fire Have on Climate?

Wildland fires emit hundreds of trace gases and aerosols into the atmosphere, some of which contribute to the greenhouse effect. The primary greenhouse gases (GHGs) from wildland fire are CO_2, CH_4, and N_2O. Carbon dioxide is produced in the greatest quantities, CH_4 in lesser quantities, and finally N_2O. When biomass is completely combusted it produces CO_2 and water; however, combustion is rarely complete.

Not all GHGs are equal in the magnitude of their contribution to global climate warming. Methane has a global warming potential (GWP) of 25, indicating it is about 25 times more efficient at warming the atmosphere than CO_2. Nitrous oxide has a GWP of 298. Thus, it is not only the quantity of a GHG that is important for understanding the impact of a gas or aerosol on the climate, but also its GWP. Often the emission of a GHG is reported in CO_2-equivalent (CO_2-Eq) units to reflect this difference.

In 2013, wildland fire in U.S. forestlands emitted about 77.9 million metric tons (MMT) of CO_2, 5.8 MMT CO_2-Eq of CH_4, and 3.8 MMT CO_2-Eq of N_2O (table 7.1.1). These values indicate that wildland fires contributed about 1.4 percent of U.S. emissions of CO_2 in 2013. Note that acres burned and thus emissions from wildland fires have great inter-annual variability. Carbon dioxide emissions for wildland fires in 2012 are over 2½ times higher than in 2013 (table 7.1.1) and comprise nearly 4% of U.S. CO_2 emissions for that year. In the U.S., fossil fuel combustion accounted for 93.7 percent of CO_2 emissions in 2013.

Table 7.1.1. Estimated 2012 and 2013 greenhouse gas emissions from fires in forestlands (lower 48 states and Alaska) compared to the total for all U.S. sources. Estimates do not include rangeland or crop-residue burning (U.S. EPA 2015).

	Carbon dioxide (CO_2) *MMT*[a]		Methane (CH_4)		Nitrous oxide (N_2O)	
			- - - - - - - *MMT CO_2-Eq* - - - - - - - -			
	2012	2013	2012	2013	2012	2013
U.S. forestlands (wildfire and prescribed fire)	209.1	77.9	15.7	5.8	10.3	3.8
United States (all sources)	5,358.3	5,505.2	647.6	636.3	365.6	355.2

[a] MMT is 1 million metric tons.

Carbon sequestration in an ecosystem is the process by which atmospheric CO_2 is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in living and dead biomass (foliage, wood, litter, and soils). Wildland fire is a natural part of many ecosystems and, even though fire is a source of greenhouse gases, growth of vegetation captures CO_2. In the U.S., forests currently sequester more carbon than they emit (table 7.1.2). United States forest lands are estimated to capture from 10 to 20% of U.S. greenhouse gas emissions each year (USDA FS [N.d.]). Carbon from forests can also be sequestered when harvested wood is made into durable products like houses or furniture (figure 7.1.2).

Table 7.1.2. Growth and biological processes in forest ecosystems, plus harvesting of forest products, results in net annual removal of carbon from the atmosphere. (Removal is represented by showing the values in parentheses) (US EPA 2015).

	Greenhouse gas sequestration in the U.S.	
	- - - - - - *MMT CO_2-Eq per year* - - - - - -	
Carbon source—	2013 Estimate	Uncertainty range
Forest ecosystems	(704.9)	(900.7) – (505.9)
Harvested wood products	(70.8)	(89.9) - (54.0)

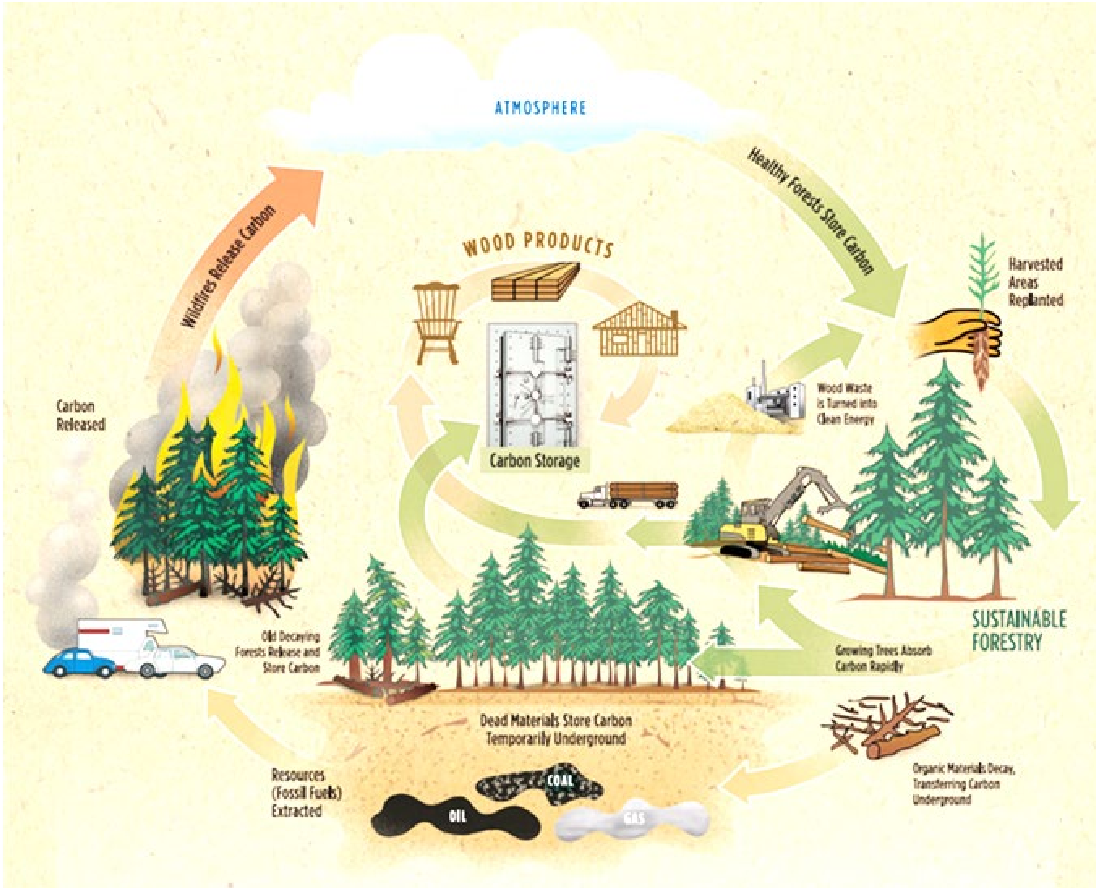

Figure 7.1.2. Forestry sector carbon pools and flows. (Adapted from California Forest Foundation, N.d.)

