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SMOKE MANAGEMENT GUIDE FOR PRESCRIBED AND WILDLAND FIRE

2001 Edition

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SMOKE MANAGEMENT GUIDE FOR PRESCRIBED AND WILDLAND FIRE

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National Wildfire Coordinating Group
Fire Use Working Team

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Forward

The National Wildfire Coordinating Group's (NWCG) Fire Use Working Team[1] has assumed overall responsibility for sponsoring the development and production of this revised Smoke Management Guide for Prescribed and Wildland Fire (the "Guide"). The Mission Statement for the Fire Use Working Team includes the need to coordinate and advocate the use of fire to achieve management objectives, and to promote a greater understanding of the role of fire and its effects. The Fire Use Working Team recognizes that the ignition of wildland fuels by land managers, or the use of wildland fires ignited by natural causes to achieve specific management objectives is receiving continued emphasis from fire management specialists, land managers, environmental groups, politicians and the general public. Yet, at the same time that fire use programs are increasing, concerns are being expressed regarding associated "costs" such as smoke management problems. This revised Guide is the Fire Use Working Team's contribution to a better national understanding and application of smoke management.

Bill Leenhouts—Chair
NWCG Fire Use Working Team

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[1] The NWCG website [http://www.nwcg.gov] contains documentation and descriptions for all NWCG working teams.

Preface

The National Wildfire Coordinating Group's Fire Use Working Team sponsored this 2001 edition of the *Smoke Management Guide for Prescribed and Wildland Fire*. A six-member steering committee was responsible for development of a general outline and for coordination of the Guide's production. The editors/compilers invited the individual contributions, edited submissions, authored many of the sections, obtained comprehensive reviews from the NWCG agencies and other partners, and compiled the final material into a cohesive guidebook.

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Table of Contents

4.0 Regulations

Chapter 1

INTRODUCTION

Introduction

Colin C. Hardy

Bill Leenhouts

Why Do We Need A National Smoke Management Guide?

As an ecological process, wildland fire is essential in creating and maintaining functional ecosystems and achieving other land use objectives. As a decomposition process, wildland fire produces combustion byproducts that are harmful to human health and welfare. Both the land management benefits from using wildland fire and the public health and welfare effects from wildland fire smoke are well documented. The challenge in using wildland fire is balancing the public interest objectives of protecting human health and welfare and sustaining ecological integrity.

Minimizing the adverse effects of smoke on human health and welfare while maximizing the effectiveness of using wildland fire is an integrated and collaborative activity. Everyone interested in natural resource management is responsible and has a role. Land managers need to assure that using wildland fire is the most effective alternative of achieving the land management objectives. State, regional, tribal and national air resource managers must ensure that air quality rules and regulations equitably accommodate all legal emission sources.

The varied smoke management issues from across the nation involve many diverse cultures and interests, include a multitude of strategies and tactics, and cover a heterogeneous landscape. No national answer or cookbook approach will adequately address them. But people with a desire for responsible smoke management working in partnership with the latest science-based smoke management information can fashion effective regional smoke management plans and programs to address their individual and collective objectives. The intent of the Guide is to provide the latest science-based smoke management information from across the nation to facilitate these collaborative efforts.

Awareness of smoke production, transport, and effects on receptors from prescribed and wildland fires will enable us to refine existing smoke management strategies and to develop better smoke management plans and programs in the future. This Guide addresses the basic control strategies for minimizing the adverse effects of smoke on human health and welfare—thus maximizing the effectiveness of using wildland fire. These control strategies are:

- Avoidance – using meteorological conditions when scheduling burning in order to avoid incursions of wildland fire smoke into smoke sensitive areas.
- Dilution – controlling the rate of emissions or scheduling for dispersion to assure tolerable concentrations of smoke in designated areas.

- Emissions-reduction – using techniques to minimize the smoke output per unit area treated and decrease the contribution to regional haze as well as intrusions into designated areas.

Guide Goals and Considerations

The Smoke Management Guide steering committee and the NWCG Fire Use Working Team developed this Guide with the following goals:

- Provide fire use practitioners with a fundamental understanding of fire-emissions processes and impacts, regulatory objectives, and tools for the management of smoke from wildland fires.
- Provide local, state, tribal, and federal air quality managers with background information related to the wildland fire and emissions processes and air, land and wildland fire management.

The following considerations provide the context within which these goals can be met:

- This document is about smoke management, not about the decision to use wildland fire or its alternatives. Its purpose is not to advocate for or against the use of fire to meet land management objectives.
- While the Guide contains relevant background material and resources generally useful to development of smoke management programs, it is not a tutorial on how to develop a state smoke management program.
- Although the Guide is replete with information and examples for potential application at the local and regional level, the Guide generally focuses on national smoke management principles. For maximum benefit to local or regional applications, appropriate supplements should be developed for the scale or geographical location of the respective application.
- The Guide is more appropriate for knowledgeable air, land, and wildland fire managers, and is not intended for novice readers.

Overview and Organization of the Guide

The ***Smoke Management Guide for Prescribed and Wildland Fire–2001 Edition*** follows a textbook model so that it can be used as a supplemental reference in smoke management training sessions and courses such as the NWCG Smoke Management course, RX-410 (formerly RX-450). Following an **Introduction**, a background chapter presents a primer on wildland fire and a discussion of the imperatives for smoke management. In the **Wildland Fire Imperative,** the Guide addresses both the ecological and societal aspects of wildland fire (not agricultural, construction debris, or other biomass burning), and provides the details necessary for fire use practitioners and air quality managers to understand the fundamentals of fire in wildlands. **The Smoke Management Imperative** discusses the needs for smoke management as well as its benefits and costs.

The background sections are followed by chapters presenting details on **Wildland Fire Smoke Impacts—**public health, visibility, problem and nuisance smoke, and smoke exposure among fireline personnel—and on **Regulations for Smoke Management**. The chapter on **Smoke Source Characteristics** follows a sequence similar to the basic pathway that smoke production does—from the pre-fire fuel characteristics and the fire phenomenon as an emissions source, through the processes of combustion, biomass consumption and emissions production.

The chapter on **Fire Use Planning** addresses important considerations for developing a comprehensive fire use plan (a "burn plan"). The general planning process is reviewed, from developing a general land use plan, through a fire management plan and, ultimately, to a unit-specific burn plan.

The **Smoke Management Meteorology** chapter presents a primer on the use of weather observations and forecasts, and then provides information regarding the transport and dispersion of smoke from wildland fires.

Techniques to Reduce or Redistribute Emissions are presented in an exhaustive list and synthesis of emissions reduction and impact reduction practices and techniques. These practices and techniques were initially compiled as the outcomes of three regional workshops held specifically for the purpose of synthesizing current and potential smoke management tools. Presented here in a nationally applicable format, they are the fundamental tools available to fire planners and fire use practitioners for the management and mitigation of smoke from wildland fires.

The **Smoke Dispersion Prediction Systems** chapter reviews current prediction tools within the context of three "families" of model applications—screening, planning, or regulating.

Air Quality Monitoring for Smoke discusses various objectives for monitoring, and emphasizes the need to carefully match the monitoring objective with the appropriate equipment. In addition, the chapter presents information on some common monitoring equipment, methods, and their associated costs.

Emission Inventories help managers and regulators understand how to better include fire in an emissions inventory. This chapter discusses the use of the three basic elements needed to perform an emission inventory—area burned, fuel consumed, and appropriate emission factor(s).

No smoke management effort can succeed without continued assessment and feedback. The chapter on **Program Administration and Assessment** discusses the need to maintain a balance between the level of effort in a program and the level of prescribed or fire use activity as well as their associated local or regional effects.

Each section in this Guide is now supported by an extensive list of relevant references. Also, authorship for a specific section is given in the table of contents, where appropriate. In such cases, the section can be cited with its respective author(s) as an independent "chapter" in the Guide.

A glossary of frequently used fire and smoke management terms[1] is provided as an appendix to the Guide.

History of Smoke Management Guidance

The first guidance document specifically addressing the management of smoke from prescribed fires was the *Southern Smoke Management Guidebook*, produced in 1976 by the Southern Forest Fire Laboratory staff

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[1] For a comprehensive presentation of fire terminology, the reader should refer to the NWCG *Glossary of Wildland Fire Terminology* (NWCG 1996—PMS #205, Boise, ID).

(1976). It was a comprehensive treatment of the various aspects fire behavior, emissions, transport and dispersion, and the management of smoke in the southern United States.

In 1985, NWCG's Prescribed Fire and Fire Effects Working Team developed the widely accepted *Prescribed Fire Smoke Management Guide* that forms the basis for this 2001 revised Guide (NWCG 1985). The 1985 edition focused on national smoke management principles and, as a result, was far less comprehensive than the Southern guidebook.

One of six state-of-knowledge reports prepared for the 1978 National Fire Effects Workshop is a review called *Effects of Fire on Air* (USDA Forest Service 1978). The six volumes, called the "Rainbow Series" on fire effects, were in response to the changes in policies, laws, regulations, and initiatives. Objectives specific to the volume on air were to: "…summarize the current state-of-knowledge of the effects of forest burning on the air resource, and to define research questions of high priority for the management of smoke from prescribed and wild fires" (USDA Forest Service 1978, p.5).[2]

Conflicts between prescribed fire and air quality began to be seriously addressed in the mid-1980s. Prior to this, only a few states had developed or implemented smoke management programs, and national-level policies addressing smoke from wildland burns were only beginning to be drafted. Much has changed since then, with numerous policies and initiatives raising the potential for conflicting resource management objectives—principally air quality and ecosystem integrity. The Clean Air Act amendments adopted in 1990 specifically addressed regional haze. Smoke Management Plans have been developed by many states as administrative rules enforceable under state law. These rules are often incorporated into State and Tribal Implementation Plans (SIPs and TIPs) for submission to the U.S. Environmental Protection Agency (EPA) and, once promulgated by EPA, are then enforceable under federal law as well. And now, the role of fire and the need for its accelerated use has become widely recognized with respect to maintenance and restoration of fire-adapted ecosystems. These issues all point to the imperative for better knowledge and more informed collaboration between managers of both the air and terrestrial resources.

The 2001 Edition of the Smoke Management Guide

Recognizing the increasing likelihood of impacting the public, the proliferation of federal, state, and local statutes, rules and ordinances pertaining to smoke, as well as major improvements to our knowledge of smoke and its management, the NWCG Fire Use Working Team (formerly named the Prescribed Fire and Fire Effects Working Team) sponsored revision of the Guide. Conceptually, the Fire Use Working Team identified the need for a revised guidebook that targeted not just prescribed fire practitioners, but state and local air quality and public health agency personnel as well. A consequence of this expansion of the target audience was the need to substantially augment the background information with respect to fire in wildlands.

A suite of potential smoke management practices and techniques are not only suggested in

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[2] The Joint Fire Sciences Program is sponsoring extensive revisions to the Rainbow Series fire effects volumes, including a new volume on fire effects on air.

this Guide, but their relative effectiveness and regionally-specific applicability are also provided. This information was acquired through three regional workshops held in collaboration with the U.S. Environmental Protection Agency's Office of Air Quality Planning and Standards.

This revised Guide now emphasizes both emission and impact reduction methods that have been found to be practical, useful, and beneficial. This new emphasis on reducing emissions is in response to regional haze and fine particle ($PM_{2.5}$) control programs that will require emission reductions from a wide variety of pollution sources (including prescribed and wildland fire). This is especially important in view of the major increases in the use of fire projected by federal land managers. Readers will also find a greatly expanded discussion of air quality regulatory requirements, reflecting the growing complexities and demands on today's fire practitioners.

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Chapter 2

OVERVIEW

The Wildland Fire Imperative

Colin C. Hardy

Sharon M. Hermann

Robert E. Mutch

Perpetuating America's Natural Heritage: Balancing Wildland Management Needs and the Public Interest

Strategies for responsible and effective smoke management cannot be developed without careful consideration of the ecological and the societal impacts of fire management in the wildlands of modern America. The need to consider both perspectives is acknowledged by most land management agencies, as well as by the U.S. Environmental Protection Agency (EPA) —the primary Federal agency responsible for protecting air quality. An awareness of this challenge is reflected in NWCG's education message, *Managing Wildland Fire: Balancing America's Natural Heritage and the Public Interest* (NWCG 1998). The preamble to this document not only states that "fire is an important and inevitable part of America's wildlands," but also recognizes that "wildland fires can produce both benefits and damages—to the environment and to people's interests."

The EPA's Interim Air Quality Policy on Wildland and Prescribed Fires (U.S. EPA 1998) employs similar language to describe related public policy goals: (1) To allow fire to function, as nearly as possible, in its natural role in maintaining healthy wildland ecosystems; and, (2) To protect public health and welfare by mitigating the impacts of air pollutant emissions on air quality and visibility. The document comments on the responsibilities of wildland owners/managers and State/tribal air quality managers to coordinate fire activities, minimize air pollutant emissions, manage smoke from prescribed fires as well as wildland fires used for resource benefits, and establish emergency action programs to mitigate the unavoidable impacts on the public. In addition, EPA asserts that "this policy is not intended to limit opportunities by private wildland owners/managers to use fire so that burning can be increased on publicly owned wildlands."

In this and the following section (2.2–The Smoke Management Imperative), we outline both ecological and societal aspects of wildland and prescribed fire. We review the historical role and extent of fire and the effects of settlement and land use changes. The influence of fire exclusion policies on historical disturbance processes is considered in light of modern landscape conditions. This provides the basis for discussion of significant, recent changes in Federal wildland fire policy and new initiatives for accelerating use of prescribed and wildland fire to achieve resource management objectives. Finally, we present examples of the impacts of wildland smoke on air quality, human health, and safety.

Fire in Wildlands

Recurring fires are often an essential component of the natural environment—as natural as rain, snow, or wind. Evidence for the recurrence of past fires is found in charcoal layers of lakes and bogs, in fire-scars of trees, and in the morphological and life history adaptations of numerous native plants and animals. Many ecosystems in North America and throughout the world are fire-dependent (Heinselman 1978) and periodic burning is essential for healthy ecosystem functioning in these wildlands. Fire acts at the individual, population, and community levels and can influence:

- Plant succession.
- Fuel accumulation and decay.
- Recruitment pattern and age distribution of individuals.
- Species composition of vegetation.
- Disease and insect pathogens.
- Nutrient cycles and energy flows.
- Biotic productivity, diversity, and stability.
- Habitat structure for wildlife.

For millennia, lightning, volcanoes, and people have ignited fires in wildland ecosystems. The current emphasis on ecosystem management calls for the maintenance of interactions between such disturbance processes and ecosystem functions. Therefore, it is incumbent on both fire and natural resource managers to understand the range of historical frequency, severity, and aerial extent of past burns. This knowledge provides a frame of reference for applying appropriate management practices on a landscape scale, including the use and exclusion of fire.

Many studies have described the historical occurrence of fires throughout the world. For example, Swetnam (1993) used fire scars to describe a 2000-year period of fire history in giant sequoia groves in California. He found that frequent small fires occurred during a warm period from about A.D. 1000 to 1300, and less frequent but more widespread fires occurred during cooler periods from about A.D. 500-1000 and after 1300. Swain (1973) determined from lake sediment analyses in the Boundary Waters Canoe Area in Minnesota that tree species and fire had interacted in complex ways over a 10,000-year period. Other studies ranging from Maine (e.g. Copenheaver and others 2000) to Florida (e.g. Watts and others 1992) have employed pollen and charcoal deposits to demonstrate shifts in fire frequency correlated with the onset of European settlement.

There is an even larger body of science that details the numerous effects of wildland fires on components of ecosystems. Some of the most compelling examples of fire dependency come from studies on plant reproduction and establishment. For instance, there are at least ten species of pines scattered over the United States that have serotinous cones; that is to say the cones are sealed by resin; the cone scales do not open and seeds do not disperse until the resin is exposed to high heat (reviewed in Whelan 1995). Examples of fire dependency in herbaceous plants include flowering of wiregrass in Southeastern longleaf pine forests that is greatly enhanced by growing season burns (Myers 1990) and seed germination of California chaparral forbs that is triggered by exposure to smoke (Keeley and Fotheringham 1997). Animals as diverse as rare Karner blue butterflies in Indiana (Kwilosz and Knutson 1999) to whooping cranes in Texas (Chavez Ramirez and others 1996) benefit when fire is re-introduced into their habitats. There are numerous other types of fire dependency in North American ecosystems and many studies on this topic are summarized in books and government publications (e.g. Agee 1993, Bond and van Wilgen 1996, Brown and Kapler Smith 2000, Johnson 1992, Kapler Smith 2000, Wade and others 1980, Whelan 1995). In addition, there is a small but growing volume of literature that evaluates the influence of fire on multiple trophic levels (e.g. Hermann and others 1998).

Knowledge of fire history, fire regimes, and fire effects allows land stewards to develop informed management strategies. Application of fire may be one of the tools used to meet resource management objectives. The role of fire as an important disturbance process has been highlighted in a classification of continental fire regimes (Kilgore and Heinselman 1990). These authors describe a natural fire regime as the total pattern of fires over time that is characteristic of a region or ecosystem. Fire regimes are defined in terms of fire type and severity, typical fire sizes and patterns, and fire frequency, or length of return intervals in years. Kilgore and Heinselman (1990) placed natural fire regimes of North America into seven classes, ranging from Class 0, in which fires are rare or absent, to Class 6, in which crown fires and severe surface fires occur at return intervals longer than 300 years. Intermediate fire regimes, Classes 1-5, are characterized by increasingly longer fire return intervals and increasingly higher fire intensities. Class 2, for example, describes the situation for long-needled pines, like longleaf pine, ponderosa pine, and Jeffrey pine; in this class low severity, surface fires occur rather frequently (return intervals of less than 25 years). Lodgepole pine, jackpine, and the boreal forest of Canada and Alaska generally fall into Class 4, a class in which high severity crown fires occur every 25 to 100 years; or into Class 5, a class in which crown fires occur every 100 to 300 years. White bark pine forests at high elevations typically fall into Class 6. For comparison, three general classes of fire are shown in figure 2.1, including a low-intensity surface fire, a mixed-severity fire, and a stand-replacing crown fire.

Figure 2.1. The relative difference in general classes of fire are shown. This series illustrates a low-intensity surface fire (a), a mixed-severity fire (b), and a stand-replacing crown fire (c).

A noteworthy aspect of continental fire regimes is that very few North American ecosystems fall into Class 0. In other words, most ecosystems in the United States have evolved under the consistent influence of wildland fire, establishing fire as a process that affects numerous ecosystem functions described earlier. Those who apply prescribed burns or use wildland fire often attempt to mimic the natural role of fire in creating or maintaining ecosystems. Sustaining the productivity of fire-adapted ecosystems generally requires application of prescribed fire on a sufficiently large scale to ensure that various ecosystem processes remain intact.

Ecological Effects of Altered Fire Regimes

As humans alter fire frequency and severity, many plant and animal communities experience a loss of species diversity, site degradation, and increases in the sizes and severity of wildfires. Ferry and others (1995) concluded that altered fire regimes was the principal agent of change affecting vegetative structure, composition, and biological diversity of five major plant communities totaling over 350 million acres in the U.S. As a way to evaluate the current amount of fire in wildland habitat, Leenhouts (1998) compared estimated land area burned 200-400 years ago (“pre-industrial”) to data from the contemporary conterminous United States. The result suggests that ten times more acreage burned annually in the pre-industrial era than does in modern times. After accounting for loss of wildland area due to land use changes such as urbanization and agriculture, Leenhouts concluded that the remaining wildland is burned approximately fifty percent less compared to fire frequency under historical fire regimes (figure 2.2).

Numerous ecosystem indicators serve as alarming examples of the effects of altered fire regimes. Land use changes, attempted fire exclusion practices, prolonged drought, and epidemic levels of insects and diseases have coincided to produce extensive forest mortality, or major changes in forest density and species composition. Gray (1992) called attention to a forest health emergency in parts of the western

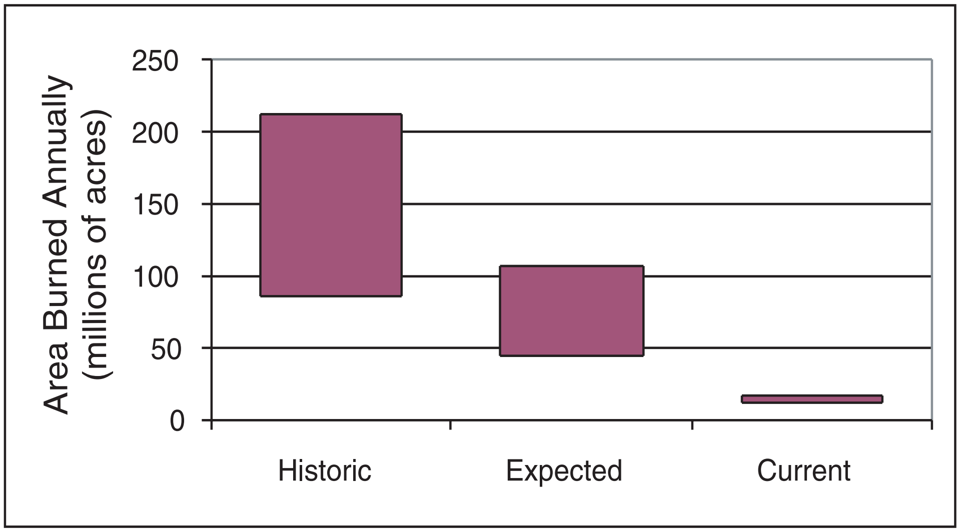

Figure 2.2. Estimates of the range of annual area burned in the conterminous United States pre-European settlement (Historic), applying presettlement fire frequencies to present land cover types (Expected), and burning (wildland and agriculture) that has occurred during the recent past (Current). Source: Leenhouts (1998).

United States where trees have been killed across millions of acres in eastern Oregon and Washington. He indicated that similar problems extend south into Utah, Nevada, and California, and east into Idaho. Denser stands and heavy fuel accumulations are also setting the stage for high severity crown fires in Montana, Colorado, Arizona, New Mexico, and Nebraska, where the historical norm in long-needled pine forests was for more frequent low severity surface fires (fire regime Class 2; Kilgore and Heinselman 1990). The paired photos in figure 2.3 illustrate 85 years of change resulting from fire exclusion on a fire-dependent site in western Montana. In North Carolina, Gilliam and Platt (1999) quantified the dramatic effects of over 80-years of fire exclusion on tree species composition and stand structure in a longleaf pine forest.

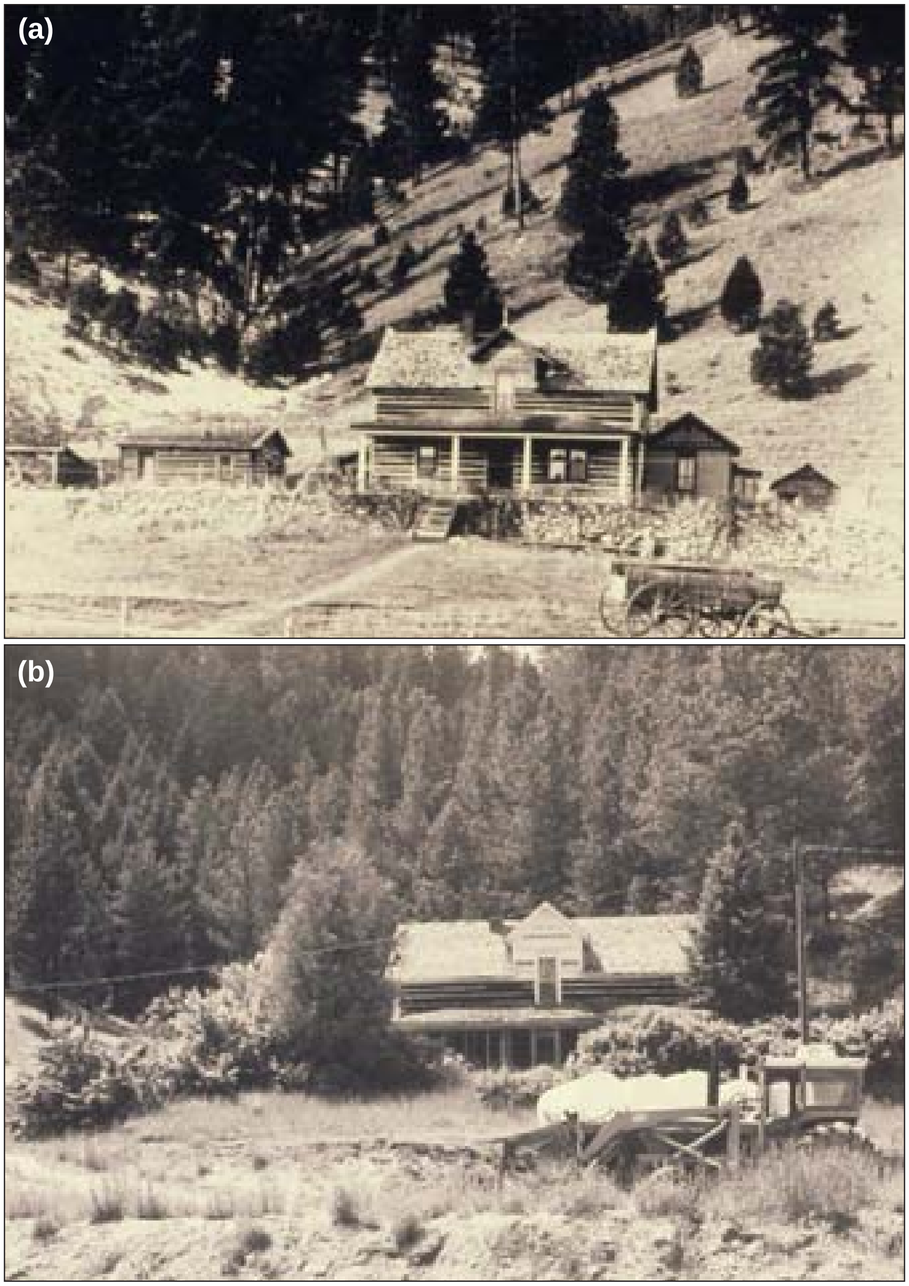

Figure 2.3. These two photos, taken of the same homestead near Sula, Montana, show 85 years of change on a fire-dependent site where fire has been excluded. The top photo (a) was taken in 1895. By 1980 (b), encroaching trees and shrubs occupy nearly all of the site. Stand-replacing crown fire visited this site in 2000.