Fire and Short-Lived Climate Forcers

Short-lived climate forcer (SLCF) is the term given to trace gases and aerosols that have a strong impact on climate but are shorter lived in the atmosphere than CO_2. Wildland fire smoke contains the short-lived-climate-forcers methane (CH_4), ozone[1] (O_3), and black carbon (BC). The atmospheric lifetime of CH_4 is about 10 to 12 years. Ozone can vary throughout the day especially over urban areas (going to near zero at night), but the typical background concentration of ozone has risen to range between 20-45 parts per billion (ppb) depending upon geographic location, elevation, and extent of anthropogenic influence. This is about double the background concentration of ozone measured over a century ago (Vingarzan 2004).

Black carbon, a major component of soot, is the SLCF of most concern with regards to wildland fire (Bond *et al.* 2013). Black carbon has a relatively short atmospheric lifetime of just days to weeks and can be transported regionally and inter-continentally. Black carbon absorbs visible light (incoming solar radiation) and emits heat to the surrounding air. This is different from greenhouse gases, which absorb infrared radiation from the earth's surface and then emit that heat to the surrounding atmosphere. Precipitation and deposition are the primary removal mechanisms of BC from the atmosphere. Deposition of BC on snow changes the albedo (reflectivity), speeding snowmelt. Transport and deposition of black carbon to the Arctic is a particular concern since warming temperatures are already reducing snow and ice there although North American wildland fires are not considered a significant contributor (Liu *et al.* 2015). For the U.S., BC is predominantly released from diesel vehicles and

[1] Ozone is not emitted directly from fires but is formed downwind through a chemical reaction of VOC's in smoke with nitrogen oxides (NO_x) from anthropogenic sources, driven by heat and sunlight.

biomass burning (about 50% from each), but globally, other important sources are residential solid fuel (i.e. coal and biomass) and industry.

What Effect Will a Changing Climate Have on Wildland Fire?

Climate and fuels are the two most important factors affecting patterns of fire in ecosystems. Climate determines the frequency of weather conditions that promote fire, whereas the amount and arrangement of fuels influences fire intensity and spread (Vose *et al.* 2012).

Interactions between climate, fuels, and wildfire are extremely complex and the science of forecasting future scenarios remains uncertain, but predictions of future climate conditions and trends have led scientists to predict some ways in which wildland fire is likely to change. Conditions that result in major wildfire events vary significantly across the United State due to variations in temperature, moisture, wind speeds, and fuel interactions so the effects of a changing climate on wildfire can be expected to be variable and ecosystem-specific.

Many of the climatic changes predicted to occur with a warming planet have long been linked with increases in wildfire including:

- Climate modeling indicates that lightning activity will increase by 12% (±5%) per degree Celsius of warming in the continental United States and thus about 50% over this century (Romps *et al.* 2014).
- Warmer spring and summer temperatures lead to earlier snowmelt, lower summer soil and fuel moisture, and thus longer fire seasons especially in the West. In some areas, climate change is expected to increase the window of time for high fire risk each year by 10-30% (Stavros *et al.* 2014).
- A warmer climate will magnify the effects of drought and increase the number of days in a year with flammable fuels, extending fire season length and area burned in ecoregions where fire extent is linked to fuel conditions (Littell *et al.* 2009).

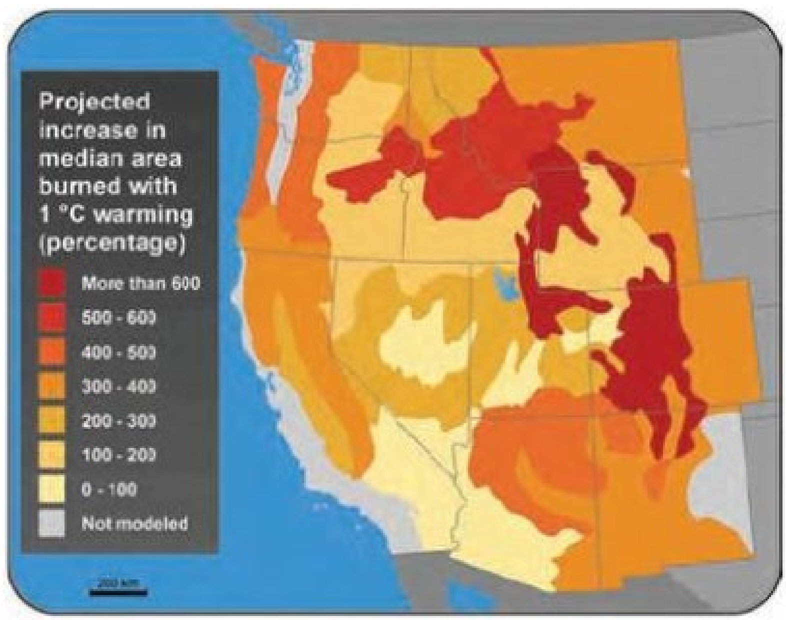

Figure 7.1.3. Modeled estimates of the percentage increase in area burned in the western United States (relative to 1950–2003) with a one degree increase in temperature (Peterson and Littell 2012).) This projection is likely a worst case scenario as certain negative feedbacks (such as moisture dynamics) were not factored in (Don McKenzie, personal communication).

Changes in climate have the potential to significantly affect fire regimes, especially in areas where climate rather than fuel, tends to be the limiting factor. Area burned by wildfire has a stronger relationship with climate in the western United States than fire frequency or severity. A recent modeled projection of potential increases in area burned is shown in figure 7.1.3 (Peterson and Littell 2012).

In the eastern United States, complex patterns of land use and active prescribed fire programs make predictions of future wildfire particularly difficult although a recent modeling effort (Bedel *et al.* 2013) indicates that the Deep South, the Gulf Coast, and the southern portion of the Piedmont are expected to experience greater fire potential, especially in the spring. Some areas of the south may have this mitigated due to possible increases in spring precipitation.

So in general, predictions indicate that as the climate warms:

- Fire seasons will lengthen. Longer fire seasons are correlated with more area burned; more area burned indicates more economic losses. Arid ecosystems may be the exception as drought could reduce fuels to the point that annual fire occurrence decreases (Littell *et al.* 2009, McKenzie and Littell 2011).
- Air quality problems from smoke are expected to worsen if projections of future fire regimes are even reasonably accurate, including more frequent extreme smoke events (McKenzie *et al.* 2014).
- The probability and frequency of very large wildfires (≥ 50,000 acres) will increase in most areas of the west (Stavros *et al.*, 2014).
    - The Pacific Northwest and Rocky Mountains, which are currently flammability limited, show the highest probability of increases.
    - Fuel-limited areas such as non-forested parts of Southern and Northern California, and much of the Western Great Basin may see reductions in fuel as a warmer climate reduces the growth of vegetation reducing the area prone to fire and possibly even the likelihood of very large wildfires.
- Weather and fuel conditions that are favorable to very large wildfires (>5,000 ha. (12,355 acres)) during the historical fire season will increase, along with a lengthening of the seasonal window when conditions support the spread of very large wildfires (Barbero *et al.* 2015).
- Wildfire may emerge as an issue in areas where it has not been for decades, for example in the upper Midwest and Northeast (USDA USDI 2014).
- Wildfire seasons are expected to be longer and more severe. (Flannigan *et al.* 2013).
- New combinations of species and associated fuel loadings will result in changed fire regimes (Stephens *et al.* 2013).

The recent National Climate Assessment Report, Forest Sector (Vose *et al.* 2012) provides a basic summary of expected climate change effects to wildfire around the U.S:

- In interior Alaska, the most important effects of climate change are permafrost thaw and changes in fire regime. South-central Alaska is also expected to experience changing fire regimes.

- In the Northwest, area burned and biomass consumed by wildfire will greatly increase, leading to changes in ecosystem structure and function.

- In the Southwest, disturbance processes aided by climatic extremes, primarily multi-year droughts, will dominate the effects of climatic variability. Increased disturbance from fire and insects, combined with lower forest productivity at most lower elevations, will result in lower carbon storage in most forest ecosystems. Increased fire followed by high precipitation may result in increased erosion.

- In the Great Plains, increased wildfire hazard, longer droughts, insect outbreaks, and fungal pathogens – individually and in combination– could significantly reduce forest cover and vigor.

- In the Midwest, increased drought and fire occurrence are expected to have rapid and extensive effects on the structure and function of forest ecosystems.

- In the Southeast, future fire potential is expected to increase in summer and autumn from low to moderate levels in the eastern sections in the South and from moderate to high levels in the western portions of the South.

How Do Forest and Fuels Management Decisions Affect Climate Change?

Carbon sequestration is the capture and long-term storage of atmospheric CO_2. One of the most important ways that forest management actions can contribute to carbon sequestration is by maintaining lands in forest cover types. Conversion of forested lands to other land uses (especially developed uses) reduces carbon storage capacity. The area covered by forests is projected to decline between 2010 and 2060, reducing the amount of carbon that can be stored in U.S. forests by 2060 (USDA FS 2012).

Fuel treatments such as thinning and prescribed fire, trade current carbon storage for the potential of avoiding larger carbon losses in wildfire but any carbon savings are highly uncertain (Ryan *et al.* 2010). Over the long term, wildfire does not cause a net loss of forest carbon as long as the forest regenerates and recaptures the carbon released during the wildfire. But if the frequency or severity of wildfire increases substantially, long-term carbon storage will be reduced because the fraction of the landscape with large, older trees (that have high carbon stores) will decline.

A large risk to forest carbon storage capacity from wildfire is that the forest may not regenerate afterwards and instead be replaced by meadow or shrubland with far less capacity to store carbon. This is already happening in the western United States as high-severity fires occur in ecosystems that are adapted to low-severity fire regimes (Ryan *et al.* 2010). Climate change may also increase the likelihood that forests will not regenerate since certain species and genotypes may have a difficult time growing under altered climatic conditions.

If a wildfire burns through a forest where fuels were thinned, treated with prescribed fire, or both, the wildfire may be less severe and more of the existing stand may survive. This difference in survival would lead to the conclusion that fuel treatments offer a carbon benefit: removing some carbon from the forest may protect the remaining carbon. However, the current evidence is contradictory. Some studies have found (or modeled) that thinned stands have much higher tree survival and lower carbon losses in a wildfire. However, other studies show no carbon benefit from fuels treatments. More research is needed to resolve these contradictory conclusions (Ryan *et al.* 2010).

Boreal forests have especially deep organic layers, and other forest types have significant peat or ground organic layers also. Burning deep forest floor organic layers releases large quantities of carbon currently locked away in long term storage. If prescribed burning can reduce the chance of a high-severity wildfire burning up these deep organic layers then the prescribed burning may help minimize the release of greenhouse gases.

With current trends already showing increases in large fire occurrence, plus the predicted climate changes that are expected to result in increased fire in many parts of the United States, effective and widespread strategies for fire and ecosystem management are especially critical. Whether or not there are direct reductions in global climate change contributions from the use of prescribed fire, managers must continue to take action in fire-prone ecosystems. Dense stands need to be thinned to reduce drought stress, and surface and ladder fuels need to be removed to decrease fire risk and increase wildfire controllability. Fire needs to be reintroduced into stands where it has been excluded, using prescribed fire under moderate conditions rather than waiting until a wildfire occurs under extreme conditions (Reinhardt 2015).

Conclusions

Fire managers need a basic understanding of the science of climate change and the role played by wildland fire, smoke emissions, and ecosystem management decisions. Ecosystems and fire regimes are expected to change due to a changing climate and fire managers need to be ready to play an appropriate role in this transition. Climate change will result in more serious and more frequent smoke effects if projections of future fire regimes are even reasonably accurate. The public will have questions about how the use of prescribed fire and wildfire contribute to climate change, and how prescribed fire can affect the production and maintenance of healthy forests and their ability to store carbon.

Wildland fire suppression efforts have traditionally been very successful with about 98 percent of fires suppressed in initial attack. Recent trends in large fires show that this success rate may not be sustainable and, despite ramped up fire suppression capacity, large fires are occurring more frequently and more area is being burned already. In the short term, prescribed fire emits greenhouse gases and particles, but if prescribed fire plays a role in improving forest health, reducing fuel loads, increasing growth rates, reducing the chance of high-severity wildfire, and preventing or slowing the conversion of forest ecosystems to other types, then its use may contribute to lessening CO_2 emissions from wildfire and maintaining carbon stored in forests. Further research is needed to measure and confirm this relationship.