Since the 1960s, records show an alarming trend towards more acres consumed by wild fires, despite all of our advances in fire suppression technology (figure 2.4). The larger, more severe wildfires have accelerated the rate of tree mortality, threatening people, property, and natural resources (Mutch 1994). These wildfires also have emitted large amounts of particulate matter into the atmosphere. One study estimated that more than 53 million pounds of respirable particulate matter were produced over a 58-day period by the 1987 Silver Fire in southwestern Oregon (Hardy and others 1992).

The ecological consequences of past policies of fire exclusion have been foreseen for some time. More than 50 years ago, Weaver (1943) reported that the "complete prevention of forest fires in the ponderosa pine region of California, Oregon, Washington, northern Idaho, and western Montana has certain undesirable ecological and silvicultural effects [and that]... conditions are already deplorable and are becoming increasingly serious over large areas." Also, Cooper (1961) stated, "…fire has played a major role in shaping the world's grassland and forests. Attempts to eliminate it have introduced problems fully as serious as those created by accidental conflagrations." Only more recently have concerns been expressed about potential loss of biodiversity as a result of fire suppression. This issue may be especially pressing in the Eastern United States. For example, in southern longleaf pine ecosystems, at least 66 rare plant species are maintained by frequent fire (Walker 1993). The ecological need for high fire frequency in large areas of Southeastern native ecosystems coupled with the region's long growing season contribute to the rapid buildup of fuel and subsequent change in habitat structure.

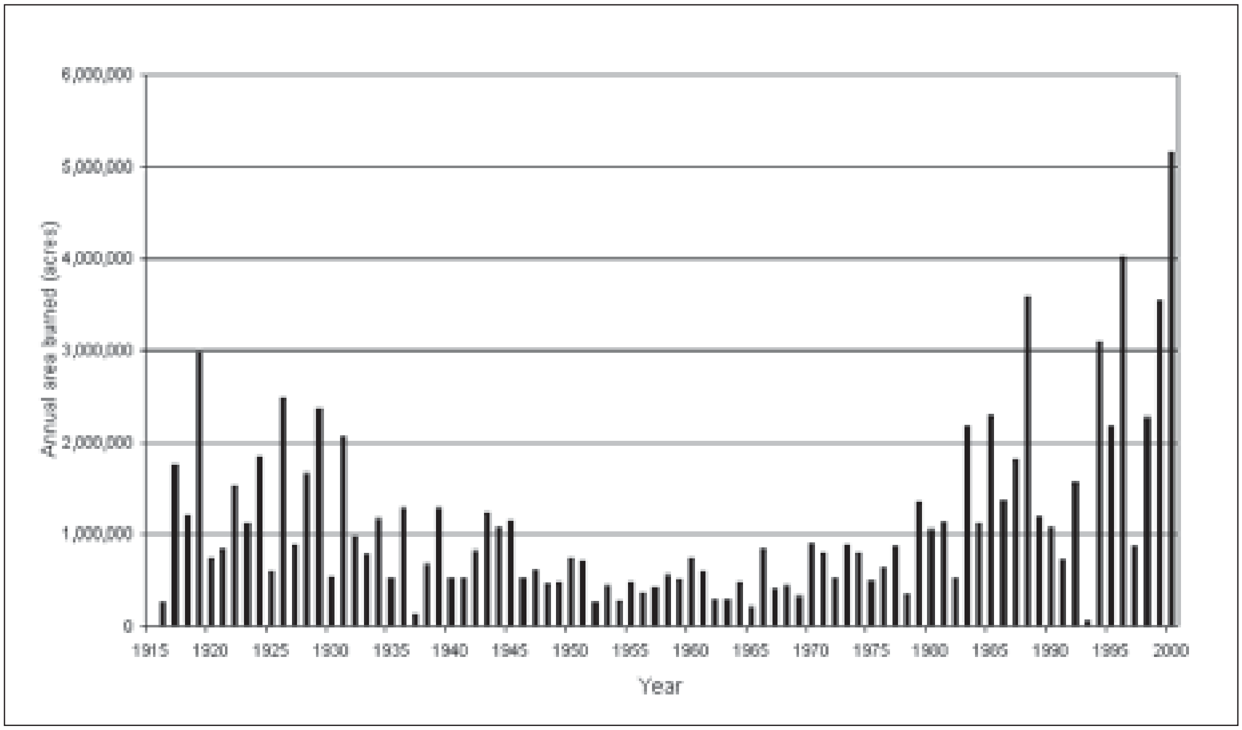

Figure 2.4. The average annual burned area for the western States, shown here for the period 1916-2000, has generally been increasing since the mid-1960s

Wildland and Prescribed Fire Terminology Update

The federal Implementation Procedures Reference Guide for Wildland and Prescribed Fire Management Policy (USDI and USDA Forest Service 1998) contains significant changes in fire terminology. Several traditional terms have either been omitted or have been made obsolete by the new policy. These include: confine/contain/control; escaped fire situation analysis; management ignited prescribed fire; pre-suppression; and prescribed natural fire, or "PNF." Additionally, there was adoption of several new terms and interpretations that supercedes earlier, traditional terminology:

- **Fire Use -** the combination of wildland fire use and prescribed fire application to meet resource objectives.
- **Prescribed Fire -** Any fire ignited by management actions to meet specific objectives. A written, approved prescribed fire plan must exist, and NEPA requirements must be met, prior to ignition. This term replaces management ignited prescribed fire.
- **Wildfire -** An unwanted wildland fire. *This term was only included to give continuing credence to the historic fire prevention products. This is NOT a separate type of fire under the new terminology.*
- **Wildland Fire -** Any non-structure fire, other than prescribed fire, that occurs in the wildland. This term encompasses fires previously called both wildfires and prescribed natural fires.
- **Wildland Fire Use -** the management of naturally-ignited wildland fires to accomplish specific pre-stated resource management objectives in predefined geographic areas outlined in Fire Management Plans. Wildland fire use is not to be confused with "fire use," which is a broader term encompassing more than just wildland fires.

Taking Action: The Federal Wildland and Prescribed Fire Policy

The decline in resiliency and ecological "health" of ecosystems has reached alarming proportions in recent decades, as evidenced by the trend since the mid-1960's towards more acres burned in wildfires (figure 2.4). While national awareness of this trend has existed for some time, the 1994 fire season created a renewed awareness and concern among Federal land management agencies and their constituents regarding the serious impacts of wildfires. The Federal Wildland Fire Management Policy and Program Review is chartered by the Secretaries of Agriculture and Interior to "ensure that uniform federal policies and cohesive interagency and intergovernmental fire management programs exist" (USDI and USDA Forest Service 1995). The review process is directed by an interagency Steering Group whose members represented the Departments of Agriculture and Interior, the U.S. Fire Administration, the National Weather Service, the Federal Emergency Management Agency, and the Environmental Protection Agency. In their cover letter accepting the Final Report of the Review (December 18, 1995), the Secretaries of Agriculture and Interior proclaimed:

> *"The philosophy, as well as the specific policies and recommendations, of the Report continues to move our approach to wildland fire management beyond the traditional realms of fire suppression by further integrating fire into the management of our lands and resources in an ongoing and systematic manner, consistent with public health and environmental*

> *quality considerations. We strongly support the integration of wildland fire into our land management planning and implementation activities. Managers must learn to use fire as one of the basic tools for accomplishing their resource management objectives."*
>
> USDI and USDA Forest Service 1995—cover memorandum

The Report asserts that "the planning, implementation, and monitoring of wildland fire management actions will be done on an interagency basis with the involvement of all partners." The term "partners" is all-encompassing, including Federal land management and regulatory agencies; tribal governments; Department of Defense; State, county, and local governments; the private sector; and the public. Partnerships are essential for establishing collective priorities to facilitate use of fire at the landscape level. Smoke does not respond to artificial boundaries or delineations. Interaction among partners is necessary to meet the dual challenge of using fire for natural resource management coupled with the need to minimize negative effects related to smoke. Both concerns must be met to fulfill the public need.

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The Smoke Management Imperative

Colin C. Hardy
Sharon M. Hermann
John E. Core

Introduction

In the past, smoke from prescribed burning was managed primarily to avoid nuisance conditions objectionable to the public or to avoid traffic hazards caused by smoke drift across roadways. While these objectives are still valid, today's smoke management programs are also likely to be driven, in part, by local, regional and federal air quality regulations. These new demands on smoke management programs have emerged as a result of Federal Clean Air Act requirements that include standards for regulation of regional haze and the recent revisions to the National Ambient Air Quality Standards (NAAQS) on particulate matter.[1]

Development of the additional requirements coincides with renewed efforts to increase use of fire to restore forest ecosystem health. These two requirements are interrelated:

- The purity of the air we breathe is essential to our health and quality of our lives and smoke from wildland and prescribed fire can have adverse effects on public health.
- The national forests, national parks and wilderness areas set aside by Congress are among the nation's greatest treasures. They inspire us as individuals and as a nation. Smoke from wildland burning can obscure these natural wonders.
- Although smoke may be an inconvience under the best conditions and a public health and safety risk under the worst conditions, without periodic fires, the natural habitat that society holds in such high esteem will decline and ultimately dissapear. In addition, as ecosystem health declines, fuel increases to levels that also pose significant risks for wildfire and consequently additional safety risks.
- Wildland and prescribed fire managers are entrusted with balancing these and other, often potentially conflicting responsibilities. Fire managers are charged with the task of increasing the use of fire to accomplish important land stewardship objectives and, at the same time, are entrusted to protect public safety and health.

Purpose of a Smoke Management Program

The purpose of a smoke management program is to:

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[1] See Chapter 4, Regulations for Smoke Management, for details on specific requirements.

- minimize the amount of smoke entering populated areas, preventing public health and safety hazards (e.g. visual impairment on roadways or runways) and problems at sensitive sites (e.g. nursing homes or hospitals),
- avoid significant deterioration of air quality and NAAQS violations, and
- eliminate human-caused visibility impacts in Class I areas.

Smoke management programs create a framework of procedures and requirements for managing smoke from prescribed fires and are typically developed by States or tribes with cooperation and participation from stakeholders. Procedures and requirements developed through partnerships are more effective at meeting resource management goals, protecting public health, and achieving air quality objectives than programs that are created in isolation. Sophisticated programs for coordination of burning both within a state and across state boundaries are vital to obtain and maintain public support of burning programs. Fire use professionals are increasingly encouraged to burn at a landscape level. In some cases, when objectives are based in both ecology and fuel reduction, there is a need to consider burning during challenging times of the year (e.g. during the growing season rather than the cooler dormant season). Multiple objectectives for fire use are likely to increase the challenges, consequently increasing the value of partnerships for smoke management.

Smoke management is increasingly recognized as a critical component of a state or tribal air quality program for protecting public health and welfare while still providing for necessary wildland burning.

Usually, either a state or tribal natural resources agency or air quality agency is responsible for developing and administering the smoke management program. Occasionally a smoke management program may be administered by a local agency. California, for example, relies on local area smoke management programs. Generally, on a daily basis the administering agency approves or denies permits for individual burns or burns meeting some criteria. Permits may be required for all fires or only for those that exceed an established de minimis level (which could be based on projections of acres burned, tons consumed, or emissions). Multi-day burns may be subject to daily reassessment and re-approval to ensure compliance with smoke management program goals.

Advanced smoke management programs evaluate individual and multiple burns; coordinate all prescribed fire activities in an area; consider cross-boundary (landscape) impacts; and weigh decisions about fires against possible health, visibility, and nuisance effects. With increasing use of fire for forest health and ecosystem management, interstate and interregional coordination of burning will be necessary to prevent episodes of poor air quality. Development of, and participation in, an effective smoke management program by state agents and land managers will go a long way towards building and maintaining public acceptance of prescribed burning.

The Need for Smoke Management Programs

The call for increasingly effective smoke management programs has occurred because of public and governmental concerns about the possible risks to public health and safety, as well as nuisance and regional haze impacts of smoke from wildland and prescribed fires. There are also concerns about contributions to health-related National Ambient Air Quality Standards. Each of these areas is summarized below.[2]

Public Health Protection: Fine Particle National Ambient Air Quality Standards.– EPA's most recent review of the National Ambient Air Quality Standards for Particulate Matter (PM_{10}) concluded that significant changes were needed to assure the protection of public health. In July of 1997, following an extensive review of the global literature, EPA adopted a fine particle ($PM_{2.5}$) standard.[3]

These small particles are largely responsible for the health effects of greatest concern and for visibility reduction in the form of regional haze. More on EPA's fine particle standard is found elsewhere in this Guide.

The close link between regional haze and the new fine particle National Ambient Air Quality Standards means that smoke from prescribed fire is again at the center of attention for air regulators charged with adopting control strategies to attain the new standards.

Public Safety and Nuisance Issues.–Perhaps the most immediate need for an effective smoke management program is related to smoke drifting across roadways and restricting motorist visibility. Each year, people are killed on the nation's highways because of dust storms, smoke and fog. Wildland and prescribed fire managers must recognize the legal issues related to their professional activities. Special care must be taken in administering the smoke management program to assure that smoke does not obscure roadway or airport visibility. Liability issues vary by state. Some states such as Florida have "right-to-burn" laws that provide some protection for fire use professionals with specific training and certification.

Probably the most common air quality issues facing wildland and prescribed fire managers are those related to public complaints about nuisance smoke. Complaints may be about the odor or soiling effects of smoke, poor visibility, and impaired ability to breathe or other health-related effects. Sometimes complaints come from the fact that some people don't like or are fearful of smoke intruding into their lives. Whatever the reason, fire managers have a responsibility to try to prevent or resolve the issue through smoke management plans that recognize the importance of proper selection of management and burning techniquesand burn scheduling based on meteorological conditions. In additioncommunity public relations and education coupled with pre-burn notification can greatly improve public acceptance of fire management programs.

Visibility Protection.–Haze that obstructs the scenic beauty of the Nation's wildlands and national parks does not respect political boundaries. Any program that is intended to reduce visibility impairment in the nation's parks and wildlands must be based on multi-state cooperative efforts or on national legislation.

In 1999, the U.S. EPA issued regional haze regulations to manage and mitigate visibility impairment from the multitude of regional haze sources.[4] Regional haze regulations call for states to establish goals for improving visibility in Class I national parks and wildernesses and to develop long-term strategies for reducing emissions of air pollutants that cause visibility impairment. Wildland and prescribed fire are some of the sources of regional haze covered by the new rules.

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[2] Details relating to *Public Health effects, Problem and Nuisance Smoke, and Regional Haze* are given in the sections 3.1, 3.3 and 4.1, respectively, of this Guide.

[3] One thousand fine particles of this size could fit into the period at the end of this sentence.

[4] [40 CFR Part 51]

Past Success and Commitment to Future Efforts

It is clearly noted in the preface to the 2001 Smoke Management Guide that conflicts among natural resource needs, fire management, and air quality issues are expected to increase. It is equally important to acknowledge the benefits to air quality resulting from the many successful smoke management efforts in the past two decades.

Since the 1980s, federal, state, tribal, and local land managers have recognized the potential impacts of smoke emissions from their activities. Additionally, they have sponsored and pursued new efforts to learn the principles of smoke management and to develop appropriate smoke management applications. Many early smoke management successes resulted from proactive, voluntary inclusion of smoke management components in many burn plans as early as the mid-1980s.

NWCG and its partners are committed to furthering their leadership role in the quest for new information, technology, and innovative techniques. These 2001 revisions to the Guide are evidence of that commitment.

Chapter 3

SMOKE IMPACTS

Public Health and Exposure to Smoke

John E. Core

Janice L. Peterson

Introduction

The purity of the air we breathe is an important public health issue. Particles of dust, smoke, and soot in the air from many sources, including wildland fire, can cause acute health effects. The effects of smoke range from irritation of the eyes and respiratory tract to more serious disorders including asthma, bronchitis, reduced lung function, and premature death. Airborne particles are respiratory irritants, and high concentrations can cause persistent cough, phlegm, wheezing, and physical discomfort when breathing. Particulate matter can also alter the body's immune system and affect removal of foreign materials from the lung like pollen and bacteria.

This section discusses the effects of air pollution, especially particulate matter, on human health and morbidity. Wildland fire smoke is discussed as one type of air pollution that can be harmful to public health[1].

Human Health Effects of Particulate Matter

Many epidemiological studies have shown statistically significant associations of ambient particulate matter levels with a variety of human health effects, including increased mortality, hospital admissions, respiratory symptoms and illness measured in community surveys (Brauer 1999, Dockery and others 1993, EPA 1997). Health effects from both short-term (usually days) and long-term (usually years) particulate matter exposures have been documented. The consistency of the epidemiological data increases confidence that the results reported in numerous studies justify the increased public health concerns that have prompted EPA to adopt increasingly stringent air quality standards (Federal Register 1997). There remains, however, uncertainty regarding the exact mechanisms that air pollutants trigger to cause the observed health effects (EPA 1996).

Figure 3.1.1 illustrates respiratory pathways that form the human body's natural defenses against polluted air. These pathways can be divided into two systems - the upper airway passage consisting of the nose, nasal passages, mouth and pharynx, and the lower airway passages consisting of the trachea, bronchial tree, and alveoli. While coarse particles (larger than about 5 microns in diameter) are deposited in the upper respiratory system, fine particles (less than 2.5 microns in diameter) can penetrate much deeper into the lungs. These fine particles are deposited in the alveoli where the body's defense mechanisms are ineffective in removing them (Morgan 1989).

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[1] Information on the effects of smoke on firefighters and prescribed burn crews can be found in Section 3.4.

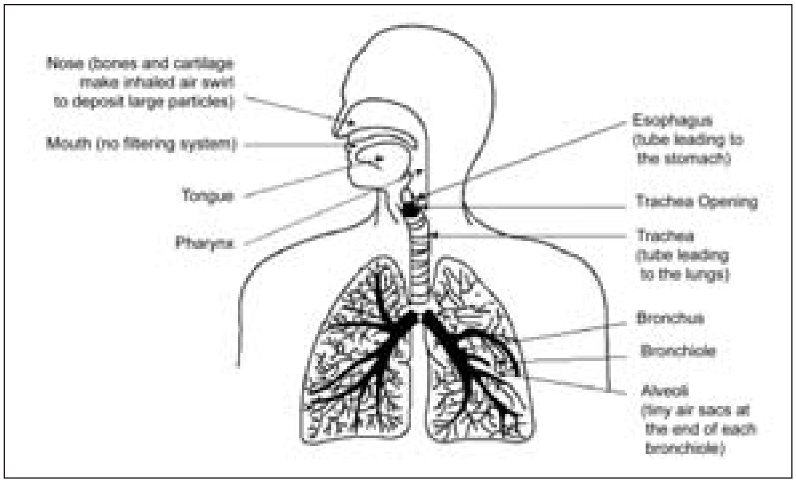

Figure 3.1.1: Particle deposition in the respiratory system.
From: Canadian Center for Occupational Health & Safety, available at http://www.ccohs.ca/oshanswers/ chemicals/how_do.html

On a smoggy day in a major metropolitan area, a single breath of air may contain millions of fine particles. Some 74 million Americans — 28% of the population — are regularly exposed to harmful levels of particulate air pollution (EPA 1997). In recent studies, exposure to fine particles – either alone or in combination with other air pollutants – has been linked with many health problems, including:

- An estimated 40,000 Americans die prematurely each year from respiratory illness and heart attacks that are linked with particulate exposure, especially elderly people (EPA 1997).
- Children and adults experience aggravated asthma. Asthma in children increased 118% between 1980 and 1993, and it is currently the leading cause of child hospital admissions (EPA 1997).
- Children become ill more frequently and experience increased respiratory problems, including difficult and painful breathing (EPA 1997).
- Hospital admissions, emergency room visits and premature deaths increase among adults with heart disease, emphysema, chronic bronchitis, and other heart and lung diseases (EPA 1997).

The susceptibility of individuals to particulate air pollution (including smoke) is affected by many factors. Asthmatics, the elderly, those with cardiopulmonary disease, as well as those with preexisting infectious respiratory disease such as pneumonia may be especially sensitive to smoke exposure. Children and adolescents may also be susceptible to ambient particulate matter effects due to their increased frequency of breathing, resulting in greater respiratory tract deposition. In children, epidemiological studies reveal associations of particulate exposure with increased bronchitis symptoms and small decreases in lung function.

Fine particles showed consistent and statistically significant relationships to short-term mortality in six U.S. cities while coarse particles showed no significant relationship to excess mortality in five of the six cities that were studied (Dockery and others 1993).

Impacts of Wildland Fire Smoke on Public Health

There is not much data which specifically examines the effects of wildland fire smoke on public health, although some studies are planned or underway. We can, however, infer health responses from the documented effects of particulate air pollutants. Eighty to ninety percent of wildfire smoke (by mass) is within the fine particle size class ($PM_{2.5}$), making public exposure to smoke a significant concern.

The Environmental Protection Agency has developed some general public health warnings for specific air pollutants including $PM_{2.5}$ (table 3.1.1) (EPA 1999). The concentrations in table 3.1.1 are 24-hour averages, which can be problematic when dealing with smoke impacts that may be severe for a short period of time and then virtually non-existent soon after. Another guidance document was developed recently to relate short-term, 1-hour averages to the potential human health effects given in table 3.1.1 (Therriault 2001).

Figure 3.1.2 contains these short-term averages plus approximate corresponding visual range in miles. Members of the public can use the methods described to estimate visual range and determine when air quality may be hazardous to their health even if they are located in an area that is not served by an official state air quality monitor.

Figure 3.1.3 is an information sheet developed during a prolonged wildfire smoke episode in Montana during the summer of 2000. The questions and answers address many common concerns voiced by the public during smoke episodes.

Other Pollutants of Concern in Smoke

Although the principal air pollutant of concern is particulate matter, there are literally hundreds of compounds emitted by wildland fires that are found in very low concentrations. Some of these compounds that also deserve mention include:

- Carbon monoxide has well known, serious health effects including dizziness, nausea and impaired mental functions but is usually only of concern when people are in close proximity to a fire (including firefighters). Blood levels of carboxyhemoglobin tend to decline rapidly to normal levels after a brief period free from exposure (Sharkey 1997).
- Benzo(a)pyrene, anthracene, benzene and numerous other components found in smoke from wildland fires can cause headaches, dizziness, nausea, and breathing difficulties. In addition, they are of concern because of long term cancer risks associated with repeated exposure to smoke.
- Acrolein and formaldehyde are eye and upper respriatory irritants to which some segments of the public are especially sensitive.

Table 3.1.1. EPA's pollutant standard index for $PM_{2.5}$ can be used for general assessment of health risks from existing air quality.

Standard Index Category	**PM2.5 24-hr concentration ($\mu g/m^3$)**	**Health Effects**	**Cautionary Statements**
Good	0-15.4	None	None
Moderate	15.5-40.4	None	None
Unhealthy for Sensitive Groups	40.5-65.4	Increasing likelihood of respiratory symptoms in sensitive individuals, aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly.	People with respiratory or heart disease, the elderly and children should limit prolonged exertion.
Unhealthy	65.5-150.4	Increased aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; increased respiratory effects in general population.	People with respiratory or heart disease, the elderly and children should avoid prolonged exertion; everyone else should limit prolonged exertion.
Very Unhealthy	150.5-250.4	Significant aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; significant increase in respiratory effects in general population.	People with respiratory or heart disease, the elderly and children should avoid any outdoor activity; everyone else should avoid prolonged exertion.
Hazardous	>250.4	Serious aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; serious risk of respiratory effects in general population.	Everyone should avoid any outdoor exertion; people with respiratory or heart disease, the elderly and children should remain indoors.

Category	PM2.5 1-hr avg. concentration ($\mu g/m^3$)	Visibility Range (miles)
Good	0-40	10 miles and up
Moderate	41-80	6 to 9 miles
Unhealthy for Sensitive Groups	81-175	3 to 5 miles
Unhealthy	176-300	1 1/2 to 2 1/2 miles
Very Unhealthy	301-500	1 to 1 1/4 mile
Hazardous	Over 500	3/4 mile or less

The procedure for using personal observations to determine the approximate PM_{25} concentration for local areas without official monitors is:

1. Face away from the sun.
2. Determine the limit of your visible range by looking for targets at known distance (miles). Visible range is that point at which even high contrast objects totally disappear.
3. Use the values above to determine the local forest fire smoke category.

Figure 3.1.2. Visibility range can be used by the public to assess air quality in areas with no state air pollution monitors.

Conclusions

The health effects of wildland smoke are of real concern to wildland fire managers, public health officials, air quality regulators and all segments of the public. Fire practitioners have an important responsibility to understand the potential health impacts of fine particulate matter and minimize the public's exposure to smoke.

Wildland fire managers should be aware of sensitive populations and sites that may be affected by prescribed fires, such as medical facilities, schools or nursing homes, and plan burns to minimize the smoke impacts. This is especially true when exposure may be prolonged. Days or weeks of smoke exposure are problematic because the lung's ability to sweep 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 and avoiding potential problems while still in the planning phase.

Wildfire Smoke and Your Health

What's in smoke from a wildfire?
Smoke is made up of small particles, gases and water vapor. Water vapor makes up the majority of smoke. The remainder includes carbon monoxide, carbon dioxide, nitrogen oxide, irritant volatile organic compounds, air toxics and very small particles.