Climate Change Terms to Know

- **Black carbon (BC)—**Black carbon is the most strongly light-absorbing component of particulate matter, and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass. It is emitted directly into the atmosphere in the form of fine particles.
- **Carbon dioxide equivalent (CO2-Eq)—**A metric used to compare the emissions from various greenhouse gases based upon their GWP relative to carbon dioxide (CO_2).
- **Global warming potential (GWP) —**A measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to carbon dioxide.
- **Greenhouse gases (GHG)—**Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include, carbon dioxide, methane, nitrous oxide, ozone, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.
- **Infrared radiation**—Infrared radiation consists of light whose wavelength is longer than the red color in the visible part of the spectrum, but shorter than microwave radiation. Infrared radiation can be perceived as heat. Also known as terrestrial or long-wave radiation.
- **Methane (CH_4)—**A hydrocarbon that is a greenhouse gas with a GWP most recently estimated at 25 times that of CO_2.
- **Nitrogen oxides (NO_x)—**Gases consisting of one molecule of nitrogen and varying numbers of oxygen molecules. In the atmosphere, nitrogen oxides can contribute to formation of photochemical ozone (smog), can impair visibility, and have health consequences.
- **Ozone (O_3)—**At lower levels of the atmosphere (troposphere) ozone is created by photochemical reactions involving gases resulting from natural sources and human activities. Tropospheric ozone acts as a greenhouse gas. High in the atmosphere (stratosphere) naturally occurring ozone shields the earth from ultraviolet B radiation.
- **Ozone precursors—**Chemical compounds, such as carbon monoxide, methane, non-methane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.
- **Radiative forcing—**A measure of the influence of a particular factor, whether greenhouse gas, aerosol, or land use change, on the net change in the earth's energy balance. It is quantified at the top of the troposphere in units of Watts/m^2, and a negative value indicates a cooling effect while a positive value indicates a warming effect.

- **Sequestration**—Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide or other forms of carbon to either mitigate or defer global warming.
- **Sink**—Any process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol, from the atmosphere.
- **Solar radiation**—Radiation emitted by the Sun; also referred to as short-wave radiation.
- **Soot**—Soot is the black material in smoke and the initial chemical composition of soot depends strongly on its sources; some sources can produce almost pure elemental carbon, while others produce soot of which 50% by mass is organic matter.

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CHAPTER 8 – PREPARING FOR PRESCRIBED FIRE

8.1. Planning for Fire Management

NWCG Smoke Management Guide Editors[1]

The success of a wildland fire management program, addressing both wildfire and prescribed fire, depends on a solid foundation established by clear and thorough planning. The products of a planning process provide program buy-in and continuity, leader's intent, tools to work with cooperators, and program information to communicate the intent to stakeholders such as the public and agency employees. This process helps to collectively develop goals and measurable objectives for fire management which are in accordance with land management goals. Smoke and air quality considerations are important at all levels of planning. Fire management planning details differ between federal, state and local agencies but, the planning progression is generally the same.

Land and Resource Management Planning

Land and resource management planning is the overarching planning process for an area that has been selected for analysis. The area manager convenes a planning team that will identify land management goals and objectives to guide future management actions for a specific timeline, determined by either policy or guiding principles. The planning team also discusses desired conditions for the area. Generally, fire management considerations are a component of this planning process.

An ongoing assessment of the land within these plans determine the need for resource management, predicts levels of resource use and outputs, and provides for a variety of resource management practices. During the assessment, documentation of any barriers to implementing a resource management treatment, such as regulations, cost, or insufficient resources needed for implementation, should be done. If a treatment is not recommended because of these barriers, the probable ecological consequences of this decision should also be documented. At locations where use of wildland fire is selected as the best alternative to accomplish the desired resource management objectives, the next step in the planning process is to develop a fire management plan (FMP).

Many private landowners are not required to write land and resource management plans, but most have a vision of what natural resource attributes they want to favor and what they want their lands to look like. It is recommended that landowners record their vision on paper to provide documentation for future needs and to describe their vision.

EPA Language for Exceptional Events Determination in Land Management Plans

In order to meet a requirement for use of the EPA's Treatment of Data Influenced by Exceptional Events Rule (EPA 2016), known as EER, all areas where prescribed fire is to be used and potentially wildfires managed using multiple strategies, the land management plan should explicitly discuss the ecological role of fire and clear objectives for fire. Specifically, the plan can be tied to specific fuels, locations and/or ecosystems, should discuss the goal or potential for the use of fire within the natural fire return interval and/or in a frequency to establish, restore and/or maintain a sustainable and resilient wildland ecosystem and/or to preserve endangered or threatened species. Some general range of fire frequency is valuable in the discussion of fire and the use of fire outlined above will facilitate the development of an exceptional event demonstration if a prescribed fire were to inadvertently cause an exceedance of a national ambient air quality standard. The EER also recognizes the use of Basic Smoke Management Practices (BSMP) when using prescribed fire and where feasible on wildfires. Statements affirming the use of BSMP within appropriate planning documents will address another EER requirement if an exceedance were to occur. See chapter 3.2 for more information on the EER and BSMP.

[1] With contribution from the NWCG Interagency Fire Planning Committee and Fuels Management Committee.

Fire Management Planning

Fire management planning is a step down planning process from the land and resource management plan. It addresses the management of wildland fire at the level of the administrative unit, such as a forest, nature preserve, park, refuge, ranch or plantation. The Fire Management Plan (FMP) is the primary tool for translating programmatic direction developed in the land management plan into on-the ground action. The FMP must satisfy legal requirements (if any exist) described by overarching management direction. Comparisons between implementing fire management activities and not implementing fire management activities on the land management unit should be described in the planning process. This includes implications of wildland fire and prescribed fire use over extended periods of time.

Fire management plans outline fire management strategies, tactics and actions that are managed on the landscape, both spatially and temporally. The process of developing a fire management plan should begin by obtaining management goals and objectives pertaining to wildland fire from the land and resource management planning effort for the site. Consideration of the use of wildland fire to achieve stated resource management goals should be an integral part of this process. In deciding whether or not the use of fire is the best option to accomplish a given objective, an analysis of potential alternative treatments should be completed. This analysis should describe the risks associated with use of a given management treatment and include any expected negative, as well as beneficial outcomes. Care should be exercised to separate statements that are supported by data (preferably local and landscape-specific), from those only professed to be true.

Fire management plans ensure that background information about the area has been researched, legal constraints reviewed, and a prescribed fire program found to be both economically and politically justified, and technically feasible. When managing for multiple resources (e.g., range, wildlife, and timber) on a tract, guidance should be provided regarding the benefits or detriments to each resource.

Items that may be addressed in the fire management plan are:

- current conditions–topography, soils, climate and fuels, etc.,
- regulations or legal issues,
- wildland fire history of the area,
- historic fire regime,
- justification for fire management,
- consideration of alternatives to prescribed fire, (e.g., ungulates, stewardship projects),
- fire management goals, both spatial and temporal, for the area,
- description of the desired condition,
- values either to be protected from or enhanced by fire management activities,
- air quality and smoke management considerations,
- transportation safety,
- adjacent land owner considerations,
- maps illustrating fuels distribution, treatment units, smoke sensitive areas, etc., and
- identification of local partnerships and agreements to assist with fire management.

When complete, the FMP should enable the resource manager to identify the resources needed to effectively and efficiently use wildland fire as a management tool for such things as: protecting species of concern, restoring wildlife habitat, controlling invasive species, reducing hazardous fuel levels, protecting communities, etc.

Community involvement is crucial at all planning levels to ensure continued support for land management considerations. Support at the fire planning process is central to garnering public acceptance of using fire as a management tool. The point at which to involve the public in the process will depend on regional issues, regulations, and organizational policy. In general, the earlier the public is involved, the easier it is to reach agreement on any concerns. Whenever it is done, it is important to remember that public support is key to the long-term success of a fire management program. Unexpected results, including under-achievement and over-achievement of objectives, are bound to occur. A discussion of the potential for such results, and their consequences, can defuse negative reaction to the occasional bad outcome, especially if the public was involved early in the planning process.

Project Implementation Planning

Once the fire management plan is complete and approved, the next step is the development of the actions needed to meet resource objectives. Implementation planning includes prescribed fire and non-fire treatments (e.g., stewardship projects, timber sales, use of ungulates, mowing, firewood sales), to achieve management objectives. However, implementation planning at this stage does not include wildfire strategies to achieve the desired resource goals.

A written implementation plan serves several important purposes:

- it serves to fulfill the goals and objectives that the manager and team set forth during the development of the land and resource management plan which get turned into implementable direction in the fire management plan,
- it allows the manager to prioritize between treatment units based on constraints and objectives,
- it functions as the operational plan that details how treatments will be safely and effectively conducted,
- it serves as the standard by which to evaluate the treatment,
- it provides a record for use when planning future treatments (which makes it essential to document any changes when the treatment is conducted, directly on the plan),
- it becomes a legal record of the intended purpose and execution of the project.

Project implementation planning may encompass more than the use of fire as a tool to achieve resource benefits. Mechanical and/or chemical treatment are used in fuel reduction projects for resource benefits. It is in the best interest to track the use of non-burning alternatives, to inform the public of emissions averted. Where fire is intentionally used for management, a prescribed fire plan is required to implement treatments.

Prescribed Fire Planning

Prescribed fire planning is for site-specific project implementation plans that outline the elements of the project needed to accomplish management objectives. Within the prescribed fire plan, include use of BSMP and consider the use of emission reduction techniques (see chapter 4.2) to reduce smoke emissions and minimize air quality impacts. Ensure that resource management objectives will be met by implementing these emission reduction techniques.

Some goals of a successful prescribed fire program include to:

- provide for firefighter and public health and safety as the highest priority,
- ensure that risk management is incorporated into all prescribed fire planning and implementation,
- use prescribed fire in a safe, carefully planned, and cost-efficient manner,
- reduce wildfire risk to communities, municipal watersheds and other values, and to benefit, protect, maintain, sustain, and enhance natural and cultural resources,
- use prescribed fire to restore natural ecological processes and functions, and to achieve land management objectives.

Federal, State and private entities may have authorities that need to be met when implementing a prescribed fire program. The principles established for the prescribed fire program should be included in a prescribed fire plan to ensure the continued integrity of the program.

The NWCG has developed the *Interagency Prescribed Fire Planning and Implementation Procedures Guide*, PMS 484 which was revised as of July 2017, https://www.nwcg.gov/publications/484. The intent of the Planning Guide is to provide standardized procedures specifically associated with planning and implementing prescribed fire. The information may be adopted by any agency or landowner.

Prescribed Fire Plan

The prescribed fire plan is the site-specific document for implementing prescribed fire. It provides the unit administrator the information needed to approve the plan and the prescribed fire burn boss with the information needed to successfully implement the prescribed fire.

Prescribed fire plan content and format can vary by state, agency, bureau or private entity. This will depend on the policy, guidance and complexity of the unit where the prescribed fire will be implemented. Many of the sections of the prescribed fire plan address smoke management. For more complex burns, a smoke management plan along with Smoke Modeling Documentation may need to be produced.

The sections of the prescribed fire plan that may have smoke management components and some examples (not all-inclusive) are:

Go/No Go Checklist

The Go/No Go Checklist allows the prescribed fire practitioner and the approving official to decide if all of the criteria in a prescribed fire plan can be attained prior to implementation of the burn.

- Ensure that the checklist has sufficient information about fuel loadings, duff layers, terrain, organic soil, nearby roadways, or other information that could lead to negative smoke issues when the approving official is determining whether to approve the prescribed fire for implementation.

Complexity Analysis Summary

The Complexity Analysis Summary is used to determine the expertise needed to implement the prescribed fire plan.

- Ensure that smoke management has been considered in the complexity analysis.

Description of Prescribed Fire Area

- **Maps of smoke impact areas.** Maps are recommended for projects with critical smoke receptors or significant smoke concerns. Figures 8.1.1 and 8.1.2 are examples of planning maps that identify and display potential smoke impact areas for a prescribed fire project. The local air quality authority usually defines categories to be considered for smoke impacts and should explicitly consider potential roadway smoke impacts.

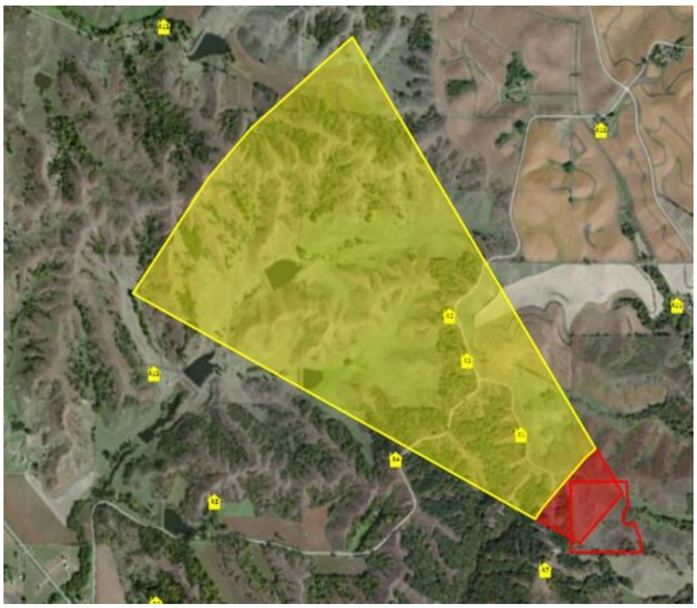

Figure 8.1.1. V-Smoke model indicating potential smoke impact areas mapped for prescribed fire project planning.