Is smoke bad for me?
Yes. It's a good idea to avoid breathing smoke if you can help it. If you are healthy, you usually are not at a major risk from smoke. But there are people who are at risk, including people with heart or lung diseases, such as congestive heart disease, chronic obstructive pulmonary disease, emphysema or asthma. Children and the elderly also are more susceptible.

What can I do to protect myself?

- Many areas report EPA's Air Quality Index for *particulate matter, or PM.* PM (tiny particles) is one of the biggest dangers from smoke. As smoke gets worse, that index changes — and so do guidelines for protecting yourself. So listen to your local air quality reports.
- Use common sense. If it looks smoky outside, that's probably not a good time to go for a run. And it's probably a good time for your children to remain indoors.
- If you're advised 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.
- Help keep particle levels inside lower by avoiding using anything that burns, such as wood stoves and gas stoves – even candles. And don't smoke. That puts even more pollution in your lungs – and those of the people around you.
- If you have asthma, be vigilant about taking your medicines, as prescribed by your doctor. If you're supposed to measure your peak flows, make sure you do so. Call your doctor if your symptoms worsen.

How can I tell when smoke levels are dangerous? I don't live near a monitor.
Generally, the worse the visibility, the worse the smoke. In Montana, the Department of Environmental Quality uses visibility to help you gauge wildfire smoke levels.

How do I know if I'm being affected?
You may have a scratchy throat, cough, irritated sinuses, headaches, runny nose and stinging eyes. Children and people with lung diseases may find it difficult to breathe as deeply or vigorously as usual, and they may cough or feel short of breath. People with diseases such as asthma or chronic bronchitis may find their symptoms worsening.

Should I leave my home because of smoke?
The tiny particles in smoke do get inside your home. If smoke levels are high for a prolonged period of time, these particles can build up indoors. If you have symptoms indoors (coughing, burning eyes, runny nose, etc.), talk with your doctor or call your county health department. This is particularly important for people with heart or respiratory diseases, the elderly and children.

Are the effects of smoke permanent?
Healthy adults generally find that their symptoms (runny noses, coughing, etc.) disappear after the smoke is gone.

Do air filters help?
They do. 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. That puts more pollution in your home.

Do dust masks help?
Paper "comfort" or "nuisance" masks are designed to trap large dust particles — not the tiny particles found in smoke.

These masks generally will not protect your lungs from wildfire smoke.

How long is the smoke going to last?
That depends on a number of factors, including the number of fires in the area, fire behavior, weather and topography. Smoke also can travel long distances, so fires in other areas can affect smoke levels in your area.

I'm concerned about what the smoke is doing to my animals. What can I do?
The same particles that cause problems for people may cause some problems for animals. Don't force your animals to run or work in smoky conditions. Contact your veterinarian or county extension office for more information.

***How* does smoke harm my health?**
One of the biggest dangers of smoke comes from *particulate matter* — solid particles and liquid droplets found in air. In smoke, these particles often are very tiny, smaller than 2.5 micrometers in diameter. How small is that? Think of this: the diameter of the average human hair is about 30 times bigger.

These particles can build up in your respiratory system, causing a number of health problems, including burning eyes, runny noses and illnesses such as bronchitis. The particles also can aggravate heart and lung diseases, such as congestive heart failure, chronic obstructive pulmonary disease, emphysema and asthma.

What about firefighters?
Firefighters do experience short-term effects of smoke, such as stinging, watery eyes, coughing and runny noses. Firefighters must be in good physical condition, which helps to offset adverse effects of smoke. In addition to being affected by particles, firefighters can be affected by carbon monoxide from smoke. A recent Forest Service study showed a very small percentage of firefighters working on wildfires were exposed to levels higher than occupational safety limits for carbon monoxide and irritants.

Why can't the firefighters do something about the smoke?
Firefighters first priorities in fighting a fire are, by necessity, protecting lives, protecting homes and containing the wildfire. Sometimes the conditions that are good for keeping the air clear of smoke can be bad for containing fires. A windy day helps smoke disperse, but it can help a fire spread.

Firefighters do try to manage smoke when possible. As they develop their strategies for fighting a fire, firefighters consider fire behavior and weather forecasts, topography and proximity to communities – all factors than can affect smoke.

Why doesn't it seem to be as smoky when firefighters are working on prescribed fires.
Land managers are able to plan for prescribed fires. They get to choose the areas they want to burn, the size of those areas and the weather and wind conditions that must exist before they begin burning. This allows them to control the fire more easily and limit its size. Those choices don't exist with wildfires. In addition, wildfires that start in areas that haven't been managed with prescribed fire often have more fuel, because vegetation in the forest understory has built up, and dead vegetation has not been removed.

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Figure 3.1.3. Public health information developed during the Montana wildfires of 2000.

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Visibility

John E. Core

Introduction

Every year there are over 280 million visitors to our nation's wilderness areas and national parks. Congress has set these special places aside for the enjoyment of all that seek spectacular and inspiring vistas. Unfortunately, many visitors are not able to see the beautiful scenery they expect. During much of the year, a veil of haze often blurs their view. The haze is caused by many sources of both natural and manmade air pollution sources, including wildland fire.

This section describes measures of scenic visibility, the properties of the atmosphere and how these properties are affected by smoke from wildland fires, natural and current visibility conditions, as well as sources that contribute to visibility degradation. This is an important issue to wildland fire practitioners because smoke is of increasing interest to air regulators responsible for solving regional haze problems.

Measures of Visibility Impairment

Visibility is most often thought of in terms of visual range or the furthest distance a person can see a landscape feature. However, visibility is more than ***how far*** one can see; it also encompasses ***how well*** scenic landscape features can be seen and appreciated. Changes in visual range are not proportional to human perception. For example, a five-mile change in visual range can result in a scene change that is either imperceptible or very obvious depending on the baseline visibility conditions. Therefore, a more meaningful visibility index has been adopted. The scale of this index, expressed in deciviews (dv) is linear with respect to perceived visual changes over its entire range, analogous to the decibel scale for sound. A one-deciview change represents a change in scenic quality that would be noticeable to most people regardless of the initial visibility conditions. A deciview of zero is equivalent to clear air while deciviews greater than zero depict proportionally increased visibility impairment (IMPROVE 1994). The more deciviews measured, the greater the impairment, which limits the distance you can see. Finally, extinction in inverse megameters (Mm^{-1}) is proportional to the amount of light lost as it travels through a million meters of atmosphere and is most useful for relating visibility directly to particulate concentrations. Table 3.2.1 compares each of these three forms of measurement (Malm 1999).

Properties of the Atmosphere & Wildland Fire Smoke

An observer sees an image of a distant object because light is reflected from the object along the sight path to the observer's eye. Any of this image-forming light that is removed from the sight path by scattering or light absorption

Visual Range (Km)	200	130	100	80	60	40	13	10	8	6
(Miles)	124	81	62	50	37	25	8	6	5	4
Deciviews (dv)	7	11	14	16	19	23	34	37	39	42
Extinction (Mm^{-1})	20	30	40	50	70	100	300	400	500	700

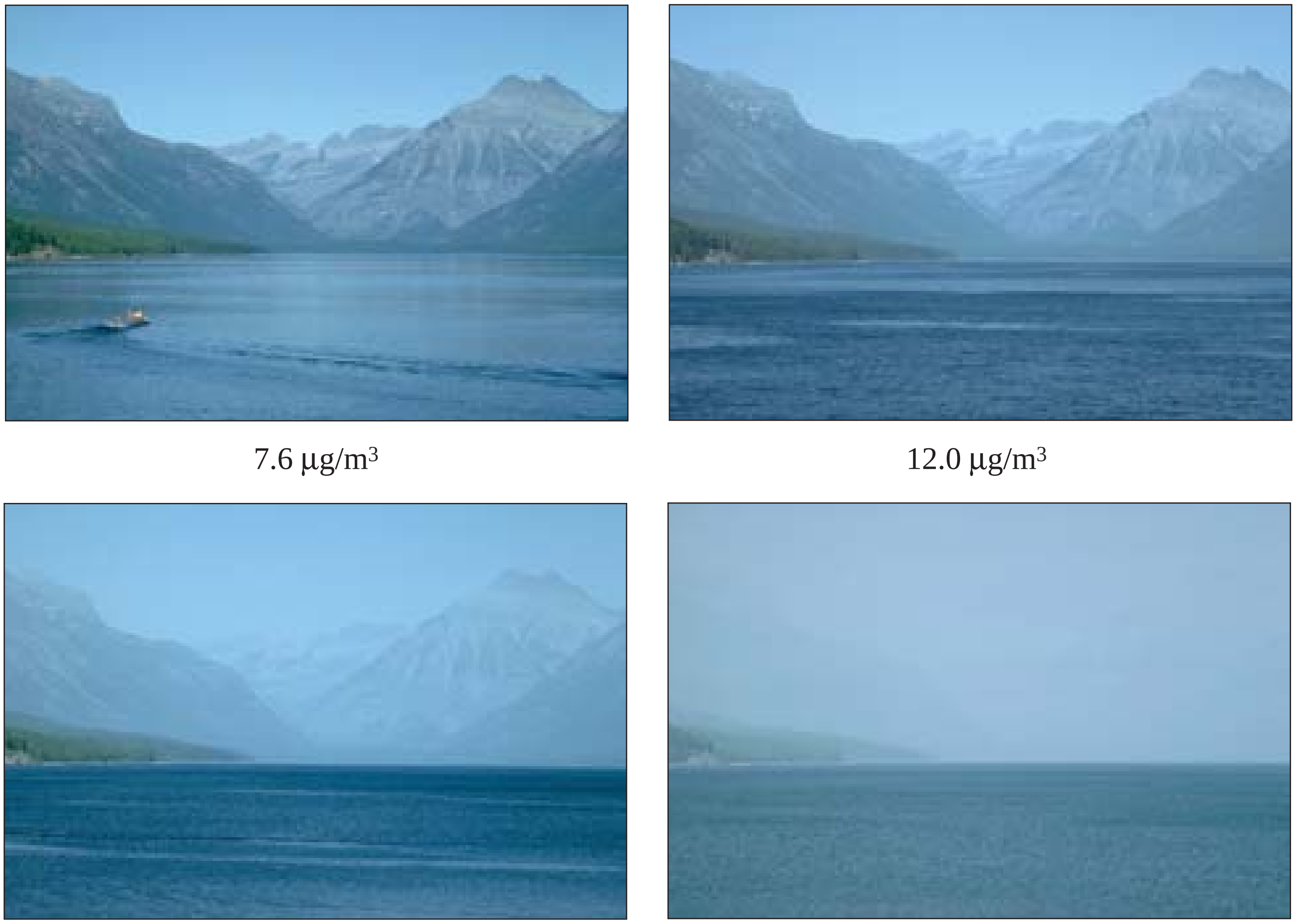
Table 3.2.1. Comparison of the four expressions of visibility measurement.

reduces the image-forming information and thereby diminishes the clarity of the landscape feature. Ambient light is also scattered into the sight path, competing with the image-forming light to reduce the clarity of the object of interest. This "competition" between image-forming light and scattered light is commonly experienced while driving in a snowstorm at night with the car headlights on.

In addition, relative humidity also indirectly affects visibility. Although relative humidity does not by itself cause visibility to be degraded, some particles, especially sulfates, accumulate water from the atmosphere and grow to a size where they are particularly efficient at scattering light. Poor visibility in the eastern states during the summer months is a result of the combination of high sulfate concentrations and high relative humidity.

The sum of scattering and absorption is referred to as atmospheric light extinction. Particles that are responsible for scattering are categorized as primary and secondary where primary sources include smoke from wildland fires and wind-blown dust. Other sources of secondary particles include sulfate and nitrate particles formed in the atmosphere. The closer the particle size is to the wavelength of light, the more effective the particle is in scattering light. As a result, relatively large particles of wind-blown dust are far less efficient in scattering light per unit mass than are the fine particles found in smoke from wildland fires. Finally, an important component of smoke from wildland fires is elemental carbon (also known as soot), which is highly effective in absorbing light within the sight path. This combination of light absorption by elemental carbon and light scattering caused by the very small particles that make up wildland fire smoke explains why emissions from wildland fire play such an important role in visibility impairment.

The effect of regional haze on a Glacier National Park vista is shown in the four panels of figure 3.2.1. The view is of the Garden Wall from across Lake McDonald. Particulate concentrations associated with these photographs correspond to 7.6, 12.0, 21.7 and 65.3 $\mu g/m^3$, respectively (Malm 1999). Note the loss of color and detail in the mountains as the particulate concentrations increase and visibility decreases.



7.6 μg/m^3

12.0 μg/m^3

21.7 μg/m^3

65.3 μg/m^3

Figure 3.2.1. The effect of regional haze on a Glacier National Park vista.
Photo courtesy of the National Park Service, Air Resources Division.

Natural Visibility Conditions

Some light extinction occurs naturally due to scattering caused by the molecules that make up the atmosphere. This is called Rayleigh scattering and is the reason why the sky appears blue. But even without the influence of human-caused air pollution, visibility would not always reach the approximately 240-mile limit defined by Rayleigh scattering. Naturally occurring particles, such as windblown dust, smoke from natural fires, volcanic activity, and biogenic emissions (e.g. pollen and gaseous hydrocarbon) also contribute to visibility impairment although the concentrations and sources of some of these particles remain a point of investigation.

Average natural visibility in the eastern U.S. is estimated to be about 60-80 miles (8-11 dv), whereas in the western US it is about 110-115 miles (4.5-5 dv) (Malm 1999). Lower natural visibility in the eastern U.S. is due to higher average humidity. Humidity causes fine particles to stick together, grow in size, and become more efficient at scattering light. Under natural conditions, carbon-based particles are responsible for most of the non-Rayleigh particle-

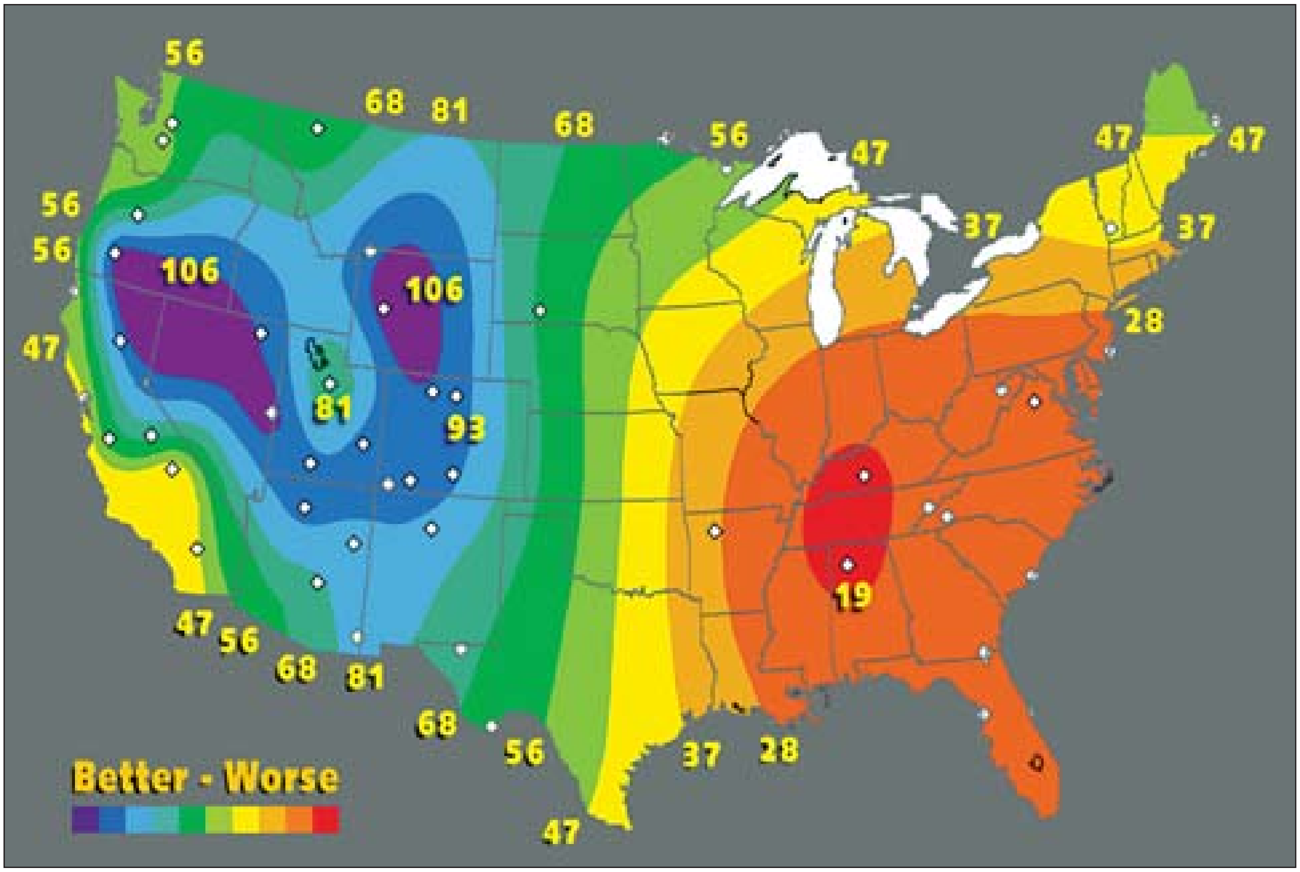


Figure 3.2.2. *Average annual visual range, in miles, for the years 1996-1998 measured at IMPROVE network monitors.*

associated visibility reduction, with all other particle species contributing significantly less. Scattering from naturally occurring sulfate particles from volcanic sulfur dioxide emissions and oceanic sources of primary sulfate particles are estimated to account for 9-12% of the impairment in the East and 5% in the West (NPS 1997). It is expected that coastlines and highly vegetated areas may be lower than these averages, while some elevated areas (mountains) could exceed these background estimates.

Current Visibility Conditions

Currently, average visual range in the eastern U.S. is about 15-30 miles, or about one-third of the estimated natural background for the East. In the West, visual range currently averages about 60-90 miles, or about one-half of the estimated natural background for the West. Current annual visual range conditions expressed in miles are shown in figure 3.2.2. Notice how much more impaired visibility is in the East versus the West.

In the East, 60-70% of the visibility impairment is attributed to sulfates. Sulfate particles form from sulfur dioxide gas, most of which is released from coal-burning power plants and other industrial sources such as smelters, industrial boilers, and oil refineries. Carbon-based particles contribute about 20% of the impairment in the East. Sources of organic carbon particles include vehicle exhaust, vehicle refueling, solvent evaporation, food cooking, and fires.

Elemental carbon particles (or light absorbing carbon) are emitted by virtually all combustion activities, but are especially prevalent in diesel exhaust and smoke from wood burning.

In the West, sulfates contribute less than 30% (Oregon, Idaho and Nevada) to 40-50% (Arizona, New Mexico and Southwest Texas) of light extinction. Carbon particles in the West are a greater percentage of the extinction budget ranging from 50% or greater in the Northwest to 30-40% in the other western regions. The higher percentages of the extinction budget associated with carbon particles in the West appear to be from smoke emitted by wildland and agricultural fires (NPS 1994).

In summary, the physics of light extinction in the atmosphere coupled with the chemical composition and physical size distribution of particles in wildland fire smoke combine to make fire (especially in the West) an important contributor to visibility impairment. Wildland fire managers responsible for the protection of the scenic vistas of this nation's wilderness areas and national parks have a difficult challenge in balancing the need to protect visibility with the need to use fire for other resource management goals.

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Problem and Nuisance Smoke

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Bill Jackson

James D. Brenner

Introduction

The particulate matter (or particles) produced from wildland fires can be a nuisance or safety hazard to people who come in contact with the smoke – whether the contact is directly through personal exposure, or indirectly through visibility impairment. Nuisance smoke is defined by the US Environmental Protection Agency as the amount of smoke in the ambient air that interferes with a right or privilege common to members of the public, including the use or enjoyment of public or private resources (US EPA 1990).

Although the vast majority of prescribed burns occur without negative smoke impact, wildland fire smoke can be a problem anywhere in the country. Complaints about loss of visibility, odors, and soiling from ash fallout are not unique to any region. Reduced visibility from smoke has caused fatal collisions on highways in several states, from Florida to Oregon. Acrolein (and possibly formaldehyde) in smoke is likely to cause eye and nose irritation for distances up to a mile from the fire, exacerbating public nuisance conditions (Sandberg and Dost 1990). The abatement of nuisance or problem smoke is one of the most important objectives of any wildland fire smoke management plan (Shelby and Speaker 1990).

This section provides information on the issue of visibility reduction from wildland fire smoke, and focuses particularly on smoke as a major concern in the Southern states. Meteorology, climate and topography combine with population density and fire frequency to make nuisance smoke a chronic issue in the South. Lessons from this regional example can be extrapolated and applied to other parts of the country. This section also briefly summarizes tools currently used or under development to aid the land manager in reducing the problematic effects of smoke.

Wildland fire smoke may also be a nuisance to the public by producing a regional haze, which is discussed in Section 3.2.

Nuisance Smoke and Visibility Reduction

A prescribed fire is a combustion process that has no pollution control devices to remove the pollutants. Instead, prescribed fire practitioners often rely on favorable atmospheric conditions to successfully disperse the smoke away from smoke-sensitive areas, such as communities, areas of heavy vehicle traffic, and scenic vistas. At times, however, unexpected changes in weather (especially wind), or planning which does not adequately factor in such elements as topography, diurnal weather patterns, or residual combustion, may result in an intrusion of smoke that causes negative impacts on the public.

Smoke intrusions and nuisance- or safety-related episodes may happen at any time during the course of a wildland fire, but they frequently occur in valley bottoms and drainages during the night. Within approximately one half hour of sunset, air cools rapidly near the ground, and wind speeds decline 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. Smoke then tends to be carried through drainages with little dispersion or dilution. If the drainages are wet, smoke can act as a nucleating agent and can actually assist the formation of local fog, a particular problem in the Southeast. Typically, the greatest fog occurs where smoke accumulates in a low drainage. This can cause hazardous conditions where a drainage crosses a road or bridge, reducing visibility for traffic.

Visibility reduction may also result from the 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. They may, however, disperse gradually back to ground level in an unstable atmosphere (figure 3.3.1). When this occurs, such intrusions of smoke can cause numerous nuisance impacts as well as specific safety hazards.

Visibility reduction is used as a metric of smoke intrusions in several State smoke management programs. The State of Oregon program operational guidance defines a "moderately" intense intrusion as a reduction of visibility from 4.6 to 11.4 miles from a background visibility of more than 50 miles (Oregon Dept. Forestry 1992). The State of Washington smoke intrusion reporting system uses "slightly visible, noticeable impact on visibility, or excessive impact on visibility" to define light, medium and heavy intrusions (Washington Dept. Natural Resources 1993). The New Mexico program requires that visibility impacts of smoke be considered in development of the unit's burn prescription (New Mexico Environmental Improvement Board 1995).

Smoke plume-related visibility degradation in urban and rural communities is not subject to regulation under the Clean Air Act. Nuisance smoke is usually regulated under state and local laws and is frequently based on either public complaint or compromise of highway safety (Eshee 1995). Public outcry regarding nuisance smoke often occurs before smoke exposures reach levels that violate National Ambient Air Quality Standards. The Courts have ruled that the taking of private property by interfering with its use and enjoyment caused by smoke without just compensation is in violation of federal constitutional provisions under the Fifth Amendment. The trespass of smoke may diminish the value of the property, resulting in losses to the owner (Supreme Court of Iowa 1998).

Smoke as a Southern Problem

The Forest Atlas of the United States (figure 3.3.2) shows that the thirteen Southern states contain approximately 40% of U.S. forests – about 200 million acres. While not all of this forested land is regularly burned, the extensive forest type generally known as "southern pines" burns with a high fire frequency, about every 2-5 years. When shrublands and grasslands are added to the total, from four to six million acres of southern wildlands are subjected to pre-

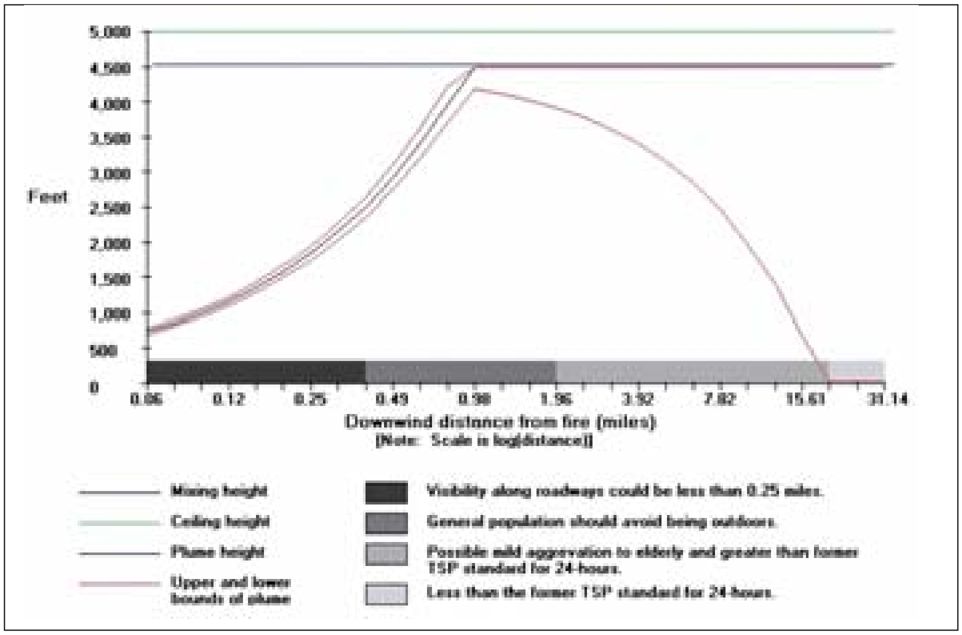

Figure 3.3.1. Graphic from the dispersion model VSmoke-GIS, showing the rise and descent of a smoke plume during a daytime prescribed fire, assuming 25% of the smoke disperses at ground level.