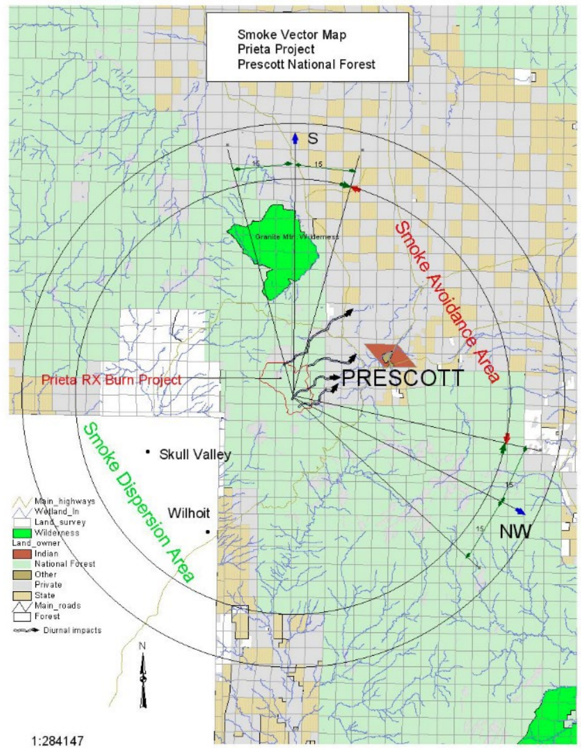

Figure 8.1.2. A smoke vector map documenting areas where smoke impacts are to be avoided and where smoke is to be dispersed from a prescribed fire project.

- Include alternative considerations for implementing the prescribed fire such as dividing the prescribed fire area into smaller units to shorten ignition and burn out time which may potentially reduce total smoke production or smoldering.

Objectives

Objectives are outcomes that you desire to achieve from implementing the prescribed fire plan.

- An example of a smoke management objective for a prescribed fire would be to keep smoke out of communities, hospitals and transportation corridors.

Prescription

The prescription describes measurable criteria during which a prescribed fire may be ignited to meet the prescribed fire objectives and safely implement the prescribed fire.

- An example of a smoke management related element is constraining wind direction to prevent smoke impacts to roadways.
- Consider burning when large fuel moistures are higher – if emissions reductions are a goal and other fuel objectives will be met.
- Identify residual burn time related to pockets of heavy fuels that could burn and smolder for long periods.

Scheduling

Identify the general implementation schedule including the time of day for ignition, duration of ignition or season(s) and note any constraints (dates, or days of the week, etc.) on when the project may be conducted. A project duration schedule should be addressed for prescribed fires with multiple ignitions or ignition days.

- Consider identifying the daytime dispersion window or time of day when active ignition can take place to maximize lofting and dispersion.
- Consideration of nighttime smoldering and drainage to minimize local impacts.
- Consider if residual in-place burning will cease and the smoke will disperse before onset of nighttime drainage flow conditions.

Pre-burn Considerations and Weather

Some examples include: clearances, mitigation actions generated by complexity analysis, method and frequency for obtaining weather and smoke management forecast(s).

- Notification of implementation of a prescribed fire to news media, known smoke sensitive individuals, adjacent landowners, law enforcement other potentially impacted publics.
- A fire weather forecast should be obtained when residual smoke has potential to impact smoke-sensitive areas.

Briefing

Briefing occurs prior to ignition to inform participants of their role and other pertinent information.

- Identify any roads or other smoke sensitive features that may be impacted by smoke and need monitoring.

Communication

A communication plan is needed to implement the prescribed fire. It should include:

- public notification prior to burn season, prior to ignitions and after action communications,
- notification of the Department of Transportation and/or Department of Public Safety if the burn is in proximity to a highway,
- notification of local and state air quality regulators, and
- coordination with state, local, tribal, and federal agencies that may also be conducting prescribed fires.

Public and Personnel Safety, Medical

Safety hazards (both personal safety and emergency procedures) unique to the prescribed fire project such as smoke exposure, smoke on the road and other smoke related risk assessments must be described along with measures taken to reduce or mitigate those hazards are required for each prescribed fire.

Test Fire

A test fire, ignited in an area that can be easily controlled, is required to verify that the prescribed fire behavior characteristics will meet management objectives.

- The test fire is the best means to verify predicted smoke dispersion.

Ignition Plan

General ignition operations are described which may include such things as: firing methods, devices, techniques and sequences within individual units, patterns, and ignition staffing needed for the prescribed fire to be successful.

- Identify special firing methods, sequences, devices and techniques that may be implemented to reduce smoke impacts.

Contingency Plan

The contingency plan, within the prescribed fire plan describes what additional actions and/or additional resources are needed to keep the prescribed fire within the ignition unit, the prescribed fire project area and/or smoke impacts to local communities, sensitive areas, or transportation corridors.

- Smoke management considerations such as impacts to critical smoke receptors are included in the contingency plan.
- Include mitigation steps to take if a significant smoke impact occurs.
- Long duration prescribed fires and weather systems that may limit smoke dispersion need to be identified and smoke mitigation steps must be identified.
- Contingency planning for nighttime smoke related problems are needed.
- Ensure that contingencies for unplanned smoke impacts consider both the day of the prescribed fire and the days following active ignition while smolder can occur.
- If a significant smoke incursion occurs notify local health and air quality agencies.

Monitoring

Monitoring is strongly advised to ensure that prescribed fire planning objectives are met. Monitoring may include fire behavior and fuels information in addition to smoke.

- Smoke dispersal monitoring information is to be tracked throughout all phases of the project.
- For prescribed fires, monitoring of smoke transport to Class I areas is appropriate.
- Monitoring for any smoke impacts to roads and highways is highly recommended.
- Any smoke impacts to other sensitive receptors such as schools, hospitals, and park gateway communities should be documented.
- Monitoring activities to consider are: visual smoke reports, webcams to identify smoke plumes or haze, and ambient air quality monitors.
- Monitor for cumulative impacts for multiple fires within the airshed.

Post-Prescribed Fire Activities

Post-prescribed fire activities include preparing a post-prescribed fire report, finalizing the project file, safety mitigation measures, closeout of applicable pre-prescribed fire considerations, smoke evaluation, and ecological monitoring or rehabilitation needs.

- Include information from the incident that involved smoke management such as: 'Did my smoke projections work as planned?' If not, how did they differ?
- What can be done to improve smoke management of prescribed fire in the future based on this experience?

Smoke Management and Air Quality

When looking through the prescribed fire plan, it is evident that smoke management and air quality are woven throughout the various elements of the plan. The potential to affect air quality is a specific concern when conducting prescribed fire treatments. Treatments that may affect smoke sensitive areas require particularly careful assessment of airshed and meteorological parameters that influence both the movement and concentration of smoke. The expected effects of wind speed and direction, air stability and nighttime inversions should be specifically outlined in the prescribed fire plan. The plan should address local issues and concerns that affect smoke dispersion or concentration, such as mountainous terrain, fog, or sea breeze effects. This information should be developed by fire managers along with air quality specialists that have personal experience and knowledge of fire behavior, smoke transport, and dispersion in the area, along with more formal emissions prediction and dispersion modeling.