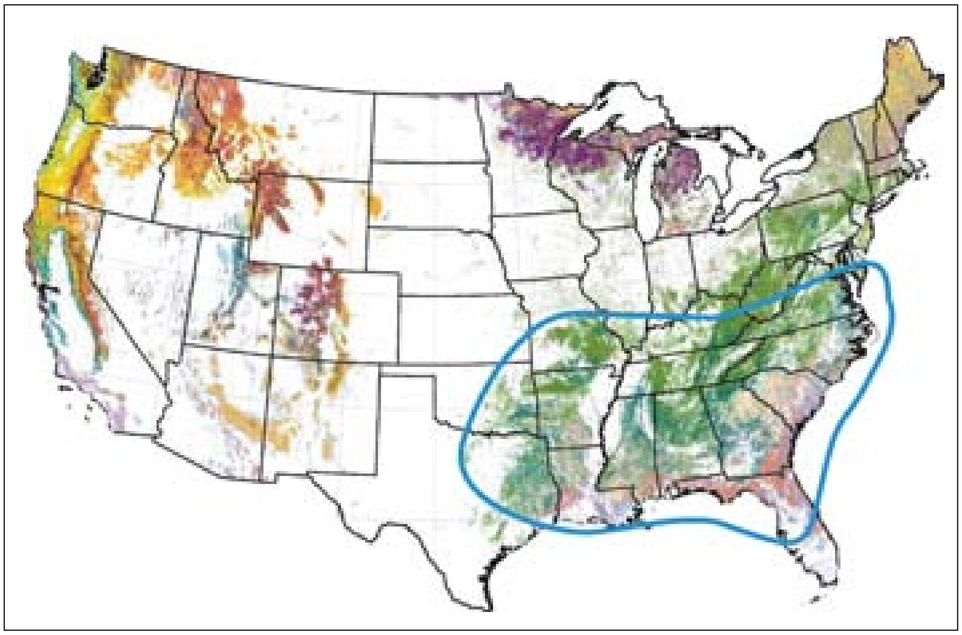

Figure 3.3.2. National Atlas of Forest Cover Types. Southern forests (outlined in blue extend from Virginia to Texas and from the Ohio River southward and account for approximately 40% of U.S. forest land.

scribed fire each year. This is by far the largest acreage of wildlland subjected to prescribed fire in any region of the country.

Figure 3.3.3 shows the 1998 Population Density Classes for the United States. Of particular importance regarding problem smoke is the class “Wildland/Urban Interface,” designated in red. A comparison with figure 3.3.2 shows that the wildland/urban interface falls within much of the range of Southern forests. Southern forests, with highest treatment intervals of prescribed fire and with the largest acreages subjected to prescribed fire, are connected with human habitation and activity through an enormous wildland/urban interface. The potential exists for significant smoke problems in this region.

Smoke and Southern Climate

Several factors regarding climate add to the smoke problem in the South. The long growing season allows time for more annual biomass production relative to other areas of the country with shorter growing seasons. Most of the Southern forests are located farther south than forests elsewhere in the country. Consequently, the sun angle is higher in the South and is capable of supplying warmth well into the late fall and early winter. Further, most southern wildlands are located at low elevations where the air is warmer. These factors contribute to the long growing season, which runs from March/April through October/November.

Abundant rainfall also encourages growth of a large number of grasses, shrubs, and trees. Most of the South receives 40-60 inches (100-150 cm) of precipitation annually. This copious rainfall, in combination with the long growing season, creates conditions for rapid buildup of both dead and live fuels. If burns are not conducted frequently, the increase in emissions from the accumulated fuels may enhance the likelihood of negative smoke impacts when fires do occur.

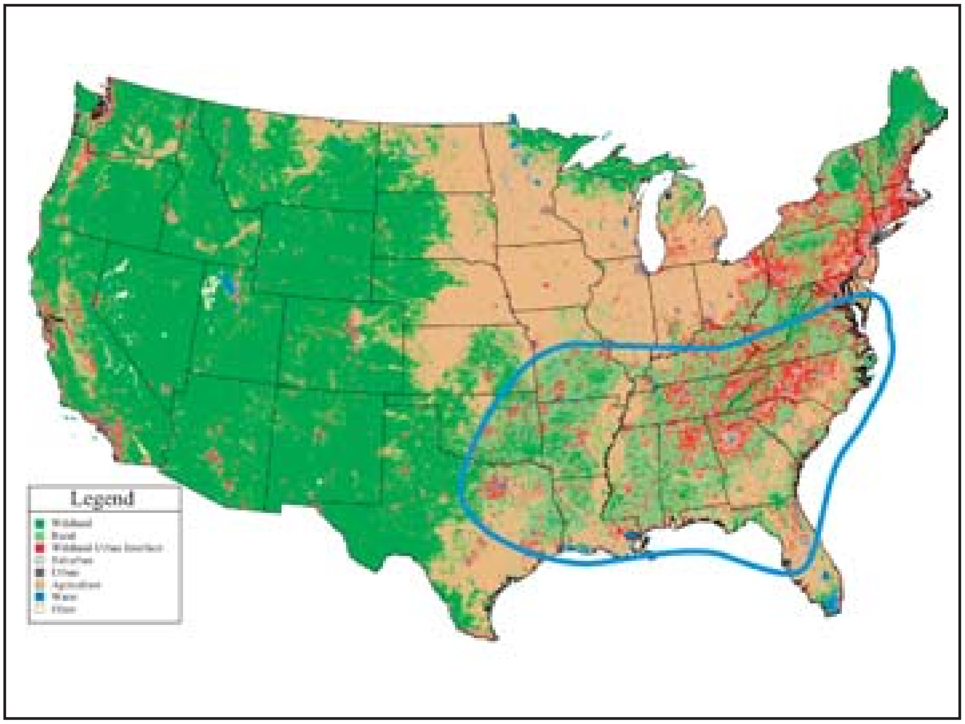

Figure 3.3.3. Population density classes showing wildland/urban interface in red. Southern forests outlined in blue. [http://www.fs.fed.us/fire/fuelman]

The coincidence of dormant-season burning with the winter rain season is a third factor contributing to nuisance smoke. Although burning is conducted year round throughout the South, a significant amount of burning is done during January through March. In a typical year, anywhere from 10-20 inches (25-50 cm) of rain will fall over Southern forests during this three-month period. In some areas of the country, the question might be, "Is it wet enough to burn?" In the South, the question is commonly, "Is it dry enough to burn?" Fires burning into moist fuel burn less efficiently and smolder longer than fires burning dry fuels. Both factors increase smoke production. In addition, less heat is produced during inefficient combustion and smoldering. Therefore, more smoke stays near the ground and increases the risk of problem smoke.

Smoke and Southern Meteorology

All thirteen Southern states have implemented burning regulations designed to limit open burning to those days when burning is considered "safe" and the risks of fire escapes are minimal. Many have implemented smoke management regulations. The need to conduct burning in a manner to reduce impacts on air quality over sensitive targets has encouraged "best practice" approaches to open burning.

Efforts to avoid smoke incursions over sensitive targets are often complicated by the highly variable meteorology of Southern weather systems during the extensive burn season. Four weather features that cause frequent wind shifts and may be accompanied by rapid changes in air mass stability and mixing height are described below.

1. Synoptic scale high- and low-pressure systems and accompanying fronts frequent the South during the winter burn season. In a typical sequence of events, the winds shift to blow from the southeast through southwest in advance of a storm, then shift rapidly to the northwest with cold front passage. Winds blow from the northwest for a day or so but gradually diminish with the approach of a high pressure system, becoming light and variable as the system passes. Then winds shift back to southerly in advance of the next storm. Low clouds, low mixing heights, and high stability often accompany low-pressure systems. Depending upon moisture availability, cold fronts may be accompanied by bands of low clouds and precipitation. Mixing heights are more favorable during high-pressure episodes. Although the movement of synoptic scale weather systems into the South can be predicted with lead times of several days, the timing of arrival of frontal wind shifts over specific burn sites is less certain.

2. Much of the Piedmont and Coastal Plain are flat and it would be expected that winds there are steady and predictable. However, the region is frequented by transient eddies that can cause unexpected wind shifts and carry smoke into sensitive areas. The vertical circulation of air that can force smoke plumes to the ground or carry smoke safely upward are well-understood, but the location, timing and strength of the vertical eddies cannot be predicted. Horizontal eddies have not been well documented, and the timing, location and intensity cannot be predicted.

3. The South has the longest coastline of any fire-prone area in the country. Thus it is axiomatic that large areas of the South are

subject to wind shifts brought on by sea breezes during the day and by land breezes during the night. However, the onset, duration, and intensity of these land/water-induced circulations are not consistent from one day to the next. The region is subject at different times to warm, humid airmasses drawn northward from the Gulf of Mexico, or cold, dry airmasses drawn southward from Canada. Both systems have an impact on land surface temperatures, which results in a significant effect on the duration and extent of land and sea breezes and whether they form at all. The unpredictability of these wind systems adds to the difficulties faced by Southern land managers planning whether smoke from a prescribed burn might impact downwind sensitive targets.

4. The "flying wedge," a wind system caused by cold air channeled southwestward along the eastern slopes of the Appalachian Mountains, can cause sudden wind shifts with large changes in wind direction and lowering of mixing heights. Although Virginia, the Carolinas and Georgia are most frequently impacted, flying wedges have been observed as far south as central Florida and as far west as the Mississippi River. "Flying wedges" occur throughout the year but are most intense, and hence bring with them strong shifting winds and lowering of mixing heights, during winter and early spring, the period of maximum wildland burning in the South.

Smoke and Southern Highways

As previously noted, several million acres of Southern wildlands are burned each year, the vast majority without incident. However, smoke and smoke-induced fog obstructions of visibility on highways sometimes cause accidents with loss of life and personal injuries. Several attempts to compile records of smoke-implicated highway accidents have been made. For the 10-year period from 1979-1988, Mobley (1989) reported 28 fatalities, over 60 serious injuries, numerous minor injuries and millions of dollars in lawsuits. During 2000, smoke from wildfires drifting across Interstate 10 caused at least 10 fatalities, five in Florida and five in Mississippi. 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 fog with fog reports at nearby National Weather Service stations. Highway accidents were more likely to be associated with local ground radiation fogs than with widespread advection fogs. Accidents tended to happen when fog created conditions of sudden and unexpected changes in visibility.

There are several reasons why smoke on the highways is a serious problem in the South, some of them interrelated.

Road density: The density of the road network in the South is far greater than in other wildland areas in the country where prescribed fire is in widespread use. The difference in road density between generally forested areas in the west and in the south exists primarily because of land use history. While Western forested lands have always been in forest, in the Southern area, roads and communities remain essentially unchanged from the old agricultural South.

Population in wildland areas: The population dwelling near or within Southern wildlands is greater than that in other areas of the country where prescribed fire is in widespread use (figure 3.3.3). Many people live in close proximity to Southern forests; many more live in areas interfacing fire-prone grasslands and shrublands. Southern States are becoming more urban, and the numbers of tourists driving to resort areas along the Gulf coast, the Atlantic coast, and the Florida peninsula are increasing. Therefore, the number of accidents related to smoke and fog can only be expected to increase.

Climate and meteorology: Factors of Southern climate and meteorology combine to produce airmasses that entrap smoke close to the ground at night. Smoke is most often trapped by either a surface inversion or inversion aloft. This is a condition 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, inversions aloft caused by large-scale subsidence may persist for several days, resulting in a prolonged smoke management problem

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 burn 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 degrees F. in one hour (Achtemeier 1993). Smoke from smoldering heavy fuels can be entrapped near the ground and carried by local drainage winds into these shallow basins where temperatures are colder and relative humidities are higher. Hygroscopic particles within smoke can assist in development of local dense fog. Weak drainage winds of approximately 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.

Problem Smoke: What is being done to Minimize the Problem

As population growth in the South continues, there is an increasing likelihood that more people will be adversely impacted by smoke. Unless methods are found to mitigate the impacts of smoke, increasingly restrictive regulations may curtail the use of prescribed fire, or fire as a management tool may be prohibited. Several approaches are underway to reduce the uncertainty in predicting smoke movement.

- Several states have devised smoke management guidelines to regulate the amount of smoke put into the atmosphere from prescribed burning. The South Carolina Forestry Commission (1998) has established guidelines to define smoke sensitive areas, amounts of vegetative debris that may be burned, and atmospheric conditions suitable for burning this debris.

- The Forestry Weather Interpretation System (FWIS) was developed by the U.S. Forest Service in the late 1970's and early 1980's in cooperation with the southern forestry community (Paul 1981; Paul and Clayton 1978). The system has been enhanced and automated by the Georgia Forestry Commission (Paul et al. 2000) to serve forestry sources in Georgia and clients in other southern states. The GFC provides weather information and forecasts specified for forest districts, and indices used for interpretations for smoke management, prescribed fire, fire danger, and fire behavior. Indices include the Keetch-Byram Drought Index, National Fire Danger Rating System, Ignition component, Burning Index, and Manning Class Day.

- High resolution weather prediction models promise to provide increased accuracy in predictions of wind speeds and directions and mixing heights at time and spatial scales useful for land managers. The Florida Division of Forestry (FDOF) is a leader in the use of high resolution modeling for forestry applications in the South (Brackett et al. 1997). Accurate predictions of sea/land breezes and associated changes in temperature, wind direction, atmospheric stability and mixing height are critical to the success of the FDOF system as much of Florida is located within 20 miles of a coastline. High resolution modeling consortia are also being established by the U.S. Forest Service to serve clients with interests as diverse as fire weather, air quality, oceanography, ecology, and meteorology.
- Several smoke models are in operation or are being developed to predict smoke movement over Southern landscapes. VSMOKE (Lavdas 1996), a Gaussian plume model that assumes level terrain and unchanging winds, predicts smoke movement and concentration during the day. VSMOKE is now part of the FDOF fire and smoke prediction system. It is a screening model that aids land managers in assessing where smoke might impact sensitive targets as part of planning for prescribed burns. PB-Piedmont (Achtemeier 2001) is a wind and smoke model designed to simulate smoke movement 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. PB-Piedmont does not predict smoke concentrations as emissions from smoldering combustion are usually not known. Two sister models are planned, one that will simulate near ground smoke movement near coastal areas influenced by sea/land circulations and the other for the Appalachian mountains.

In summary, the enormous wildland/urban interface and dense road network located in a region where up to six million acres of wildlands per year are subject to prescribed fire combine to make problem smoke the foremost land management-related air quality problem in the South. During the daytime, smoke becomes a problem when it drifts into areas of human habitation. At night, smoke can become entrapped near the ground and, in combination with fog, create visibility reductions that cause roadway accidents. Public outcry regarding problem smoke usually occurs before smoke exposures increase to levels that violate air quality standards. With careful planning and knowledge of local conditions, the fire manager can usually avoid problematic smoke intrusions on the public.

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Smoke Exposure Among Fireline Personnel

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Timothy R. Reinhardt

Wildland firefighting presents many hazards to fireline workers, including inhalation exposure to smoke (Sharkey 1998; Reinhardt and Ottmar 1997; Sharkey 1997). Many experienced fireline personnel consider this to be only an inconvenience, occasionally causing acute cases of eye and respiratory irritation, nausea and headache. Others express concern about long-term health impacts, especially when large-scale fires occur in terrain and atmospheric conditions that force fireline workers to work for many days in smoky conditions. At the present time, no one can say whether there are long-term adverse health effects from occupational smoke exposure. This is because there have been no epidemiological studies to track the health of fireline personnel and compare it with other workers to see if fireline personnel have more or fewer health problems during and after their careers. Until such long-term data are examined to tell us if a problem exists, we can only assess the occurrence of relatively short-term adverse health effects. We can measure fireline worker's exposure to particles and individual chemicals found in smoke and compare these exposures to standards established to protect worker health (Reinhardt and Ottmar 2000; Reinhardt and others 2000; Reinhardt and others 1999). We can evaluate the relative risk of disease among fireline workers based on the exposure data and the potency of the health hazards (Booze and Reinhardt 1996).

Health Hazards in Smoke

Smoke from wildland fires is composed of hundreds of chemicals in gaseous, liquid, and solid forms (Sandberg and Dost 1990; Reinhardt and Ottmar 2000; Reinhardt and others 2000; Sharkey 1998; Sharkey 1997). The chief inhalation hazards for fireline personnel and to the general public when they are exposed to smoke appear to be carbon monoxide and respirable irritants which include particulate matter, acrolein, and formaldehyde.

Carbon Monoxide — Carbon monoxide (CO) has long been known to interfere with the body's ability to transport oxygen. It does this by bonding with hemoglobin, the molecule in the bloodstream which shuttles oxygen from the lungs throughout the body, to form carboxyhemoglobin (COHb). When people are exposed to CO, the time until a toxic level of COHb results can be predicted as a function of CO concentration, breathing rate, altitude, and other factors (Coburn, Forster and Kane 1965). The harder the work and the higher the altitude, the more rapidly COHb forms at a given level of atmospheric CO. At the highest CO levels found in heavy smoke, symptoms of excessive COHb can result in 15 minutes during hard physical labor.

Carbon monoxide causes acute effects ranging from diminished work capacity to nausea, headache, and loss of mental acuity. It has a well-established mechanism of action, causing displacement of oxygen from hemoglobin in the blood and affecting tissues that do not stand the loss of oxygen very well, such as the brain, heart, and unborn children. Fortunately, most of these effects are reversible and CO is rapidly removed from the body, with a half-life on the order of 4 hours. Some studies have linked CO exposure to longer-term heart disease, but the evidence is not clearcut.

Respirable Irritants — Experienced fireline workers can attest to eye, nose and throat irritation at both wildfires and prescribed burns. Burning eyes, runny nose, and scratchy throat are common symptoms in smoky areas at wildland fires, caused by the irritation of mucous membranes. These adverse health effects are symptoms of exposure to aldehydes, including formaldehyde, acrolein, as well as respirable particulate matter ($PM_{2.5}$)—very fine particles less than a few micrometers (µm) in diameter—composed mostly of condensed organic and inorganic carbon (Dost 1991). Other rapid adverse health effects of aldehydes include temporary paralysis of the respiratory tract cilia (microscopic hairs which help to remove dust and bacteria from the respiratory tract) and depression of breathing rates (Kane and Alarie 1977), while over the long term, formaldehyde is considered a potential cause of nasal cancer (U.S. Department of Labor, Occupational Safety and Health Administration 1987).

Adverse health effects of smoke exposure begin with acute, instantaneous eye and respiratory irritation and shortness of breath but can develop into headaches, dizziness and nausea lasting up to several hours. The aldehydes, such as acrolein and formaldehyde, and $PM_{2.5}$ cause rapid minor to severe eye and upper respiratory tract irritation. Total supsended particulate (TSP) also irritates the eyes, upper respiratory tract and mucous membranes, but the larger particulates in TSP do not penetrate as deeply into the lungs as the finer $PM_{2.5}$ particles. Longer-term health effects lasting days to perhaps months have recently been identified among fireline workers, including modest losses of pulmonary function. These include a slightly diminished capacity to breathe, constriction of the repsiratory tract, and hypersensitivity of the small airways (Letts and others 1991; Reh and others 1994).

A discussion of particulate inhalation hazards faced by fireline personnel is incomplete without mentioning crystalline silica, which can be an additional hazard in the presence of smoke. If crystalline silica is a component of the soil at a site, dust stirred up by walking, digging, mop-up, or vehicles may be a significant irritation hazard, and the threat of silicosis (fibrous scarring of the lungs decreasing oxygenation capability) is a possibility.

Evaluation Criteria

On what basis do we decide whether smoke exposure is safe or unsafe? Workplace exposures to health hazards must be evaluated with care for several reasons. First, people vary in their sensitivity to pollutants. Second, personal habits and physical condition are important factors. For example, smokers already commonly experience 5% COHb because of the CO from their cigarettes, thus they may be at greater risk of adverse health effects from additional CO exposure at fires. Assumptions are made by regulatory agencies when establishing exposure limits. These assumptions may not be valid for the wildland fire workplace. For example, the current CO standard was set to protect a sedentary worker in an 8-hour per day job over a working lifetime, not a hard-working fireline worker on a 12-hour/day job for a few summers.

Given these issues, how should we judge the safety of smoke exposure? At a minimum, a fireline worker's inhalation exposures must comply with the occupational exposure limits, called "Permissible Exposure Limits" (PEL's), by the Occupational Safety and Health Administration (OSHA) (U.S. Department of Labor, Occupational Safety and Health Administration 1994). These limits are set at levels considered feasible to attain, and necessary to protect most workers from adverse health effects over their working lifetime. The more stringent exposure limits recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) are the "Threshold Limit Values" (TLVs) (American Conference of Governmental Industrial Hygienists 2000). These are also established to prevent adverse health effects in most workers, but without adjustment for economic feasibility. The ACGIH limits are periodically updated to incorporate the latest scientific knowledge where as many of the PEL's have not been revised since the 1960's. All exposure limits are expressed in terms of a time-weighted average (TWA) exposure, which is an average exposure over the workshift. For health hazards which quickly cause adverse effects from acute exposures, the limits are supplemented by short-term exposure limits (STELs) for 15-minute periods in a workshift and ceiling exposure limits (C), which are not to be exceeded at any time. These various exposure limits are listed in table 3.4.1, along with a third set of "Recommended Exposure Limits" established by the National Institute for Occupational Safety and Health; these also incorporate recent scientific evidence. Depending on the pollutant, the units of measure are either milligrams per cubic meter of air (mg/m^3) or parts per million by volume (ppm). Without a more detailed analysis of a given work/rest regime, adhering to the ACGIH TLV limits should provide reasonable protection for workers.

Table 3.4.1. Occupational exposure limits[a]

Organization	Acrolein (ppm)	Benzene (ppm)	CO (ppm)	HCHO (ppm)	Respirable particulate (mg/m^3)
OSHA Permissible Exposure Limit	0.1 TWA	1.0 TWA 5.0 STEL-C	50 TWA	0.75 TWA 2.0 STEL	5.0 TWA
NIOSH Recommended Exposure Limit	0.1 TWA 0.3 STEL	0.1 TWA 1.0 STEL-C	35 TWA 200 STEL-C	0.016 TWA 0.1 STEL-C	N/A
ACGIH Threshold Limit Value	0.1 C (Skin)	0.5 TWA 2.5 STEL (Skin)	25 TWA	0.3 TWA-C	3.0 TWA

[a] **TWA**: Time Weighted Average; **TWA-C**: Time Weighted Average Ceiling Exposure Limit; **STEL**: Short Term Exposure Limit; **TEL-C**: Short Term Exposure Ceiling Limit; **C**: Ceiling Limit; **N/A**: Not Applicable; **(Skin)** Potential skin contact with vapors or liquid should be considered as well.

Smoke Exposure at Prescribed Burns and Wildfires

Several studies (Reinhardt and Ottmar 1997) have evaluated smoke exposure during prescribed burns by obtaining personal exposure samples, which are collected within a foot of a worker's face (the breathing zone) while they are on the job (figure 3.4.1). One study in particular measured smoke exposure among fireline workers at 39 prescribed burns in the Pacific Northwest. The study found that about 10% of firefighter exposures to respiratory irritants and CO exceeded recommended occupational exposure limits (Reinhardt and others 2000) and could pose a hazard. The actual incidence of illness and mortality among wildland fireline workers has not been systematically studied, but short-term adverse health impacts have been observed among fireline personnel at prescribed fires. A study in 1992-93 found small losses in lung function among 76 fireline personnel working at prescribed burns (Betchley and others 1995).

Between 1992 and 1995 a study of smoke exposure and health effects at wildfires in the western United States found results similar to those at prescribed fires. Exposure to carbon monoxide and respiratory irritants exceeded recommended occupational exposure limits for 5 percent of workers (Reinhardt and Ottmar 2000).

At wildfires where fireline workers encounter concentrated smoke, or moderate smoke over longer times, there is a likelihood that many will develop symptoms similar to those seen at prescribed fires. In 1988, 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

Figure 3.4.1. Bitterroot Hotshot crew member wearing backpack that obtains smoke exposure samples collected within several inches of a worker's face.

were associated with the amount of recent firefighting activity in the study period. The firefighters also reported increased eye and nose irritation and wheezing during the fire season.

Monitoring Smoke Exposure of Fireline workers

During prescribed fire and wildfire exposure studies, it was found that exposure to respiratory irritants could be predicted from measurements of carbon monoxide (Reinhardt and Ottmar 2000). Fire managers and safety officers concerned with smoke exposure among fire crews can use electronic carbon monoxide (CO) monitors to track and prevent overexposure to smoke (figure 3.4.2). Commonly referred to as dosimeters, these lightweight instruments measure the concentration of CO in the air thatfireline personnel breath. Protocols have been developed for sampling smoke exposure among fireline workers with CO dosimeters. These protocols and a basic template have been outlined by Reinhardt and others (1999) for managers and safety officers interested in establishing their own smoke-exposure monitoring program.

Respirator Protection

The Missoula Technology and Development Center (MTDC) has the lead role in studying respiratory protection for fireline workers (Thompson and Sharkey 1966, Sharkey 1997).

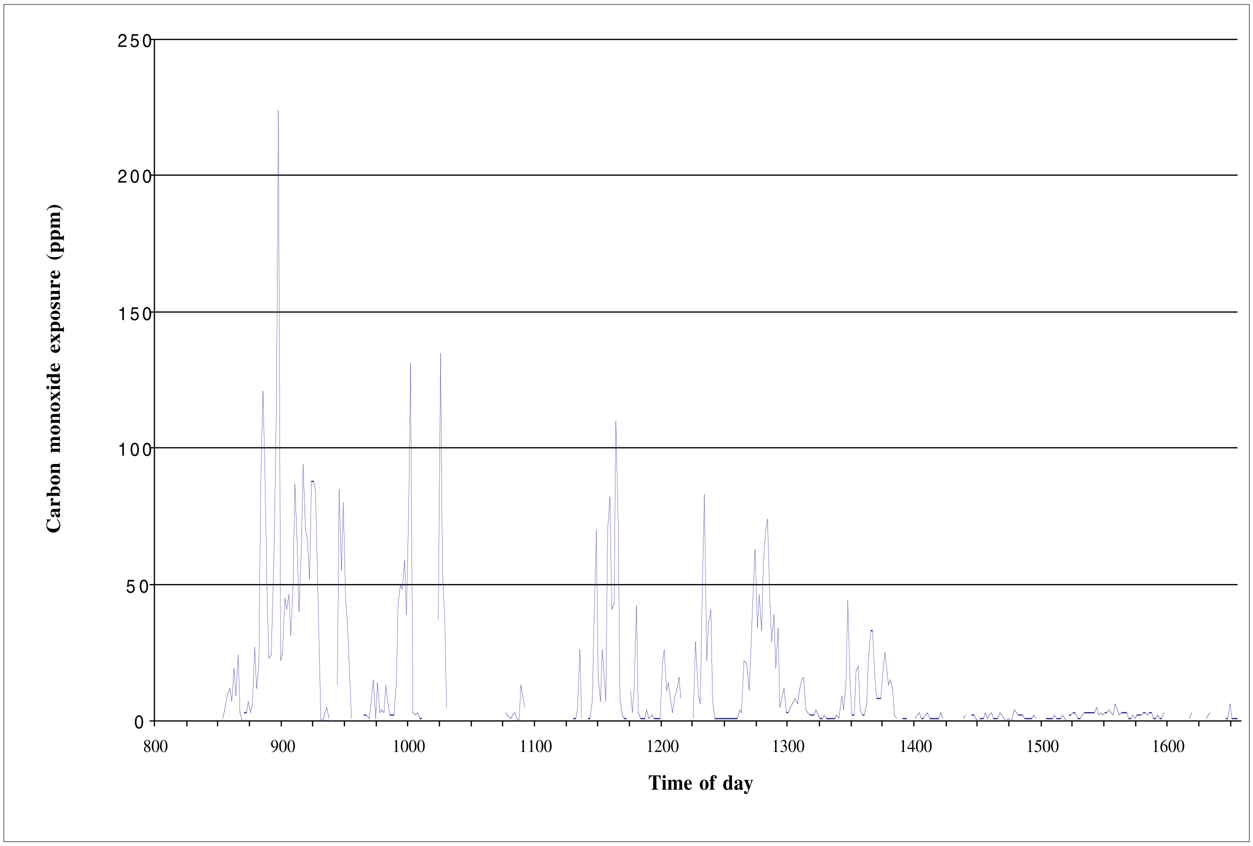

Figure 3.4.2. Carbon monoxide exposure data from a electronic CO data recorder for a fireline worker during a work-shift on a prescribed fire (Reinhardt and others 2000)

Although respirators reduce work capacity, they may have merit under certain circumstances to minimize hazardous exposures. Field evaluations by MTDC found that disposable respirators were acceptable for short-term use but they deteriorated in the heat during several hours of use (Sharkey 1997). Maintenance free half-mask devices were satisfactory, except for the heat stress found with all facemasks. Full-face masks were preferred for the long-term use on prescribed fires because of the eye protection they provided, but workers often complained of headaches, a sign of excess CO exposure since respirators do not eliminate the intake of CO (Sharkey 1997). Full-face respirators protect the eyes, removing eye irritation as an important early warning of exposure to smoke. Any respiratory protection program for fireline workers would require employees to be instructed and trained in the proper use and limitations of the respirators issued to them.

Management Implications

Evidence to date suggests that fireline workers exceed recommended exposure limits during prescribed burns and wildfires less than 10 percent of the time (Reinhardt and others 2000; Reinhardt and Ottmar 2000). The concept that few fireline personnel spend a working lifetime in the fire profession and should be exempt from occupational exposure standards which are set to protect workers over their careers is little comfort to those who do, and irrelevant for irritants and fast-acting hazards such as CO. Most of the exposure limits that are exceeded are established to prevent acute health effects, such as eye and respiratory irritation, headache, nausea and angina. An exposure standard specifically for fireline workers, and appropriate respiratory protection, needs to be developed. In addition, a long-term program to manage smoke exposure at wildland fires is needed (Sharkey 1997). The program could include: 1) hazard awareness training; 2) implementation of practices to reduce smoke exposure; 3) routine CO monitoring with electronic dosimeters (Reinhardt and others 1999); 4) improved record keeping on accident reports to include separation of smoke related illness among fireline workers and fire camp personnel; and 4) implementing and training for an OSHA-compliant respirator program to protect fireline personnel from respiratory irritants and CO when they must work in smoky conditions.

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Chapter 4

REGULATIONS

Regulations For Smoke Management

Janice L. Peterson

Some of the components of smoke from prescribed fire are regulated air pollutants. And, as with any other rule or regulation, fire managers must understand and follow federal, state, and local regulations designed to protect the public against possible negative effects of air pollution.

Air pollution is defined as the presence in the atmosphere of a substance or substances added directly or indirectly by a human act, in such amounts as to adversely affect humans, animals, vegetation, or materials (Williamson 1973). Air pollutants are classified into two major categories: **primary** and **secondary**. **Primary pollutants** are those directly emitted into the air. Under certain conditions, primary pollutants can undergo chemical reactions within the atmosphere and produce new substances known as **secondary pollutants**.

Emissions from prescribed fire are managed and regulated through an often-complex web of interrelated laws and regulations. The overarching law that is the foundation of air quality regulation across the nation is the Federal Clean Air Act (Public Law 95-95).

Federal Clean Air Act

In 1955, Congress passed the first Federal Clean Air Act with later amendments in 1967, 1970, 1977, and 1990. The Clean Air Act is a legal mandate designed to protect public health and welfare from air pollution. States develop specific programs for implementing the goals of the Clean Air Act through their State Implementation Plans (SIP's). States may develop programs that are more restrictive than the Clean Air Act requires but never less. Burners must know the specifics of state air programs and how fire emissions are regulated to responsibly conduct a prescribed fire program.

Roles and Responsibilities

Although the Clean Air Act is a federal law and therefore applies to the entire country, the states do much of the work of implementation. The Act recognizes that states should have the lead in carrying out provisions of the Clean Air Act, since appropriate and effective design of pollution control programs requires an understanding of local industries, geography, transportation, meteorology, urban and industrial development patterns, and priorities.

The Clean Air Act gives the Environmental Protection Agency (EPA) the task of setting limits on how much of various pollutants can be in the air where the public has access[1] (ambient air). These air pollution limits are the National Ambient Air Quality Standards or NAAQS and

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

are intended to be established regardless of possible costs associated with achieving them, though EPA is allowed to consider the costs of controlling air pollution during the implementation phase of the NAAQS in question. In addition, EPA develops policy and technical guidance describing how various Clean Air Act programs should function and what they should accomplish. 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. 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. The individual states and tribes can require more stringent pollution standards, but cannot weaken pollution goals set by EPA. The Environmental Protection Agency must approve each SIP/TIP, and if a proposed or active SIP/TIP is deemed inadequate or unacceptable, EPA can take over enforcing all or parts of the Clean Air Act requirements for that state or tribe through implementation of a Federal Implementation Plan or FIP (figure 4.1.1).

National Ambient Air Quality Standards

The primary purpose of the Clean Air Act is to protect humans against negative health or welfare effects from air pollution. National Ambient Air Quality Standards (NAAQS) are defined in the Clean Air Act as amounts of pollutant above which detrimental effects to public health or welfare may result. NAAQS are set at a conservative level with the intent of protecting even the most sensitive members of the public including children, asthmatics, and persons with cardiovascular disease. NAAQS

FEDERAL CLEAN AIR ACT

EPA Responsibilities
1. Establish NAAQS.
2. Develop policy and technical guidance for states/tribes.
3. Approve SIPs/TIPs and control measures.
4. Backup to state enforcement.
5. Administer air grant money.

STATE AND TRIBAL IMPLEMENTATION PLANS

State and Tribe Responsibilities
1. Develop SIPs or TIPs that meet Clean Air Act requirements and submit to EPA for approval.
2. Implement SIP/TIP programs.
3. Develop and maintain emission inventories.
4. Conduct air quality monitoring.
5. Establish and operate a permitting program for new and existing air pollution sources.

Figure 4.1.1. Role of EPA and the states and tribes in Clean Air Act implementation.

have been established for the following criteria pollutants: particulate matter[2] (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone, carbon monoxide and lead (table 4.1.1). Primary NAAQS are set at levels to protect public health; secondary NAAQS are to protect public welfare. The standards are established for different averaging times, for example, annual, 24-hour, and 3-hour.

The major pollutant of concern in smoke from wildland fire is fine particulate matter, both PM_{10} and $PM_{2.5}$. Studies indicate that 90 percent of smoke particles emitted during wildland burning are PM_{10} and about 90 percent of PM_{10} is $PM_{2.5}$ (Ward and Hardy 1991). The most recent human health studies on the effects of particulate matter indicate that it is fine particles, especially $PM_{2.5}$, that are largely responsible for health effects including

Table 4.1.1. National Ambient Air Quality Standards.

	Standard [a]	
Pollutant / Time-weighted period	Primary	Secondary
PM_{10}		
Annual Arithmetic Mean	50 $\mu g/m^3$	50 $\mu g/m^3$
24-hour Average	150 $\mu g/m^3$	150 $\mu g/m^3$
$PM_{2.5}$		
Annual Arithmetic Mean	15 $\mu g/m^3$	15 $\mu g/m^3$
24-hour Average	65 $\mu g/m^3$	65 $\mu g/m^3$
Sulfur Dioxide (SO_2)		
Annual Average	0.03 ppm	– –
24-hour Average	0.14 ppm	– –
3-hour Average	– –	0.50 ppm
1-hour Average	– –	– –
Carbon Monoxide (CO)		
8-hour Average	9 ppm	– –
1-hour Average	35 ppm	– –
Ozone (O_3)		
1-hour Average	0.12 ppm	0.12 ppm
8-hour Average	0.08 ppm	0.08 ppm
Nitrogen Dioxide (NO_2)		
Annual Average	0.053 ppm	0.053 ppm
Lead (Pb)		
Quarterly Average	1.5 $\mu g/m^3$	1.5 $\mu g/m^3$

[a] $\mu g/m^3$ = micrograms per cubic meter; ppm = parts per million

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[2] 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.

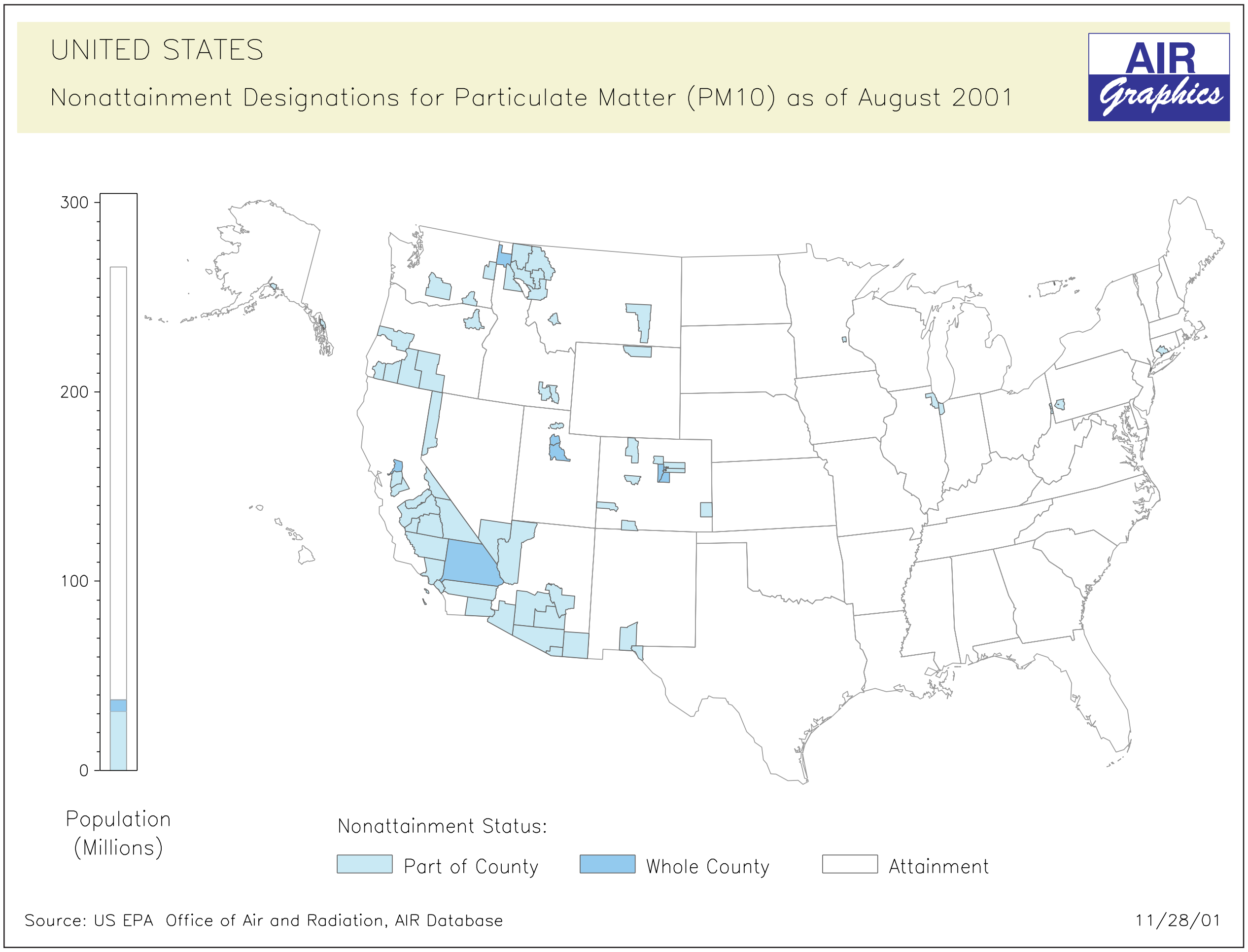

Figure 4.1.2. PM_{10} nonattainment areas as of August 2001. See the EPA AIR*Data* web page for current nonattainment status for PM_{10} and al other criteria pollutants (http://www.epa.gov/air/data/mapview.html).

mortality, exacerbation of chronic disease, and increased hospital admissions (Dockery and others 1993, EPA 1996).

An area that is found to be in violation of a primary NAAQS is labeled a non-attainment area (figure 4.1.2). An area once in non-attainment but recently meeting NAAQS, and with appropriate planning documents approved by EPA, is a maintenance area. All other areas are attainment or unclassified (due to lack of monitoring). State air quality agencies can provide up-to-date locations of local non-attainment areas[3]. States are required through their SIP's to define programs for implementation, maintenance, and enforcement of the NAAQS within their boundaries. A non-attainment designation is a black mark on the states air agency's ability to protect citizens from the negative effects of air pollution so states generally develop aggressive programs for bringing non-attainment areas into compliance with clean air goals. Wildland fire in and near non-attainment areas will be scrutinized to a greater degree than in attain-

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[3] $PM_{2.5}$ is a newly regulated pollutant so attainment/non-attainment status has not yet been determined. Monitoring must take place for at least 3 years before a designation can be made.

ment areas (and may be subject to General Conformity rules, see section 4.3: Federal Land Management-Special Requirements). Extra preplanning, documentation, and careful scheduling of wildland fires will likely be required to minimize smoke effects in the non-attainment area to the greatest extent possible. In some cases, the use of fire may not be possible if significant impacts to a non-attainment area are likely.

Natural Events Policy

PM_{10} NAAQS exceedences caused by natural events are not counted toward non-attainment designation if a state can document that the exceedance was truly caused by a natural event and if the state then prepares a Natural Events Action Plan (NEAP) to address human health concerns during future events[4]. Natural events are defined by this policy as wildfire, volcanic and seismic events, and high wind events. Prescribed fires used to mimic the natural role of fire in the ecosystem are not considered natural events under this policy. In response to this potential conflict of terms, the Interim Air Quality Policy on Wildland and Prescribed Fires (EPA 1998) states that EPA will exercise its discretion not to redisignate an area as non-attainment if the evidence is convincing that fires managed for resource benefits caused or significantly contributed to violations of the daily or annual $PM_{2.5}$ or PM_{10} standards and the state has a formal smoke management program (see Section 4.2: State Smoke Management Programs for more information).

A NEAP is developed by the state air pollution control agency in conjunction with the stakeholders affected by the plan. States should include input from Federal, state, and private land managers in areas vulnerable to fire when developing a wildland fire NEAP. Also, agencies responsible for suppressing fires, local health departments, and citizens in the affected area should be involved in developing the plan. The NEAP should include documented agreements among stakeholders as to planned actions and the parties responsible for carrying out those actions.

A wildfire NEAP should include commitments by the state and stakeholders to:

1. Establish public notification and education programs.
2. Minimize public exposure to high concentrations of PM_{10} due to future natural events such as by:
   - identifying the people most at risk,
   - notifying the at-risk public that an event is active or imminent,
   - recommending actions to be taken by the public to minimize their pollutant exposure,
   - suggesting precautions to take if exposure cannot be avoided.
3. Abate or minimize controllable sources of PM_{10} including the following:
   - prohibition of other burning during pollution episodes caused by wildfire,
   - proactive efforts to minimize fuel loadings in areas vulnerable to fire,
   - planning for prevention of NAAQS exceedances in fire management plans.

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[4] Nichols, Mary D. 1996. Memorandum dated May 30 to EPA Regional Air Directors. Subject: Areas Affected by PM_{10} Natural Events. Available from the EPA Technology Transfer Network, Office of Air and Radiation Policy and Guidance at http://www.epa.gov/ttn/oarpg.

4. Identify, study, and implement practical mitigating measures as necessary.
5. Periodic reevaluation of the NEAP.

Preparation of a NEAP provides the opportunity for land managers to formally document, in cooperation with state air agencies, that it is appropriate to consider prescribed fire a prevention, control, and mitigation measure for wildfire (see item 4 above). Prescribed fire can be used to minimize fuel loadings in areas vulnerable to fire so that future wildfires can be contained in a smaller area and will produce less emissions. This can lead to a greater understanding by state air agencies of the potential air quality benefits from some types of prescribed fire in certain ecosystems. A recent NEAP prepared for the Chelan county area of Washington State accomplished this goal[5]. The Chelan County NEAP recognizes planned efforts by the Wenatchee National Forest to reduce fuel loadings through thinning, pruning of lower branches, and careful use of prescribed fire as ways to minimize public exposure to particulate matter during wildfire season.

Hazardous Air Pollutants

Hazardous air pollutants or (HAPs) are identified in Title III of the Clean Air Act Amendments of 1990 (Public Law 101-549) as 188 different pollutants "which present, or may present, through inhalation or other routes of exposure, a threat of adverse human health or environmental effects whether through ambient concentrations, bioaccumulation, deposition, or other routes." The listed HAPs are substances which are known or suspected to be carcinogenic, mutagenic, teratogenic, neurotoxic, or which cause reproductive dysfunction. Criteria pollutants (the six pollutants that are regulated through established National Ambient Air Quality Standards) are excluded from the list of HAPs.

De minimis Emission Levels

Air quality regulations allow omission of certain pollution sources in air quality impact analyses if they are considered very minor and are certain to have no detrimental effects. These sources are considered to emit pollutant amounts below de minimis levels. For example, burning a slash pile with less than 100 tons of material is not subject to permit or regulation in some areas. Emissions below de minimis levels are often excluded from air quality regulations so this is an important concept to define in reference to wildland fire. De minimis levels have been defined for many industrial sources but little guidance is available for many wildland activities including prescribed fire. Some states have locally defined de minimis levels for example in Utah, fires less than 20 acres per day in size and emitting less than 0.5 ton of total particulate per day are considered de minimis and can be ignited without permit if burners register the project and comply with clearing index procedures. Definition of de minimis levels is a topic that needs further discussion between wildland fire managers and regulatory agencies so guidance can be developed at the local and/or national level.

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[5] Washington Department of Ecology. June 1997. Natural event action plan for wildfire particulate matter in Chelan County, Washington. 21p. Available from the Washington Department of Ecology, PO Box 47600, Olympia, WA 98504-7600.

Prevention of Significant Deterioration

Another provision of the Clean Air Act that sometimes comes up when discussing wildland burning activities is the Prevention of Significant Deterioration provisions or PSD. The goal of PSD is to prevent areas that are currently cleaner than is allowed by the NAAQS from being polluted up to the maximum ceiling established by the NAAQS. States and tribes use the permitting requirements of the PSD program to manage and limit air pollution increases over a baseline concentration. A PSD baseline is the pollutant concentration at a point in time when the first PSD permit was issued for the airshed. New or modified major air pollution sources must apply for a PSD permit prior to construction and test their proposed emissions against allowable PSD increments.

Three air quality classes were established by the Clean Air Act, PSD provisions, including Class I, Class II, and Class III. Class I areas are subject to the tightest restrictions on how much additional pollution, or increment, can be added to the air. Class I areas include Forest Service wildernesses and national memorial parks over 5000 acres, National parks exceeding 6000 acres, and international parks, all of which must have been in existence as of August 7, 1977, plus later expansions to these areas (figure 4.1.3). These original Class I areas are declared “mandatory” and can never be redesignated to another air quality classification. In addition, a few Indian tribes have redesignated their lands to Class I. Redesignated Class I areas are not mandatory Class I areas so are not automatically protected by all the same rules as defined by the Clean Air Act unless a state or tribe chooses, through a SIP or TIP, to do so. Since no areas have ever been designated Class III, all other lands are Class II, including everything from non-Class I wildlands to urban areas.

Historically, EPA has regarded smoke from wildland fires as temporary and therefore not subject to issuance of a PSD permit, but whether or not wildland fire smoke should be considered when calculating PSD increment consumption or PSD baseline was not defined. EPA recently reaffirmed that states could exclude managed fire emissions from increment analyses, provided the exclusion does not result in permanent or long-term air quality deterioration (EPA 1998). States are also expected to consider the extent to which a particular type of burning activity is truly temporary, as opposed to an activity that can be expected to occur in a particular area with some regularity over a period of time. Oregon is the only state that has thus far chosen to include prescribed fire emissions in PSD increment and baseline calculations.

Visibility

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 manmade air pollution” (Public Law 95-95). States are required to develop implementation plans that make “reasonable progress” toward the national visibility goal.

Atmospheric visibility is influenced by scattering and absorption of light by particles and gases. Particles and gases in the air can obscure the clarity, color, texture, and form of what we see. The fine particles most responsible for visibility impairment are sulfates, nitrates, organic compounds, elemental carbon (or soot), and soil dust. Sulfates, nitrates, organic carbon, and soil tend to scatter light, whereas elemental carbon tends to absorb light. Wildland fire

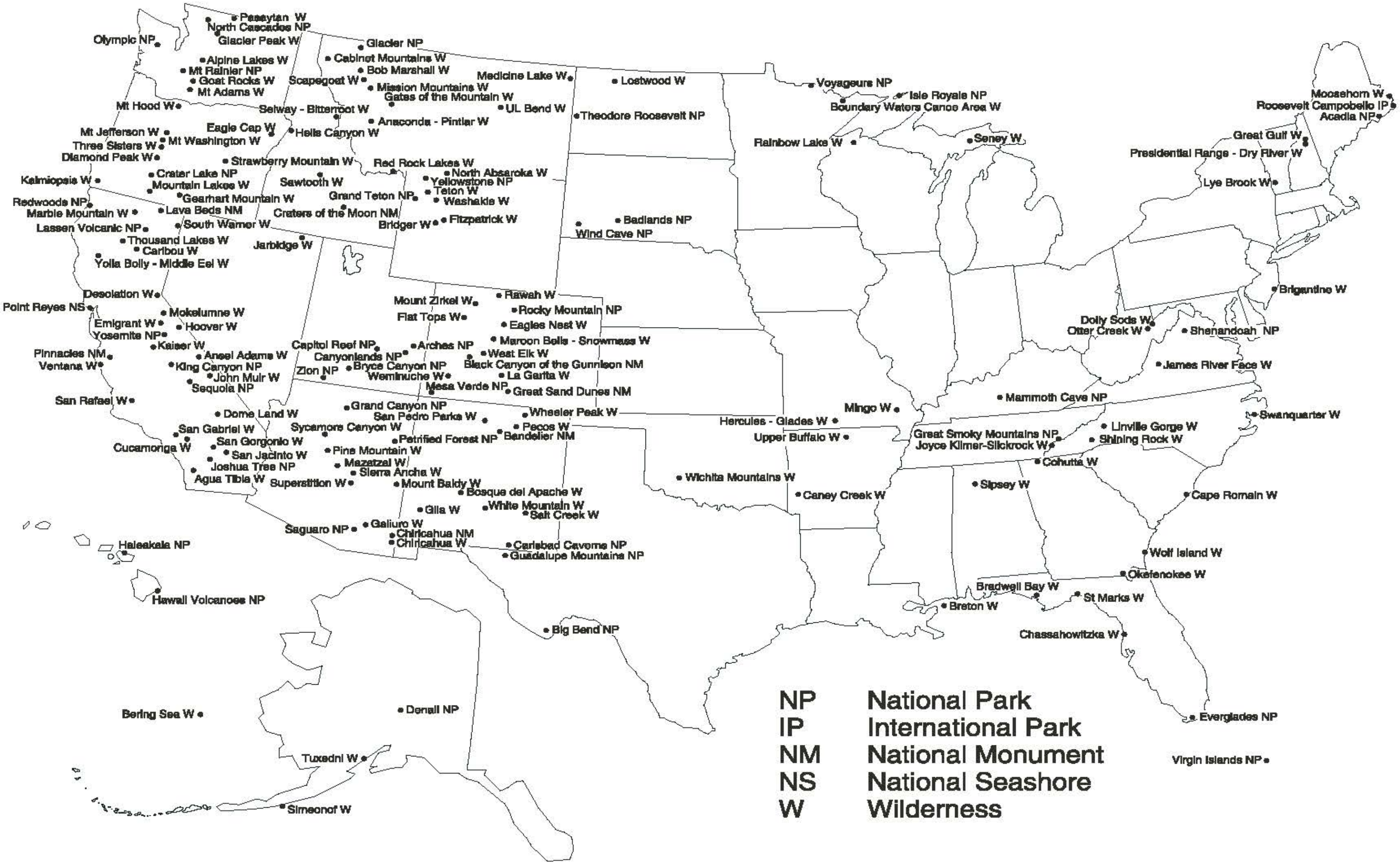

Figure 4.1.3. Mandatory Cass I areas.

smoke is primarily made up of elemental carbon, organic carbon, and particulate matter. Fine particles ($PM_{2.5}$) are more efficient per unit mass than coarse particles (PM_{10} and larger) at causing visibility impairment. Naturally occurring visual range in the East is estimated to be between 60 and 80 miles, while natural visual range in the West is between 110-115 miles (Trijonis and others 1991). Currently, visual range in the Eastern US is about 15 to 30 miles and about 60 to 90 miles in the Western US (40 CFR Part 51). The theoretical maximum visual range with nothing in the air except air molecules is about 240 miles.