Once an analysis of significant smoke management factors is complete, the fire manager should set specific, measurable smoke objectives for the prescribed fire. These may include minimum visibility standards for safety (such as on roads, especially in areas and conditions prone to superfog formation) or a maximum pollutant concentration if air quality monitoring equipment is used or available. Objectives provide a common understanding for all individuals and the public at large of what will constitute acceptable smoke effects. They also provide a management action point for the burn boss when considering the need to implement contingency, or communication plans or alter treatment strategies or tactics due to smoke and air quality concerns.

Summary

The amount of air quality analysis required at all levels of fire planning (land use planning, fire management planning and prescribed fire planning) will be influenced by the potential for smoke to impact smoke sensitive receptors, affect the public, exceed federal and state air quality standards, and comply with smoke management regulations. Communities, air quality specialists, air regulators and other stakeholders should be engaged in fire management planning at appropriate levels when smoke may be an issue. Planning in advance of actual smoke impacts is the preferred approach and helps retain support for the fire management program. Thorough attention and collaborative fire and smoke management planning can minimize future difficulties and complications brought on by prescribed fire smoke unduly affecting public values.

Literature Cited

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8.2 The Well Prepared Fire Manager

Peter Lahm, Michael George, and Dennis Haddow

The well-prepared fire practitioner understands the importance of balancing the benefits of fire on the landscape, while managing and minimizing negative smoke effects. How well smoke is managed will have a substantial effect on how well fire management activities are perceived and accepted by the public. As one in three households is home to someone with a respiratory issue, it is critical to plan for and manage smoke throughout the prescribed fire process.

Planning for smoke from a burn includes identifying smoke-sensitive receptors, and addressing potential negative impacts on those receptors. Making the right plans and decisions are key because public support for operations will be tested when the inevitable yet unforeseen wind shift occurs and smoke ends up somewhere it is unexpected and unwanted. After the fire is ignited and has burned to its planned boundaries, it is critical to plan for smoke which may linger from smoldering fuels because this is when many public impacts are observed. Understanding and following pertinent air regulatory and smoke management program requirements is another important part of a successful burn. Consideration of smoke effects on fireline personnel and transportation safety is also crucial to safe prescribed fire operations.

Challenges in managing fire on the landscape are increasing. Climate models predict more acres burned by wildfires, and that the wildfires will be more severe and last longer aided by longer wildfire seasons. This may increase the need for prescribed fire to attempt to reduce risk of catastrophic wildfire while maintaining resilient landscapes. These same climate changes will likely shorten periods when prescribed fire can be conducted. As these climate influences occur, coupled with the ever-present natural accumulation of fuels, air quality standards are also becoming stricter to a point where prescribed fire smoke can contribute to exceedances of the standards. This intersection of prescribed fire activities and air quality standards (national, state, tribal, and local) is a much newer challenge and requires due diligence by all burners. Previously, burners had to address primarily the nuisance concerns surrounding smoke impacts. Now the current standards for fine particulate matter and ozone are strict enough that there is substantially less allowable air pollution from sources such as prescribed fire before the standard is exceeded. This allowable addition of smoke is much smaller than encountered by the previous generations of burners. Another factor to consider when using prescribed fire and the need to manage smoke is that more than half of new homes built after 1999 were built on the edge of wildland. This new wildland urban interface area adds significant complexity and cost to most prescribed fire planning and implementation.

Careful management of smoke is an essential element of all prescribed fire programs and every burn. Many areas of the country have a smoke management program with specific requirements for actively addressing smoke impacts. Fire managers' active participation in program development and implementation helps maintain the support of air quality regulators for the use of prescribed fire. Whether a smoke management program is present or not, use of Basic Smoke Management Practices (BSMPs) will be important to avoid unwanted smoke and public relations problems. The well-prepared practitioner not only understands but puts into practice what is necessary to maintain that balance of returning fire to ecosystems where it is needed while managing smoke appropriately.

A well-prepared fire practitioner plans to manage smoke during all phases of the fire. This includes considering smoke in broader planning documents like resource management plans and land management plans. Smoke also needs to be considered in the fire program-specific fire management plan and individual burn plan—including contingency measures for unwanted smoke impacts. When preparing individual burn plans, "higher level" and overarching documents should be reviewed and considered with regard to the role of fire in that location. Smoke management–specific requirements or other elements of the plans that might affect the amount of smoke generated or transport of smoke to smoke sensitive areas should also be addressed.

There are several information-gathering and process-related tasks that should be part of most any burn plan:

- Understand and follow air quality regulatory requirements, including state or local smoke management program rules;
- Identify all potential smoke sensitive areas and develop a strategy for those areas that accounts for public health and tolerance of smoke as well as communication methods;
- Build upon and reference past smoke experience and local knowledge in the area;
- Predict emissions and smoke impacts with tools that are appropriate to the situation;
- Include potential air quality impacts in the "go/no-go" ignition decision;
- Understand the emissions from the burn and, whenever possible use, BSMPs that minimize the amount and/or impact of smoke produced w meeting resource objectives; and
- Develop a contingency strategy which includes a plan for communications to the public and air quality regulators for when unplanned smoke impacts occur.

On the days prior to a scheduled prescribed burn, the well-prepared fire practitioner monitors weather and fuels to determine if conditions will be favorable to meet burn objectives and then manages smoke appropriately. Appropriate smoke management is not necessarily total avoidance of impacts, but minimizing their severity and duration while addressing public and regulator concerns. Notification of the potentially affected public, and local or state regulators, early is important because, whether burning takes place or not, it can help establish credibility that potential smoke effects are a key concern. Before the burn it may be necessary to obtain state approval for your project or coordinate with neighbors seeking to burn at the same time.

On the day of a burn, verify that meteorological conditions are consistent with the burn plan prior to ignition and that consumption of fuels follows the burn objectives. If conditions are not within ranges defined in the planning documents, then burning should be postponed. Don't fall prey to pressure to complete the burn, or become goal-focused without consideration of effects such as smoke. For example, a several hour delay due to helicopter issues or personnel availability can push the most active part of the fire into the period of the day when smoke can be trapped due to atmospheric stability changes. Loss of credibility from a hasty decision that resulted in unwanted smoke effects will take time and effort to rebuild with the public or local air quality regulator. If a decision is made to delay a burn or if plans change after ignition due to smoke concerns, document the facts and share them with the public. This will help to instill confidence that smoke effects and public health are serious considerations.

Once a prescribed fire is ignited, monitor the situation to ensure the amount of smoke being generated is as planned and its transport speed as well as direction are what was intended. Smoke monitoring is a key element of most burn projects and may be done through visual observations or through the use of a fine particulate monitor which may be available locally or ordered from the national cache.

The Practical Lessons of Good Smoke Management

Kevin Hiers

Many smoke management lessons learned are for a specific area (i.e., from local knowledge) and it is imperative that practical lessons be shared. It is important to evaluate successes as well as those fires which have unplanned impacts. The fact is that impacts, rather than emissions, are what managers are most familiar with incorporating into burn plans and when managing smoke.