Federal Land Managers (FLMs) have somewhat conflicting roles when it comes to protecting visibility in the Class I areas they manage. On the one hand, FLMs are given the responsibility by the Clean Air Act for reviewing PSD permits of major new and modified stationary pollution sources and commenting to the state on whether there is concern for visibility impacts (or other resource values) in Class I areas downwind of the proposed pollution source. In this case FLMs play a proactive role in air pollution prevention. On the other hand, however, FLMs also use wildland fire, which emits visibility-impairing pollutants. In this case the FLM is the polluter and is often in the difficult position of trying to explain why wildland burning smoke may be acceptable in wilderness whereas other types of air pollution are not. The answer to this dilemma is that wildernesses are managed to preserve and protect natural conditions and processes. So in this context, smoke and visibility impairment from wildland fire that closely mimics what would occur naturally is generally viewed as acceptable under wilderness management objectives, whereas visibility impairment from “unnatural” pollutants and “unnatural” pollution sources is not. The key to successfully promoting this distinction is an honest and scientific definition of how much, and what types, of fire are “natural” that FLMs, air quality regulators, and the public can agree upon. This is a critical area of future cooperation in smoke management and air quality regulation.

Regional Haze

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 single, very large pollution source. Until recently, the only regulations for visibility protection addressed impairment that is reasonably attributable to a permanent, large emission source or small group of large sources. Recently, 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 call for states to establish goals for improving visibility in Class I national parks and wildernesses and to develop long-term strategies for reducing emissions of air pollutants that cause visibility impairment. Wildland fire is one of the sources of regional haze covered by the new rules.

Current data from a national visibility monitoring network (Sisler and others 1996) do not show fire to be the predominant source of visibility impairment in any Class I area (40 CFR Part 51). Emissions from fire are an important episodic contributor to atmospheric loading of visibility-impairing aerosols, including organic carbon, elemental carbon, and particulate matter. Certainly the contribution to visibility impairment from fires can be substantial over short periods of time, but fires in general, occur relatively infrequently and thus have a lesser contribution to long-term averages. Fire events contribute less to persistent visibility impairment than sources with emissions that are more continuous.

Reasonable Progress

The visibility regulations require states to make "reasonable progress" toward the Clean Air Act goal of "prevention of any future, and the remedying of any existing, impairment of visibility…". The regional haze regulations did not define visibility targets, but instead gave the states flexibility in determining reasonable progress goals for Class I areas. States are required to conduct analyses to ensure that they consider the possibility of setting an ambitious reasonable progress goal, one that is aimed at reaching natural background conditions in 60 years. The rule requires states to establish goals for each affected Class I area to 1) improve visibility on the haziest 20 percent of days and 2) ensure no degradation occurs on the clearest 20 percent of days over the period of each implementation plan.

The states are to analyze and determine the rate of progress needed for the implementation period extending to 2018 such that, if maintained, this rate would attain natural visibility conditions by the year 2064. To calculate this rate of progress, the state must compare baseline visibility conditions to estimate natural visibility conditions in Class I areas and determine the uniform rate of visibility improvement that would need to be maintained during each implementation period in order to attain natural visibility conditions by 2064. Baseline visibility conditions will be determined from data collected from a national network of visibility monitors representing all Class I areas in the country for the years 2000 to 2004. The state must determine whether this rate and associated emission reduction strategies are reasonable based on several statutory factors. If the state finds that this rate is not reasonable, it must provide a demonstration supporting an alternative rate.

Regional Visibility Protection Planning

Regional haze is, by definition, from widespread, diverse sources. The regional haze rule encourages states to work together to improve visibility. The Environmental Protection Agency (EPA) has encouraged the 48 contiguous states to engage in regional planning to coordinate development of strategies for controlling pollutant emissions across a multi-state region. This means that groups of states will be addressing groups of "Class I" areas through established organizations. In the West, the Western Regional Air Partnership, sponsored through the Western Governors' Association and the National Tribal Environmental Council is coordinating regional planning and needed technical assessments. In the Eastern U.S., four formal groups address regional planning issues: CENRAP (Central States Response Air Partnership), OTC (Ozone Transport Commission), and VISTAS (Visibility Improvement State and Tribal Association of the Southeast) and the Midwest Regional Planning Organization (figure 4.1.4).

Natural Visibility

Air quality regulations often distinguish between human-caused and natural sources of air pollution. Natural sources of air pollution generally are not responsive to control efforts,

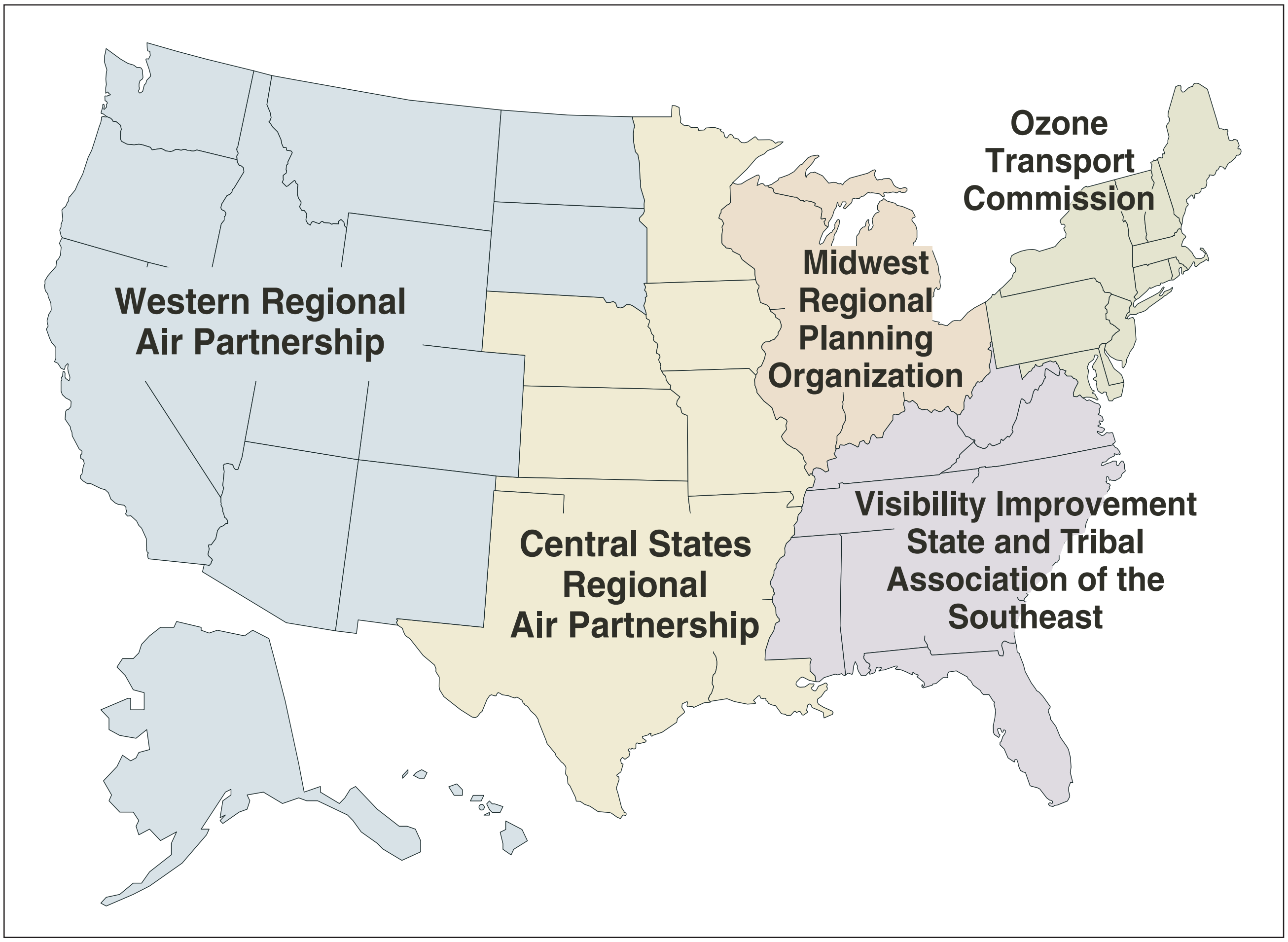

Figure 4.1.4. Regional air quality planning groups.

and state air regulatory agencies manage and monitor them in a manner different from human-caused air pollution. The definition of natural sources of air pollution includes volcanoes, dust, and wildfires. The regional haze regulations propose to measure progress towards achieving natural visibility conditions, but how do we define natural visibility impairment when considering wildland fires as a source?

In most parts of the country, much less fire occurs today than historically. Should natural visibility consider the contribution to haze from these historic, natural fires? And if so, how will we reconcile a definition of natural visibility that includes historic levels of smoke with the need to improve air quality and meet the national visibility goal? Previously, wildfires have been considered natural sources while prescribed fires have generally been classified as human-caused for the purpose of air regulation. That classification is proving to be unsatisfactory because aggressive wildfire suppression and land use changes have made the current pattern of wildfires anything but natural. Are some prescribed fires destined to be categorized as natural emission sources along with the resulting visibility impairment, and how much prescribed burning should be considered natural?

How Much Smoke is Natural?

Few wildlands in the United States are without significant modification by humans, whether by resource utilization, fire suppression, or invasion of exotic species. So in defining natural emissions some possible definitions of natural fire may include: 1) historic fire frequency in vegetation types present on wildlands today, 2) historic fire frequency only on wildlands where the current overriding management goal is to maintain natural ecosystem processes, 3) human-defined fire needed on wildlands to maintain natural ecosystem processes, 4) human-defined fire needed to maximize wildfire controllability, and 5) prescribed fire needed to minimize the sum of prescribed fire and wildfire emissions.[6]

Most any approach to estimating natural emissions from fire will look to historic fire frequencies for preliminary guidance. Historic fire frequency can be defined in numerous ways and called by various terms (fire frequency, fire return interval, natural fire rotation, ecological fire rotation). Fire frequency can vary greatly by vegetative cover type, site-specific meteorology, stand age, aspect, and elevation. Fire frequency is often defined as a range that reflects site variation. For example, a given area of ponderosa pine ecosystem may have a defined fire rotation of 7 to 15 years. The drier southwestern slopes will have an average fire rotation of approximately 7 years, whereas the northern slopes will have an average fire rotation of approximately 15 years. Even within the average site fire rotation interval there can be significant temporal variation depending on weather and ignition potential.

Any change in fire frequency will eventually be expressed by change in the ecosystem. The natural fire regime for an ecosystem may not be the same as the historic fire regime, because neither the current fuel condition nor the climate is the same as in the past. Nor will they be the same in the future.

Wildland fire is highly variable in place and time. Historic fire regimes are well known and described for most major ecosystem types. These historic frequencies can be used as a starting point for definition of natural emissions although, in many parts of the country,historic fire frequency would likely result in much more emissions than would be acceptable in today’s society (figure 4.1.5). Prescribed burning in the southeastern US is, in some cases, near the natural rotation and the public has been largely tolerant of the smoke. Burning to maintain natural ecosystem conditions may not need to occur any more frequently than the middle to upper end of the historical average fire frequency. Some areas may be maintained adequately even if the infrequent end of the natural fire frequency range is increased although potential long-term effects of this sort of ecological manipulation are uncertain. On the other hand, the environment is not static. Climate change, for example, may change the frequency of fire necessary to maintain any given ecosystem in the future or make retention of the present ecosystem impossible.

Conclusions

Because smoke from fire can cause negative effects to public health and welfare, air quality protection regulations must be understood and followed by responsible fire managers. Likewise, air quality regulators need an understanding of how and when fire use decisions are

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[6] Peterson, Janice; Sandberg, David, Leenhouts, Bill. 1998. Estimating natural emissions from wildland and prescribed fire. An unpublished technical support document to the EPA Interim Air Quality Policy on Wildland and Prescribed Fires. April 23, 1998. (Available from the author).

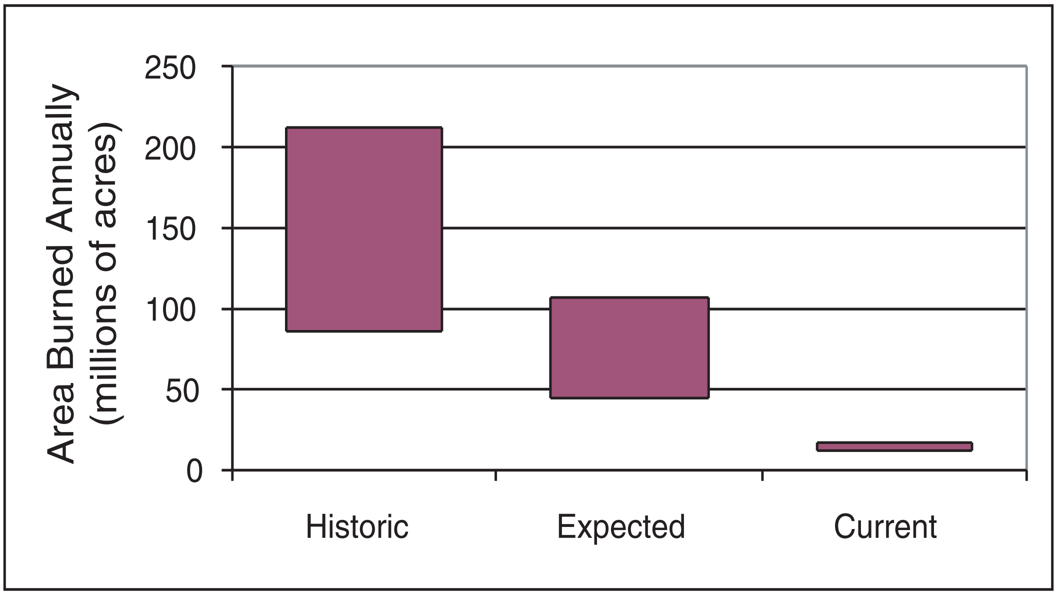

Figure 4.1.5. Estimates of the range of annual area burned in the conterminous United States pre-European settlement (Historic), applying presettlement fire frequencies to present land cover types (Expected), and burning (wildland and agriculture) that has occurred during the recent past (Current). Source: Leenhouts (1998).

Table 4.1.2. Recommended cooperation between wildland fire managers and air quality regulators depending on air quality protection instrument.

Air Quality Protection Instrument	Cooperation[a]	
	Wildland Fire Managers	Air Quality Regulators
NAAQS	Aware	Lead
Attainment Status	Aware	Lead
SIP Planning and Development	Involved	Lead
Conformity	Involved	Lead
Smoke Management Programs	Partner	Lead
Visibility Protection	Involved	Lead
Regional Planning Groups	Partner	Lead
Natural Emissions	Partner	Lead
Natural Events Action Plan (NEAP)	Partner	Lead
Land use planning	Lead	Involved
Project NEPA documents	Lead	Involved
Other Fire Planning Efforts	Lead	Involved

[a] **Lead**: Responsibility to initiate, bring together participants, complete, and implement the particular air quality protection instrument.

Partner: Responsibility to fully participate with Lead organization toward development and implementation of the air quality protection instrument in a nearly equal relationship.

Involved: Responsibility to participate in certain components of development and implementation of the air quality protection instrument although not at full partner status.

Aware: Responsibility to have a complete working knowledge of the air quality protection instrument but likely little or no involvement in it's development or daily implementation.

made and should become involved in fire and smoke management planning processes, including the assessment of when and how alternatives to fire will be used. Many fire and air quality issues need further work including, definition of de minimis emission levels from fire, prescribed fire as BACM for wildfire, clarification of the difference between visibility impairment from fire vs. industrial sources, amounts of smoke from natural ecosystem burning that is acceptable to the public, and definition of natural visibility. Cooperation and collaboration between wildland fire managers and air quality regulators on these and other issues is of great importance. Table 4.1.2 contains recommendations for various types of cooperation by these two groups depending on the applicable air quality protection instrument.

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State Smoke Management Programs

John E. Core

Introduction

Smoke management programs establish a basic framework of procedures and requirements for managing smoke from prescribed fires. The purposes of a smoke management program are to minimize smoke entering populated areas, prevent public safety hazards (such as smoke impairment on roadways or runways), avoid significant deterioration of air quality and National Ambient Air Quality Standards (NAAQS) violations, and to avoid visibility impacts in Class I areas. Smoke management is increasingly recognized as a critical component of a state's air quality program for protecting public health and welfare, while still providing for necessary wildland burning. Sophisticated programs for coordination of burning both within a state and across state boundaries are vital to obtain and continue public support of burning programs. States typically develop these programs, with cooperation and participation from stakeholders. Smoke management programs developed through partnerships are much more effective at meeting resource management goals, protecting public health, and meeting air quality objectives.

Usually, either the state or tribal natural resources agency or air quality agency is responsible for developing and administering the smoke management program. Occasionally, a program may be administered by a local agency and apply to a subset of a state. Generally the administering agency will give daily approval or disapproval of individual bums. All burning may be subject to permit, or only burning exceeding an established de minimis level that could be based on projections of acres burned, tons consumed, or emissions. Multi-day burns may be subject to daily reassessment and reapproval to ensure smoke does not violate program goals.

An advanced smoke management program will evaluate individual and multiple bums; coordinate all prescribed fire activities in an area; consider cross-boundary impacts; and weigh burning decisions against possible health, visibility, and nuisance effects.

With increasing use of fire for forest health and ecosystem management, interstate and interregional coordination of burning will be necessary to prevent poor air quality episodes. Every state has unique needs and issues driving development of smoke management programs so a specific program cannot be defined that is applicable to all. State and land manager development of, and participation in, an effective, locally specific smoke management program will go a long way to build and maintain public acceptance of prescribed burning.

EPA Interim Fire Policy - Recommendations on Smoke Management Programs

In the Interim Air Quality Policy on Wildland and Prescribed Fires (EPA 1998), EPA urges State and tribal air quality managers to collaborate with wildland owners and managers to mitigate the air quality impacts that could be caused by the increase of fires managed to achieve resource benefits. The EPA especially urges development and implementation of at least basic smoke management programs when conditions indicate that fires will adversely impact the public. In exchange for states and tribes proactively implementing smoke management programs, EPA intends to exercise its discretion not to redesignate an area as nonattainment if the evidence is convincing that fires managed for resource benefits caused or significantly contributed to violations of the daily or annual $PM_{2.5}$ or PM_{10} standards. Rather, EPA will call on the state or tribe to review the adequacy of the smoke management program in collaboration with wildland owners and managers and make appropriate improvements to mitigate future air quality impacts. The state or tribe must certify in a letter to the EPA Administrator that at least a basic program has been adopted and implemented in order to receive special consideration for NAAQS violations under this policy.

To be certifiable by EPA, a smoke management program should include the following basic components, some of which are the responsibility of the administering agency and some of which are provided by the land manager:

1. Process for assessing and authorizing burns.

   Reporting of burn plan information to administering agency (not mandatory for states to be compliant with EPA recommendations for a certified smoke management program, but is highly recommended especially for fires greater than a predefined de minimis size), including the following information:

   - location and description of the area to be burned,
   - personnel responsible for managing the fire,
   - type of vegetation to be burned,
   - area (acres) to be burned,
   - amount of fuel to be consumed (tons/acre),
   - fire prescription including smoke management components,
   - criteria the fire manager will use for making burn/no burn decisions, and
   - safety and contingency plans addressing smoke intrusions.

2. Plan for long-term minimization of emissions and impacts, including promotion of alternatives to burning and use of emission reduction techniques.
3. Smoke management goals and procedures to be described in burn plans (when burn plan reporting is required):
   - actions to minimize fire emissions,
   - smoke dispersion evaluation,
   - public notification and exposure reduction procedures to be implemented during air pollution episodes or smoke emergencies, and
   - air quality monitoring.
4. Public education and awareness.
5. Surveillance and enforcement of smoke management program compliance.
6. Program evaluation and plan for periodic review.

7. Optional programs (for example, special protection zones or buffers or performance standards).

Smoke Management Programs

Prescribed burning programs across the nation use both emission reduction methods and smoke management techniques (avoidance and dilution) to minimize the impacts of smoke on air quality as well as concerns about public exposure to smoke. The complexity of these programs varies greatly from state to state, ranging from the comprehensive and well-funded programs found in Oregon and Washington to the far simpler program found in Alaska. While the comprehensive programs gather detailed information on all burning activity needed for burn coordination, emission inventory calculation purposes, and to assure compliance with air quality regulations, many prescribed fire practitioners work independently with mainly self-imposed constraints. In most cases, smoke management programs focus primarily on achieving land management objectives. Other issues in priority order are: minimizing public exposure to smoke, achieving and/or maintaining healthful air quality, and achieving emission reductions. Often, emission reductions are only an important side benefit of a burning technique selected for another management purpose. Few existing smoke management programs quantify emission reductions achieved either intentionally or unintentionally. Table 4.2.1 summarizes a few of the features of the smoke management programs. Significantly, only Oregon and Washington have active, on-going programs to calculate pollutant emissions and pollutant emission reductions on a daily basis for each burn. The Utah program has been certified under the EPA Interim Air Quality Policy on Wildland and Prescribed Fire; Nevada and Florida have incorporated the Policy into the design of their programs. Oregon and Washington have adopted special provisions for prescribed burning for forest health restoration purposes. The Oregon program includes an emissions cap and offset program for Eastern Oregon burning. Although most state air agencies estimate annual emissions from land manager records, only those states that calculate emissions on a daily basis, burn-by-burn, are listed as having an emissions calculation program. The adequacy of each program to the specific state situation is not addressed in table 4.2.1. That issue is best addressed by the stakeholders of each program and the citizens of the state.

A summary of smoke management program reporting attributes related to emissions tracking is shown in table 4.2.2.

As an example, in the Colorado program, field personnel collect pre-burn acreage, predominate fuel type and fuel loading information annually before the burning season begins. A generalized emissions estimate is reported on the SASEM output they submit with their permit application (see Chapter 9 for information on SASEM and other models). Post-burn information including acreage actually burned, fuel types, fuel loading, and fuel consumption is collected in the field at the end of the season. If the project is classified as “High Risk for Smoke Impacts,” the central office Program Coordinator compiles the end-of-year acreage actually burned and fuel actually consumed from all cooperating agencies. The program office then uses this information to calculate annual emissions. The program office has no responsibilities related to fuel type data. The Colorado smoke management program is fairly basic compared to some more complex programs, but is appropriate to the specifics of the state burning programs and their potential impacts to air quality.

Table 4.2.1. Smoke Management Program features. Smoke Management programs are periodically reviewed and revised; the features listed here reflect program status in 2001.

State		Program Fees [b]					
Alabama	No	None	Yes	No	Informal	No	No
Alaska	No	None	Yes	No	Informal	Some	No
Arizona	Yes	None	Yes	No	Formal	Yes	Yes
California[c]	Yes	Yes	Yes	Yes	Formal	Yes	No
Colorado	Yes	Yes	Yes	Yes	Informal	Some	Yes
Florida	Yes	None	Yes	No	Formal	Yes	No
Idaho/Montana	Yes	Based on Emissions	Yes	No	Formal	Yes	No
Louisiana	No	None	No	No	No	No	No
Mississippi	No	None	No	No	Informal	No	No
Nevada	No	None	Yes	No	Informal	No	No
New Mexico	No	None	Yes	No	Informal	Yes	Considered
NE Region	No	None	No	No	Informal	No	No
North Carolina	No	None	No	No	No	No	No
Oregon	Yes	Based on Acres	Yes	Yes	Formal	Yes	Yes
Tennessee	No	None	No	No	No	No	No
South Carolina	Yes	None	Yes	No	Informal	No	No
Utah	Yes	None	Yes	Yes	Formal	Some	Considered
Washington	Yes	Based on Emissions	Yes	Yes	Formal	Yes	Yes

[a] Full time staff means a position with duties dedicated only to meteorological forecasting and program administration

[b] The Arizona and Utah programs are funded through an MOU with participating agencies rather than acreage/tonnage fees. Other agency programs not funded by fees are supported through state/agency budget allocations.

[c] Each of California's 35 air pollution control districts have a unique smoke management plan. Features reported here exist somewhere in the state but do not necessarily apply statewide.

Table 4.2.2. Selected Smoke Management Program Emission Inventory Reporting Attributes.

State	Area Burned		Fuel Type		Fuel Loading		Fuel Consumption		Emissions	
	Field	Program	Field	Program	Field	Program	Field	Program	Field	Program
Arizona	Pre$_d$/Post$_d$	Post$_d$	Pre$_d$/Post$_d$	Post$_d$	Pre$_d$/Post$_d$	Post$_d$	Pre$_d$/Post$_d$	Post$_d$	None	Post$_d$
CO-Normal	Pre$_a$/Post$_a$	None	Pre$_a$/Post$_a$	None	Pre$_a$/Post$_a$	None	Pre$_a$/Post$_a$	None	Pre$_a$	Post$_a$
CO-High Risk	Pre$_a$/Post$_d$	None	Pre$_a$/Post$_d$	None	Pre$_a$/Post$_d$	None	Pre$_a$/Post$_d$	None	None	Post$_d$
Montana	Pre$_a$/Pre$_a$	Post$_a$	Pre$_a$	None	Pre$_a$	None	Post$_a$	None	None	Post$_a$
Florida	Pre$_d$	Post$_d$	None	None	None	None	None	None	None	None
Michigan	Michigan has no statewide program. Forest Service acreage (only) to be burned is tabulated at the beginning of the season. Actual acreage burned is estimated shortly after project completion and reported to their regional office, which then compiles the data annually.									
New York	Pre$_d$/Post$_d$	Post$_a$	Pre$_a$	Post$_a$	Pre$_a$	None	Post$_a$	None	None	None
Washington	Pre$_d$/Post$_d$	Post$_d$	Pre$_d$	None	Pre$_a$	None	None	Post$_d$	None	Post$_a$

Key to subscripts:

Pre$_a$ ----Pre-burn estimate conducted once **annually** at the beginning of the season.
Pre$_d$ ----Pre-burn estimates made on a **daily** basis.
Post$_a$ ---Post-burn estimates made once **annually** at the end of the season.
Post$_d$ ---Post-burn surveys conducted on a **daily** basis soon after completion.
None ---Not applicable or no estimate prepared.

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Federal Land Management–Special Requirements

Janice L. Peterson

Federal agencies are subject to certain laws and requirements that are not necessarily applicable to states or private entities in the same manner or at all. Federal agencies are required to do long-range planning for management of the lands they manage through numerous agency-specific planning mandates. The National Environmental Policy Act (NEPA) requires Federal agencies to examine and disclose potential impacts of their actions on the environment. The General Conformity regulations require federal agencies to examine the effect of their actions on the ability of a state to reach air quality goals and modify their actions if air quality targets would be delayed. Federal agencies also manage wilderness areas and the Wilderness Act contains language with implications for air quality protection.

Land Management Planning

Each Federal land management agency has some sort of overarching planning mandate. These broad scale, long-term plans define how Federal lands will be managed for many years into the future. For the USDA Forest Service, the National Forest Management Act (NFMA) (Public Law 94-588) requires National Forests to prepare plans for land management that address a long-term planning perspective and provide the opportunity for other agencies and the public to comment on decisions on how these public lands are managed. Forest Plans are to address protection, management, improvement, and use of renewable resources on the National Forests and should "recognize the fundamental need to protect and, where appropriate, improve the quality of soil, water, and air resources." Forest Plans must be updated and revised at least every 15 years and many National Forests are in the process of, or have recently completed this task. Other federal agencies have similar land management planning mandates. For the U.S. Department of the Interior, the Bureau of Land Management has the Integrated Resource Management Plan; the National Park Service has the Resource Management Plan; and the Fish and Wildlife Service has the Comprehensive Conservation Plan.

In some parts of the country, resource management agencies have fairly recently recognized the importance of fire as an ecological process in the maintenance of sustainable ecosystems. Therefore, existing federal land management plans do not always adequately address this topic. Planning revisions provide the opportunity to define and resolve issues that involve wildland fire, its relationship to forest health, and its environmental costs and benefits. Revisions should address the fact that smoke knows no boundaries and alternative management scenarios must be analyzed in this same context.

A Forest Service Example

Forest Plans provide the long-term, big picture view of goals for management of a National Forest. Specific projects are planned at a later date to fit the goals and framework of the Forest Plan and to meet more short term planning horizons. For example, the philosophy of how fire will be used to manage various ecosystems on a National Forest and the general effects of this fire on air quality will be described in the Forest Plan whereas specific prescribed fire projects and specific air quality effects will be defined at a later date. The environmental consequences of specific projects are analyzed through the National Environmental Policy Act (NEPA) planning process.

Recent Forest Service internal guidance[1] advises that air quality status within 100km of the Forest boundary be assessed for attainment/non-attainment status, Class I or Class II, availability of monitoring data, and identification of special smoke sensitive areas (such as airports, hospitals, etc.). The complexity of the subsequent Forest Plan air quality analysis will be determined by what is found in this initial assessment and can range from preparation of a simple emissions inventory and development of standards and guidelines for smoke management if the complexity is low; up to a detailed emissions inventory, standards and guidelines for smoke management including visibility protection, modeling to estimate mitigation benefits and/or consequences, worst case emissions analysis, and identification of possible emissions offsets if complexity is high.

National Environmental Policy Act

The National Environmental Policy Act (NEPA) (Public Law 91-190) directs all federal agencies to consider every significant aspect of the environmental impacts of a proposed action. It also ensures that an agency will inform the public that it has considered environmental concerns in its decision-making process. NEPA does not require agencies to elevate environmental concerns over other appropriate considerations; only that agencies fully analyze, understand, and disclose environmental consequences before deciding to take an action. NEPA is a procedural mandate to federal agencies to ensure a fully informed decision where short- and long-term environmental consequences are not forgotten.

An analysis of possible air quality impacts may be needed in a NEPA analysis if the project:

- raised air quality as a significant issue in scoping[2],
- includes burning,
- includes significant road construction, road use, or other soil disturbing procedures where fugitive dust may be a concern,
- includes significant machinery operation in close proximity to publicly accessible areas,
- may have any impact on air quality in a Class I area,
- may have any impact on sensitive vistas or visibility in a Class I area,

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[1] USDA Forest Service. 1999. Draft desk guide for integrating air quality and fire management into land management planning. USDA Forest Service guidance document. Available at: http://www.fs.fed.us/clean/air/

[2] Scoping is the process of determining the issues to be included in NEPA analysis and for identifying any significant issues that will need to be addressed in depth. Scoping requires the lead agency to invite participation of affected Federal, State, and local agencies, any affected Indian tribe, the proponent of the action, and other interested persons (including those who might not be in accord with the action on environmental grounds).

- is in close proximity to a non-attainment area,
- will make a significant amount of firewood available to the public.

The appropriate level of analysis for each project will vary with the size of the project. For example, a small project will likely have a brief analysis and a large project will require a detailed analysis. The complexity and potential effects of the project will determine whether an environmental impact statement (EIS), an environmental assessment (EA), a biological evaluation (BE), or a categorical exclusion (CE) is the appropriate NEPA tool. If an air quality analysis is deemed unnecessary, the NEPA document should state that potential air quality impacts were considered but were determined to be inconsequential. In this case, a justification for this determination must be included.

A project NEPA analysis is where specific environmental effects from specific projects are analyzed and assessed. This process provides a good opportunity for fire managers and air quality regulators to come to a common understanding of how smoke from prescribed fire projects will be managed and reduced. Section 309 of the 1977 Clean Air Act Amendments (Public Law 95-95) gives EPA a role in reviewing NEPA documents and making those reviews public. How actively EPA pursues this role tends to vary between EPA regions and with the complexity and potential environmental risk from the project.

A complete disclosure of air quality impacts in a NEPA document should include the following information:

1. Description of the air quality environment of the project area
2. Description of alternative fuel treatments considered and reasons why they were not selected over prescribed fire.
3. Quantification of the fuels to be burned (areas, tons, types).
4. Description of the types of burning planned (broadcast, piles, understory, etc.).
5. Description of measures taken to reduce emissions and emission impacts.
6. Estimation of the amount and timing of emissions to be released.
7. Description of the regulatory and permit requirements for burning (for example, smoke management permits).
8. Modeled estimates of where smoke could go under certain common and worst case meteorological scenarios and focusing on new or increased impacts on down wind communities, visibility impacts in Class I wildernesses, etc. In some areas and for some fuel types, an appropriate dispersion model is not available. In this situation, qualitative analysis will need to suffice. Qualitative analysis can also be used for simple projects with little risk of air quality impact.

Conformity

> *"No department, agency, or instrumentality of the Federal Government shall engage in, support in any way or provide financial assistance for, license or permit, or approve, any activity which does not conform to a State Implementation Plan."*
>
> Clean Air Act Amendments of 1990

The 1990 Clean Air Act Amendments (Public Law 101-549) require planned federal actions to conform to state or tribal implementation plans (SIPs/TIPs). EPA's General Conformity rule established specific criteria and procedures for determining the conformity of planned federal projects and activities. In so doing, EPA chose to apply general conformity directly to non-attainment and maintenance areas only. EPA continues to consider application of general conformity rules to attainment areas but at present has not done so, although an activity in an attainment area that causes indirect emission increases within a non-attainment area may have to be analyzed for conformity. Federal agencies have the responsibility for making conformity determinations for their own actions.

General conformity rules prohibit federal agencies from taking any action within a non-attainment or maintenance area that causes or contributes to a new violation of air quality standards, increases the frequency or severity of an existing violation, or delays the timely attainment of a standard as defined in the applicable SIP or area plan. If a proposed federal project (non-temporary) were projected to contribute pollution to a non-attainment area the project would likely be canceled or severely modified. Temporary proposed federal projects that could impact a non-attainment area must also pass a conformity determination.

Federal activities must not:

1. Cause or contribute to new violations of any standard.
2. Increase the frequency or severity of any existing violations.
3. Interfere with timely attainment or maintenance of any standard.
4. Delay emission reduction milestones.
5. Contradict SIP requirements.

A conformity determination is required for each pollutant where the total of direct and indirect emissions caused by an agency's actions would equal or exceed conformity de minimis levels (table 4.3.1), or are regionally significant. Regionally significant is defined as emissions representing 10 percent or more of the total emissions for the area.

Table 4.3.1. Particle and carbon monoxide de minimis levels for general conformity.

Pollutant / Attainment level	De minimis level (tons per year)
Non-attainment areas	
CO	100
PM_{10}	
Moderate Non-attainment	100
Serious Non-attainment	70
Maintenance areas	
CO	100
PM_{10}	100

The general conformity rule covers direct and indirect emissions of criteria pollutants or their precursors that are caused by a Federal action, reasonably foreseeable, and can practicably be controlled by the Federal agency through its continuing program responsibility. In general, a conformity analysis is not required for wildland fire emissions at the Forest Plan level because specifics of prescribed fire timing and locations are not known, so at this planning level the reasonably foreseeable trigger is not met. A conformity determination will likely be required at a later date when planning specific projects under NEPA.

Wilderness Act

The Wilderness Act (Public Law 88-157) (and subsequent Acts designating individual Wilderness Areas) was enacted to preserve and protect wilderness resources in their natural condition. Wildernesses are to be administered for "the use and enjoyment of the American people in such manner as will leave them unimpaired for future use and enjoyment as wilderness, and so as to provide for the protection of these areas, the preservation of their wilderness character, and for the gathering and dissemination of information regarding their use and enjoyment as wilderness…" Although air quality is not directly mentioned in the Wilderness Act, the Act requires wilderness managers to minimize the effects of human use or influence on natural ecological processes and preserve "untrammeled" the earth and its community of life. Federal agencies have interpreted the goals of the Wilderness Act to mean that wilderness character and ecosystem health should not be impacted by unnatural, human-caused air pollution. Most Class I areas are entirely wilderness although some Class I National Parks contain areas that are not wilderness.

Literature Citations

U.S. Laws, Statutes, etc.; Public Law 88-157. Wilderness Act of Sept. 3, 1964. 78 Stat. 890; 16 U.S.C. 1131-1136.

U.S. Laws, Statutes, etc.; Public Law 91-190. [S. 1075], National Environmental Policy Act of 1969. Act of Jan. 1, 1970. In its: United States statutes at large, 1969. 42 U.S.C. sec. 4231, et seq. (1970). Washington, DC: U.S. Government Printing Office: 852-856. Vol. 83.

U.S. Laws, Statutes, etc.; Public Law 94-588. National Forest Management Act of 1976. Act of Oct. 22, 1976. 16 U.S.C. 1600 (1976).

U.S. Laws, Statutes, etc.; Public Law 95-95. Clean Air Act as Amended August 1977. 42 U.S.C. 1857 et seq.

U.S. Laws, Statutes, etc.; Public Law 101-549. Clean Air Act as Amended Nov. 1990. 104 Stat. 2399.

Chapter 5

SMOKE SOURCE CHARACTERISTICS

Smoke Source Characteristics

Roger D. Ottmar

Whether you are concerned with particulate matter, carbon monoxide, carbon dioxide, or hydrocarbons, all smoke components from wildland fires are generated from the incomplete combustion of fuel. The amount of smoke produced can be derived from knowledge of area burned, fuel loading (tons/acre), fuel consumption (tons/acre), and pollutant-specific emission factors. Multiplying a pollutant-specific emission factor (lbs/ton) by the fuel consumed, and adding the time variable to the emission production and fuel consumption equations results in emission and heat release rates that allow the use of smoke dispersion models (figure 5.1). This section discusses the characteristics of emissions from wildland fire and the necessary inputs to obtain source strength and heat release rate for assessing smoke impacts.

Prefire Fuel Characteristics

Fuel consumption and smoke production are influenced by preburn fuel loading categories such as grasses, shrubs, woody fuels, litter, moss, duff, and live vegetation; condition of the fuel (live, dead, sound, rotten); fuel moisture; arrangement; and continuity. These characteristics can vary widely across fuelbed types (figure 5.2) and within the same fuelbed type (figure

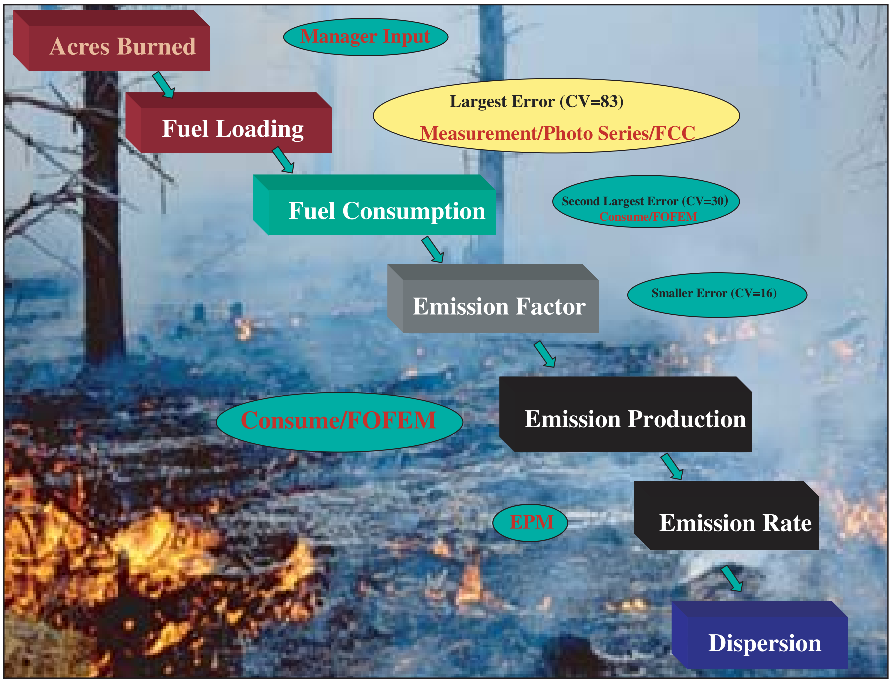

Figure 5.1. Combustion and emission processes.

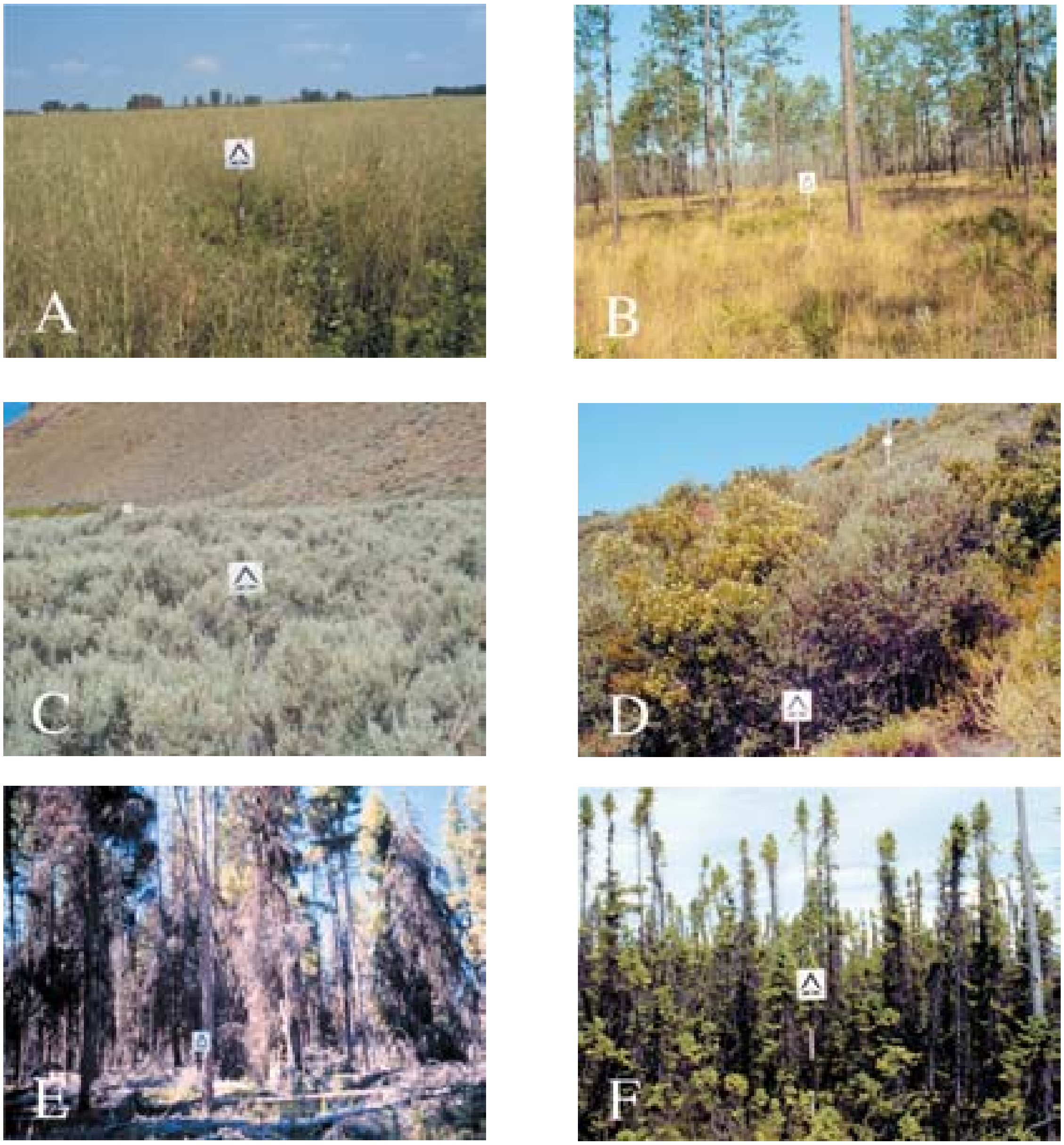

Figure 5.2. The preburn fuel loading (downed, dead woody, grasses, shrubs, litter, moss, and duff) can vary widely between fuel types as shown in (A) midwest grassland, 2.5 tons/acre; (B) longleaf pine, 4 tons/acre; (C) southwest sage shrubland, 6 tons/acre; (D) California chaparral, 40 tons/acre; (E) western mixed conifer with mortality, 67 tons/acre; and (F) Alaska black spruce, 135 tons/acre.

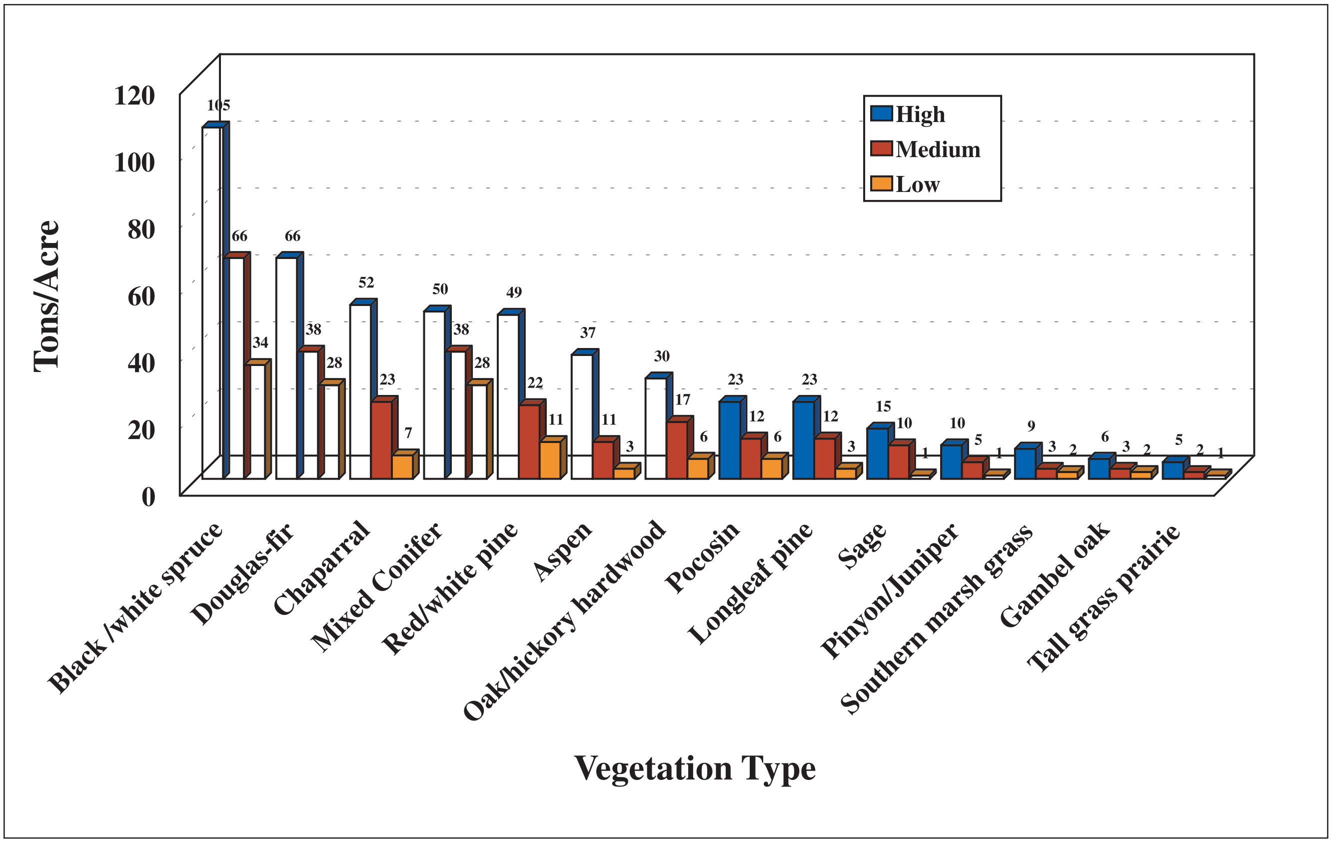

Figure 5.3. Variability of fuel loading across several fuelbed types. Sources are referenced in the text.

5.3). For instance, fuel loadings range considerably: less than 3 tons/acre for perennial grasses in the Midwest with no rotten material or duff (Ottmar and Vihnanek 1999); 4 tons per acre of mostly grass and a shallow litter and duff layers for a southern pine stand treated regularly with fire (Ottmar and Vihnanek 2000b); 6 tons/acre in a Great Basin sage shrubland (Ottmar and others 2000a); 40 tons per acre in a mature California chaparral shrubland (Ottmar and others 2000a); 67 tons per acre of 80 percent of which is rotten woody fuels, stump, snags, and deep duff in a multi-story, ponderosa pine and Douglas-fir forest with high mortality from disease and insects (Ottmar and others 1998); to 167 tons/acre in a black spruce forest in Alaska with a deep moss and duff layer (Ottmar and Vihnanek 1998). The heaviest fuel loadings encountered are normally associated with material left following logging, unhealthy forests, mature brush and tall grasses, or deep layers of duff, moss or organic (muck) soils. The large variation in potential fuel loading can contribute up to 80 percent of the error associated with estimating emissions (Peterson 1987, Peterson and Sandberg 1988).

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 tons per acre while a recently harvested pine stand with logging slash left on the ground may have a fuel loading of 50 tons per acre. Prescribed burning under a moderately dry fuel moisture situation would achieve 50 percent biomass consumption equating to 3 tons per acre consumed in the unlogged pine stand and 25 tons/acre consumed in the logged stand.

There are several techniques available for determining fuel loading (U.S. Department of Interior 1992). Collecting and weighing the fuel is the most accurate method but is impractical for many fuel types except grasses and small shrubs. Measuring some biomass parameter and estimating the biomass using a pre-derived equation is less accurate but also less time consuming (Brown 1974). Ongoing development of several techniques including the natural fuels photo series (Ottmar and others 1998, Ottmar and Vihnanek 2000a) and the Fuel Characteristic Class system (FCC) (Sandberg and others 2001) will provide managers new tools to better estimate fuel loadings and reduce the uncertainty that currently exist with assigning fuel characteristics across a landscape. The photo series is a sequence of single and stereo photographs with accompanying fuel characteristics. Over 26 volumes are available for logging and thinning slash and natural fuels in forested, shrubland, and grassland fuelbed types throughout the United States. The Fuel Characteristic Class System is a national system being designed for 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.

Fuel moisture content is one of the most influential factors in the combustion and consumption processes. 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 affects the flame temperature that in turn influences the ease of ignition, the amount and rate of consumption, and the combustion efficiency (the ratio of energy produced compared to energy supplied). In other words, higher fuel moisture content requires more energy to drive off the water, enabling fuel to reach a point where pyrolysis can begin. Generally, fuels with low fuel moisture content burn more efficiently and produce fewer emissions per unit of fuel consumed. On the other hand, even though emissions per unit of fuel burned will be greater at higher fuel moistures because of a less efficient combustion environment, total emissions may be less if some fraction of the fuels do not totally burn—typically the large wood fuels and forest floor.