In the Florida Panhandle, the Northwest Florida Water Management District frequently burns a 1000-acre peninsula wedged between Interstate 10, several neighborhoods, and the city of Pensacola. This wetland area is highly susceptible to fast moving wildfires, making prescribed fire the best management alternative to reduce wildfire hazard. While eliminating all smoke impacts from a burn such as this is not possible; use of rapid/aerial ignition can reduce the duration of the impacts by lofting smoke via a plume-dominated column. Smoke in the column, if contained within the mixing layer, will eventually mix down but by then it is frequently beyond critical smoke sensitive areas. Moreover, if impacts occur, they are of short duration. Slow ignition of the unit would not achieve the same result with lighting occurring later in the day, and risking smoke-fog on nearby roads which is far worse than temporary daytime smoke impacts.

Utilizing techniques which allow both minimization of impacts and emissions is the epitome of good smoke management. The challenge for a well prepared fire practitioner is balancing overall burn objectives with the need to manage smoke by minimizing both impacts and emissions.

Clearly articulating smoke management objectives is critical for understanding and mitigating impacts to acceptable levels. Some questions to be considered when developing smoke management objectives and management alternatives should include:

- Is prescribed fire the best tool to accomplish management goals?
- Will emissions contribute to exceeding the NAAQS?
- What are both day and nighttime impacts?
- If impacts are unavoidable, are there smoke sensitive areas that can be temporarily affected with minimal effect (e.g., while school is out or homeowner is at work)?

If daytime smoke issues are paramount, limiting the duration of smoke in the immediate vicinity of the unit through ignition method, rate and pattern may be possible. If nighttime issues of down draining smoke are of concern, ignition early in the morning—even prior to the best dispersion of the day—may be necessary for burnout of smoldering fuels prior to nightfall when dispersion routinely decreases.

Minimizing emissions should also be considered whenever possible. Use moist prescription parameters to reduce the consumption of fuel but note one has to be specific about the component of the fuelbed likely to cause impacts for this to work in practice. Smoke settling at night, particularly when associated with fog, continues to be the most common and potentially deadly smoke management issue. Long duration smoldering in organic fuel types (e.g., duff, peat, organic soils, and 1000-hr fuels) present one of the biggest challenges, but also debris piles, snags, and activity fuels are common contributors to nighttime smoke impacts all over the U.S. Minimizing consumption of fuels which smolder will lead to reduced emissions and less smoke impacts. Consumption of duff is tied to days since last significant rain and is a key fuelbed to consider before ignition to reduce smoldering fuels. Snags and other coarse woody debris can contribute to the smoke problem if too dry. Understanding these interactions is critical in order to minimize smoke impacts as well as reduce the potential for re-burn. It is crucial that smoke management strategies, both impact and emissions minimization, are evaluated, noted for future plans and passed on to the next burner.

One of the BSMPs is tracking planned and executed burns. Note that the well-prepared fire practitioner not only documents conditions at the end of a prescribed burn but also keeps thorough records throughout the burn including consumption, blackened acres, and smoke observations. These records are useful for tracking use of emissions reduction techniques and as documentation for future discussions with the public and regulators. Documentation is also valuable in the event of an exceedance of an air quality standard, one will be prepared for further public and regulatory scrutiny and able to demonstrate the level of planning and preparedness.

A Practical Approach to Understanding Your Public

Kevin Hiers

Communication, education and public outreach are an important element in smoke management. Not all communities have the same concerns regarding fire and smoke. Taking time to understand the social, health, economic and/or political apprehensions towards the use of fire is critical. If the community depends on summer visitors for their economy, talking about fire and ecosystem health will not sway the community to accept the benefits of burning. However, scheduling burns to avoid days before holidays, might be more acceptable. Working with the public is a challenge and not everyone will be convinced of the benefits of fire. The public will tolerate some impacts for a short time, if benefits of burning are understood (wildfire risk reduction, game management, endangered species, etc.). The public tolerance to smoke varies in each region of the country but it also may vary among communities on either side of a burn unit. Understanding each community's smoke sensitivity and tolerance will help in planning and adjusting projects to meet their needs. Make sure the public knows when there is burning in the area and why. Reach out to local groups before the prescribed fire season, and notify the community the week before the burn. One of the most critical steps if a smoke impact occurs is to be proactive. If unplanned impacts do occur, be present, be visible, and address the situation. Finally, manage for the shortest duration of smoke impacts possible. In some rural communities, there may be a general tolerance for modest smoke during school or work hours, but the same community would be up in arms if smoke impacts the community baseball tournament on a Saturday.

Know and communicate with your public so you are ready for the inevitable unplanned smoke impact. All managers must be sensitive to a local regions' and individual's needs for clean air. Good planning prior to ignition is key and if in doubt, wait a day. Keep the credibility of the program and good smoke management decisions as a goal. Inevitably there will be a burn day when the weather forecast will not meet expectations after ignition has begun and all program credibility will be tested by an unplanned smoke impact.

After the burn has been ignited, any mop-up should consider fire personnel exposure during such operations. Assess smoldering and the potential for associated downslope smoke transport and make appropriate notifications. Consider all possibilities and don't be surprised by what your smoke does. Be ready to respond accordingly. What you know and learn about smoke on prescribed fires has direct ties to the same or worse impacts that can occur with a wildfire. Pass on these lessons to those that are new to the program or area because each area has its own unique challenges.

As air quality improves in the United States with clean-up and control of mobile and industrial air pollution sources, the focus on wildland fire smoke is increasing. Being aware of this and being prepared for it will improve the likelihood of successful and supported prescribed fire programs. Air quality rules change periodically as do the tools available to plan, execute, and track burns and manage smoke. It is critical to stay engaged in state or local smoke management programs, know how they affect your burn operations, and participate in program reviews and updates. It is equally important to keep up with the evolution of smoke management tools and consider how they might lead to more successful burning operations.

The tips here for being a well-prepared fire practitioner correspond closely with the list of BSMPs (see Chapter 3.2 on State Smoke Management Programs). The importance of addressing smoke through effective planning, implementation, and communication is underscored in many federal and state policy directives. The challenge in creating resilient forests and maintaining fire-dependent ecosystems while managing smoke effectively is also well-documented. The basic principles presented in this guide, along with the tools and strategies for managing smoke, are intended to prepare you for success and increase the use of fire on this American landscape which was, and still is, shaped by this critical disturbance.

The *NWCG Smoke Management Guide for Prescribed Fire* is developed and maintained by the Technical Smoke Topics Subcommittee (TSTS), under the direction of the Smoke Committee (SmoC), an entity of the National Wildfire Coordinating Group (NWCG).

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