Since combustion generally takes place at the fuel/atmosphere interface, the time necessary to ignite and consume an individual fuel particle with a given fuel moisture content depends upon the smallest dimension of the particle. The surface area to volume ratio of a particle is often used to depict a particle's size—the greater the ratio, the smaller the particle. Small twigs and branches have a much larger surface to volume ratio than large logs and thus a much greater fuel surface exposed to the atmosphere. Consequently, fine fuels will have a greater probability of igniting and consuming for a given fuel moisture.

The arrangement of the particles is also important. The structuring of fuel particles and air spaces within a fuel bed can either enhance or retard fuel consumption and affect combustion efficiency. The packing ratio (the fraction of the fuel bed volume, occupied by fuel) is the measure of the fuel bed porosity. A loosely packed fuel bed (low packing ratio) will allow plenty of oxygen to be available for combustion, but may result in inefficient heat transfer 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) allows efficient heat transfer between the particles, but may restrict oxygen availability and reduce consumption and combustion efficiency. An efficiently burning fuel bed will have particles close enough for adequate heat transfer while at the same time large enough spaces between particles for oxygen availability.

Fuel discontinuity—both horizontal and vertical—isolates portions of the fuel bed from pre-ignition heating and subsequent ignition. Sustained ignition, and combustion will not occur when the spacing between the fuel particles is too large.

Biochemical differences between species also play a role in combustion. Certain species such as hoaryleaf ceanothus (*Ceanothus crassifolius*), 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.

Fire Behavior

Fire behavior is the manner in which fire reacts to the fuels available for burning (DeBano and others 1998) and is dependent upon the type, condition, and arrangement of smaller woody fuels, local weather conditions, topography and in the case of prescribed fire, lighting pattern and rate. Two aspects of fire behavior include fire line intensity (the amount of heat released per unit length of fire line) and rate of spread (activity of the fire in extending its horizontal dimensions). These aspects influence combustion efficiency of consuming biomass and the resultant pollutants produced from wildland fires. During fires with rapid rates of spread and high intensity but relatively short duration, a majority of the biomass consumed will be smaller woody fuels and will occur during the more efficient flaming period resulting in less smoke. Burning dry grass and shrublands, forestlands with high large woody and duff fuel moisture contents, clean, dry piles, and rapidly igniting an area with circular or strip-head fires will produce these characteristics. In simple, uniform fuelbeds such as pine and leaf litter with only shallow organic material beneath, a backing fire with lower rates of spreads and intensities may consume fuels very efficiently producing less smoke. In more complex fuelbeds, the backing flame may become more turbulent and this combustion efficiency may lessen. During wildland fires with a range of fire intensities and spread rates but long burning durations, a large portion of the biomass consumed 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 Emissions Production Model (EPM) (Sandberg and Peterson 1984, Sandberg 2000) and FARSITE (Finney 2000) take into account fire behavior and lighting pattern to estimate emission production rates.

Fuel Consumption

Fuel consumption is the amount of biomass consumed during a fire and is another critical component required to estimate emissions production from wildland fire. Fuels are consumed in a complex combustion process that adds to a variety of combustion products including particulate matter, carbon dioxide, carbon monoxide, water vapor and a variety of various hydrocarbons. Biomass consumption varies widely among fires and is dependent on the fuel type (e.g. grass versus woody fuels), arrangement of the fuel (e.g. piled versus non-piled woody debris), condition of the fuel (e.g. high fuel moisture versus low fuel moisture) and the way the fire is applied in the case of a prescribed fire (e.g. a helicopter or fixed wing aircraft ignited high intensity, short duration mass fire versus a slow, low intensity hand ignition). As with fuel characteristics, extreme variations associated with fuel consumption can contribute errors of 30 percent or more when emissions are estimated for wildland fires (Peterson 1987; Peterson and Sandberg 1988).

In the simplest terms, combustion of vegetative matter (cellulose) is a thermal/chemical reaction where by plant material is rapidly oxidized producing carbon dioxide, water, and heat (figure 5.4). This is the reverse of plant photosynthesis where energy from the sun combines with carbon dioxide and water, producing cellulose (figure 5.4).

In the real world, the burning process is much more complicated than this. 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 hydrocarbon vapors and gases, and particulate matter. Combustion follows as the escaping 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. Pyrolsis and combustion proceed at many different rates since wildland fuels are often very complex and non-homogeneous (DeBano and others 1998).

It has been recognized that there are four major phases of combustion when fuel particles are consumed (figure 5.5) (Mobley 1976, Prescribed Fire Working Team 1985). These phases are: (1) pre-ignition; (2) flaming; (3) smoldering; and (4) glowing (figure 5.4). During the pre-ignition phase, fuels ahead of the fire front are heated by radiation and convection and water vapor is driven to the surface of the fuels and expelled into the atmosphere. As the fuel's internal temperature rises, cellulose and lignin begin to decompose, releasing combustible organic gases and vapors (Ryan and McMahon 1976). Since these gases and vapors are extremely hot, they rise and mix with oxygen in the air and ignite at temperatures between 617^0 F and 662^0 F leading to the flaming phase (DeBano and others 1998).

In the flaming phase, the fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by flaming of the combustible gases and

$$\textbf{CELLULOSE} + \mathbf{O_2} \xrightarrow[\textbf{Heat/chemical energy}]{} \mathbf{CO_2} + \mathbf{H_2 0} + \textbf{ENERGY}$$

$$\textbf{CELLULOSE} + \mathbf{O_2} \xleftarrow[\textbf{Sun/thermal energy}]{} \mathbf{CO_2} + \mathbf{H_2 0} + \textbf{ENERGY}$$

Figure 5.4. The energy flow for combustion is reverse to that for photosynthesis.

Figure 5.5. The four phases of combustion.

vapors. The combustion efficiency during the flaming stage is usually relatively high as long as volatile emissions remain in the vicinity of the flames. The predominant products of flaming combustion are carbon dioxide (CO_2) and water vapor (H_2O). The water vapor is a product of the combustion process and also derives from moisture being driven from the fuel. Temperatures during the flaming stage range between 932^0 F to 2552^0 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 approximately 24 minutes to completely consume if flaming combustion was sustained during the entire time period.

During the smoldering phase, emissions of combustible gases and vapors above the fuel is too low to support a flaming combustion resulting in a fire spread decrease and significant temperature drop. Peak smoldering temperatures range from 572^oF to 1112^oF (Agee 1993). The gases and vapors condense, appearing as visible smoke as they escape into the atmosphere. The smoke consists mostly of droplets less than a micrometer in size. 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 prevalent in certain fuel types (e.g. duff, organic soils, and rotten 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, and small diameter woody fuels) (Sandberg and Dost 1990). Since the heat generated from a smoldering combustion is seldom sufficient to sustain a convection column, the smoke stays near the ground and often concentrates in nearby valley bottoms, compounding the impact of the fire on air quality.

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.

In the glowing phase, most volatile gases have 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 1117°F (DeBano and others 1998). There is little visible smoke. Carbon dioxide, carbon monoxide, and methane 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. Between 20 and 90 percent of the biomass consumed during a wildland fire occurs during the flaming stage, with the remainder occurring during the smoldering and glowing stages (Ottmar and others [in preparation]. The flaming stage has a high combustion efficiency; that is it tends to emit the least emissions relative to the mass of fuel consumed. The smoldering stage has a low combustion efficiency and produces more smoke relative to the mass of fuel consumed.

Biomass consumption of the woody fuels, piled slash, and duff in forested areas has become better understood in recent years (Sandberg and Dost 1990, Sandberg 1980, Brown and others 1991, Albini and Reinhardt 1997, Reinhardt and others 1997, Ottmar and others 1993, Ottmar and others [in preparation]). Large woody fuel consumption generally depends on moisture content of the woody fuel and duff. Approximately 50 percent of the consumption occurs during the flaming period. Duff consumption depends on fire duration of woody fuels and duff moisture content. Consumption occurs primarily during the smoldering stage when duff moisture is low. Consumption of tree crowns in forests and shrub crowns in shrublands are poorly understood components of biomass consumption and research is currently underway (Ottmar and Sandberg 2000) to develop or modify existing consumption equations for these fuel components.

Since consumption during the flaming phase is more efficient than during the smoldering phase, separate calculations of flaming consumption and smoldering consumption are required for improved assessment of total emissions. Equations for predicting biomass consumption by combustion phase are widely available in two major software packages including Consume 2.1 (Ottmar and others [in preparation]) and First Order Fire Effects Model (FOFEM 5.0) (Reinhardt and Keane 2000).

Consume 2.1 is a revision of Consume 1.0 (Ottmar and others 1993) and uses a set of theoretical models based on empirical data to predict the amount of fuel consumption from the burning of logging slash, piled woody debris, or natural forest, shrub, grass fuels. Input variables include the amount of fuel, woody fuel and duff moisture content, and meteorological data. The software product incorporates the original Fuel Characteristic System (Ottmar and others [in preparation]) for assigning default fuel loadings.

It also incorporates features that allow users to receive credit for applying fuel consumption reduction techniques. FOFEM 5.0 (Reinhardt and Keane 2000) is a revision of FOFEM 4.0 (Reinhardt and others 1997) and relies on BURNUP. a new model of fuel consumption (Albini and Reinhardt 1997). The software computes duff and woody fuel consumption for many forest and rangeland systems of the United States. Both Consume 2.1 and FOFEM 5.0 packages are updated on a regular basis as new consumption models are being developed.

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—Two products of complete combustion during fires are carbon dioxide (CO_2) and water (H_2O) and generally make up over 90 percent of the total emissions from wildland fire. Under ideal conditions complete combustion of one ton of forest fuels 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. Neither carbon dioxide nor water vapor are considered air pollutants in the usual sense, even though carbon dioxide is considered a greenhouse gas and the water vapor will sometimes condense into liquid droplets and form a visible white smoke near the fire. This fog/smoke mixture can dramatically reduce visibility and create hazardous driving conditions. As combustion efficiency decreases, less carbon is converted to CO_2 and more carbon is available to form other combustion products such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides(NOx), and sulfur oxides (SOx), all of which are considered pollutants.

Carbon Monoxide—Carbon monoxide (CO) is the most abundant emission product from wildland fires. 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 source of 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 fire line at prescribed fires and wildfires, and at fire camps (Reinhardt and Ottmar 2000, Reinhardt and others 2000).

Hydrocarbons—Hydrocarbons (HC) 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 a majority of the HC pollutants may have no harmful effects, there are a few that are toxic. More research is needed to characterize hydrocarbon production from fires.

Nitrogen Oxides—In wildland fires, small amounts of nitrogen oxides (NOx) are produced, primarily from oxidation of the nitrogen contained in the fuel. Thus the highest emissions of No_x occur from fuels burning with a high nitrogen content. Most fuels contain less than 1 percent nitrogen. Of that about 20 percent is converted to NO_x when burned.

Hydrocarbons and possibly nitrogen oxides from large wildland fires contribute to increased ozone formation under certain conditions.

Particulate Matter—Particulate matter produced from wildland fires limits visibility, absorbs harmful gases, and aggravates respiratory conditions in susceptible individuals (figure 5.6). Over 90 percent of the mass of particulate matter produced by wildland is less than 10 microns in diameter and over 80-90 percent is less than 2.5 microns in diameter (figure 5.7). These small particles are inhalable and respirable. Respirable suspended particulate matter is that proportion of the total particulate matter that, because of its small size has an especially long residence time in the atmosphere and penetrates deeply into the lungs. Small smoke particles also scatter visible light and thus reduce visibility.

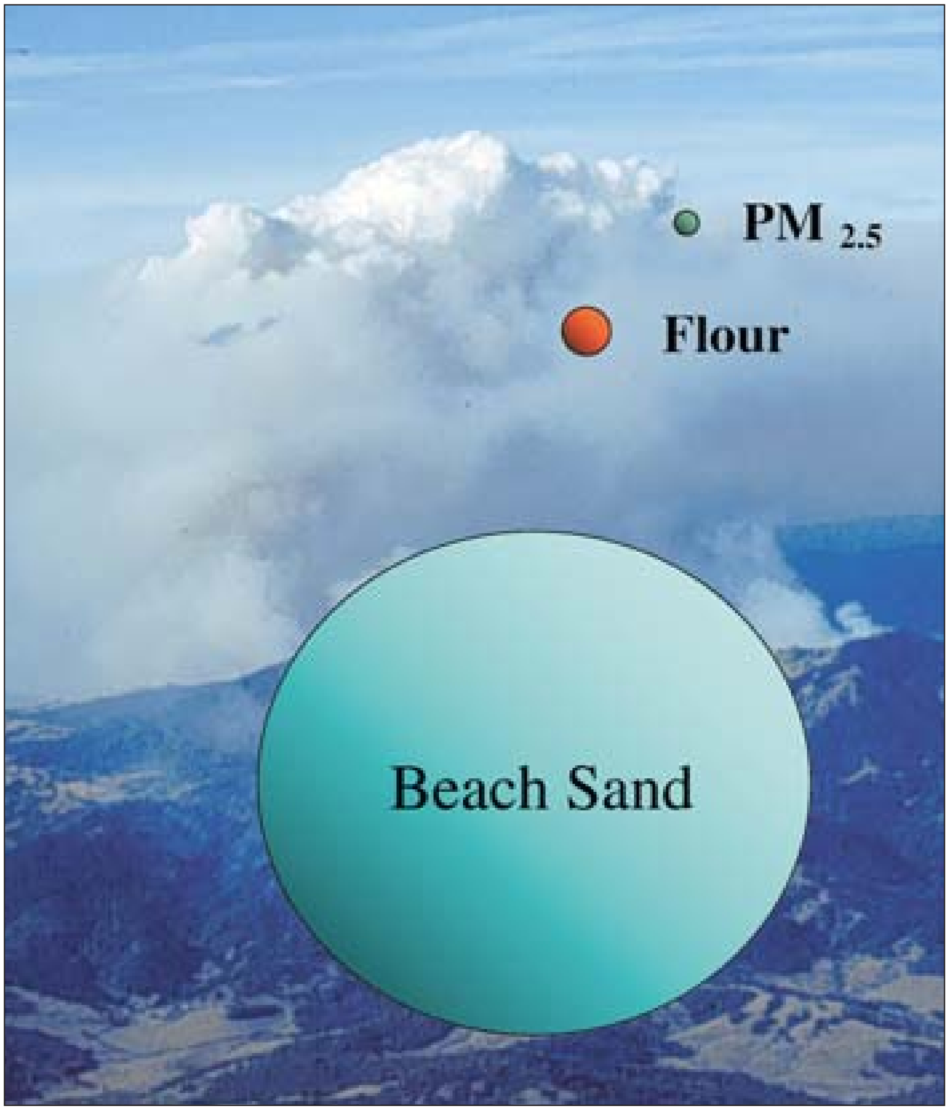

Figure 5.6. Relative sizes of beach sand, flour, and a PM2.5 particle in smoke.

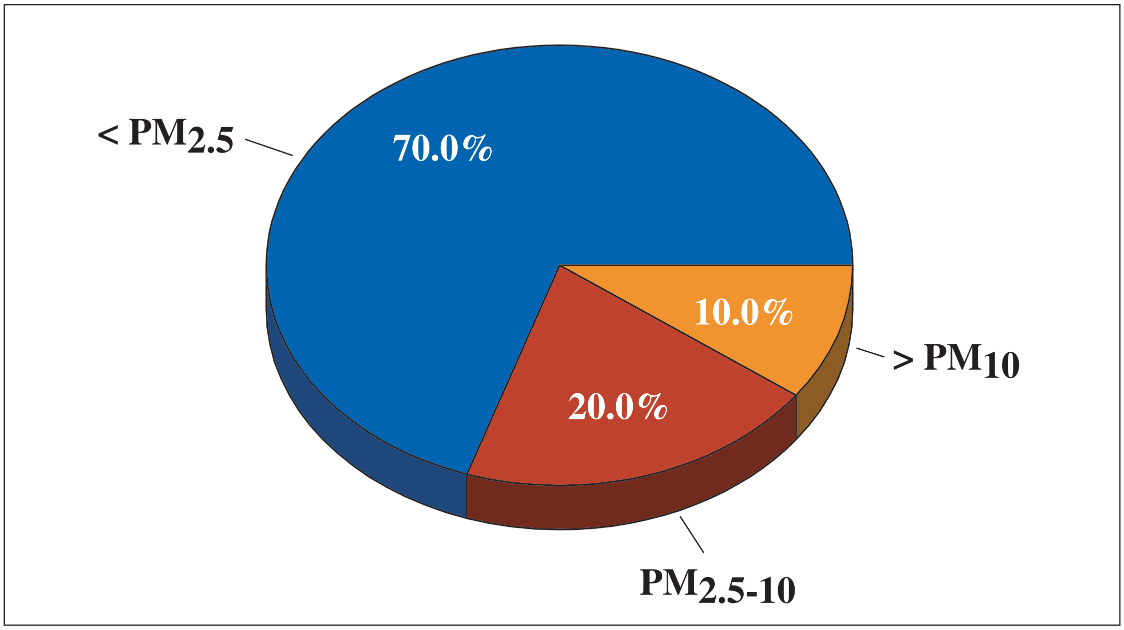

Figure 5.7. Particulate matter size-class distribution from typical wildland fire smoke.

Emission Factors

An emission factor for a particular pollutant of interest is defined as the mass of pollutant produced per mass of fuel consumed (i.e., lbs/ton in the English system or g/kg as the metric equivalent). Multiplying an emission factor in grams/kg by a factor of two will convert the emission factor to English units (pounds/ton).

Emission factors vary depending on type of pollutant, type and arrangement of fuel and combustion efficiency. The average fire emission factors have a relatively small range and contributes approximately 16 percent of the total error associated with predicting emissions production (Peterson 1987; Peterson and Sandberg 1988). In general, fuels consumed by flaming combustion produce less smoke than fuels consumed by smoldering combustion. Emission factors for several smoke compounds are presented in table 5.1 for the flaming, smoldering, and fire average for generalized fuel types and arrangements. Emission factors can be used by air quality agencies to calculate local and regional emissions inventories or by managers to develop strategies to mitigate downwind smoke impacts. Additional emission factors have been determined for other fuel types and will be available in the future.

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 that emission factor by the biomass consumed and an accurate assessment of the total acreage burned. For instance, assume that 10 tons/acre of fuels will be con-

Table 5.1. Forest and rangeland emission factors [1]Ward and others 1989; [2]Hardy and others 1996; [3]Hardy and Einfield 1992).

Fuel or Fire Configuration	**Combustion Phase**[a]	**Emission Factors**						
		PM	**PM_{10}**[b]	**$PM_{2.5}$**	**CO**	**CO_2**	**CH_4**	**NMHC**
		(Pounds emission per ton fuel consumed)						
BROADCAST BURNED SLASH[1]								
Douglas fir/ hemlock	FLAMING	24.7	16.6	14.9	143	3385	4.6	4.2
	SMOLDERING	35.0	27.6	26.1	463	2804	15.2	8.4
	FIRE AVERAGE	29.6	23.1	21.8	312	3082	11.0	7.2
Hardwoods	FLAMING	23.0	14.0	12.2	92	3389	4.4	5.2
	SMOLDERING	38.0	25.9	23.4	366	2851	19.6	14.0
	FIRE-AVERAGE	37.4	25.0	22.4	256	3072	13.2	10.8
Ponderosa/ **l.pole pine**	FLAMING	18.8	11.5	10.0	89	3401	3.0	3.6
	SMOLDERING	48.6	36.7	34.2	285	2971	14.6	9.6
	FIRE AVERAGE	39.6	25.0	22.0	178	3202	8.2	6.4
Mixed conifer	FLAMING	22.0	11.7	9.6	53	3458	3.0	3.2
	SMOLDERING	33.6	25.3	23.6	273	3023	17.6	13.2
	FIRE AVERAGE	29.0	20.5	18.8	201	3165	12.8	9.8
Juniper	FLAMING	21.9	15.3	13.9	82	3401	3.9	5.5
	SMOLDERING	35.1	25.8	23.8	250	3050	20.5	15.5
	FIRE AVERAGE	28.3	20.4	18.7	163	3231	12.0	10.4
PILE-AND BURN SLASH[1]								
Tractor-piled	FLAMING	11.4	7.4	6.6	44	3492	2.4	2.2
	SMOLDERING	25.0	15.9	14.0	232	3124	17.8	12.2
	FIRE AVERAGE	20.4	12.4	10.8	153	3271	11.4	8.0
Crane-piled	FLAMING	22.6	13.6	11.8	101	3349	9.4	8.2
	SMOLDERING	44.2	33.2	31.0	232	3022	30.0	20.2
	FIRE AVERAGE	36.4	25.6	23.4	185	3143	21.7	15.2
"Average" Piles	FIRE AVERAGE	28.4	19.0	17.1	169	3207	16.6	11.6
BROADCAST-BURNED BRUSH[2]								
Sagebrush	FLAMING	45.0	31.8	29.1	155	3197	7.4	6.8
	SMOLDERING	45.3	29.6	26 4	212	3118	12.4	14.5
	FIRE-AVERAGE	45.3	29.9	26.7	206	3126	11.9	13.7
Chaparral	FLAMING	31.6	16.5	13.5	119	3326	3.4	17.2
	SMOLDERING	40.0	24.7	21.6	197	3144	9.0	30.6
	FIRE AVERAGE	34.1	20.1	17.3	154	3257	5.7	19.6
WILDFIRES FIRES (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 $PM_{2.5}$.

sumed during a 200 acre landscape prescribed burn in a ponderosa pine stand. Following the fire, ground surveys and aerial reconnaissance indicate a mosaic fire pattern and only 100 acres of the 200 acres within the fire perimeter actually burned. Since the emission factor for particulate matter 2.5 microns in diameter or less ($PM_{2.5}$) for pine fuels is approximately 22 lbs/ton, then total emission production would be:

$$\underset{\textbf{(lbs)}}{\textbf{Total Emissions}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumed}} \;\mathbf{X}\; \underset{\textbf{(lb/ton)}}{\textbf{Emission Factor}} \;\mathbf{X}\; \underset{\textbf{(acres)}}{\textbf{Area Burned}}$$

Therefore: $10\,tons/acre * 22\,lbs/ton * 100\,acres \Rightarrow 22{,}000\ lbs \Rightarrow 11\,tons$

Managers can make better estimates of emissions produced from a wildland fire if the amount of fuel consumption in the flaming and smoldering combustion period 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 a particular fuel type, then summed. Computer software such as Consume 2.1 (Ottmar and others [in preparation]) and FOFEM 5.0 (Reinhardt and Keane 2000) use this approach to improve estimates of total emissions produced from wildland fire as compared with the fire average approach. An emission inventory is the aggregate of total emissions from all fires in a given period for a specific geographic area and requires total emissions.

Modeling emissions from wildland fires requires not only total emissions, but also source strength. Source strength is the rate of air pollutant emissions in mass per unit of time or in mass per unit of time per unit of area and is the product of the rate of biomass consumption and an emission factor for the pollutant(s) of interest. Source strength can be calculated by the equation:

$$\underset{\textbf{(lbs/minute)}}{\textbf{Source Strength}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumption}} \;\mathbf{X}\; \underset{\textbf{(acre/minute)}}{\textbf{Rate of Area Burned}} \;\mathbf{X}\; \underset{\textbf{(lb/ton)}}{\textbf{Emission Factor}}$$

Emission rates vary by fuel loading, fuel consumption, and emission factors. Figure 5.8 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.

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:

$$\underset{\textbf{(BTU/minute)}}{\textbf{Heat Release Rate}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumption}} \;\mathbf{X}\; \underset{\textbf{(acre/minute)}}{\textbf{Rate of Area Burned}} \;\mathbf{X}\; \underset{\textbf{(BTU/ton)}}{\textbf{Heat Output}}$$

Both source strength and heat release rate are required by all sophisticated smoke dispersion models (Breyfogle and Ferguson 1996). Dispersion models are used to assess the impact of smoke on the health and welfare of the public in cities and rural communities and on visibility in sensitive areas such as National Parks, Wilderness areas, highways, and airports. The Emissions Production Model (EPM) (Sandberg and Peterson 1984; Sandberg 2000) is the only model that predicts source strength and heat release rate for wildland fires. The EPM software package imports fuel consumption predictions from Consume 2.1 or FOFEM 5.0 and uses ignition pattern, ignition periods, and burn area components to calculate source strength, heat release rate, and plume buoyancy.

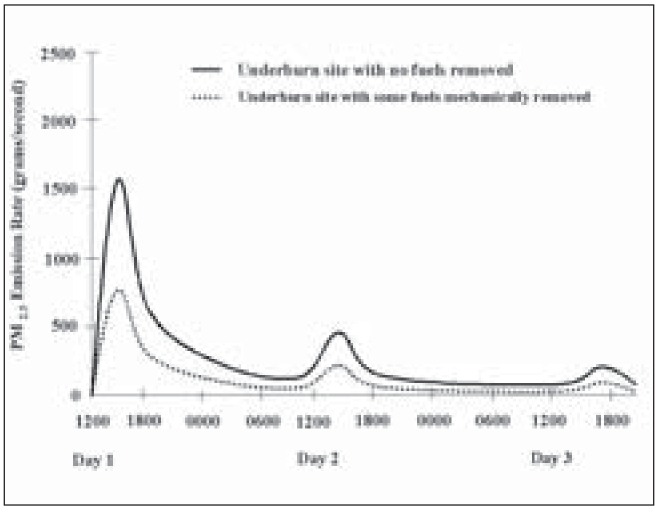

Figure 5.8a. Emission production rate over time for $PM_{2.5}$ during an underburn with and without fuels mechanically removed.

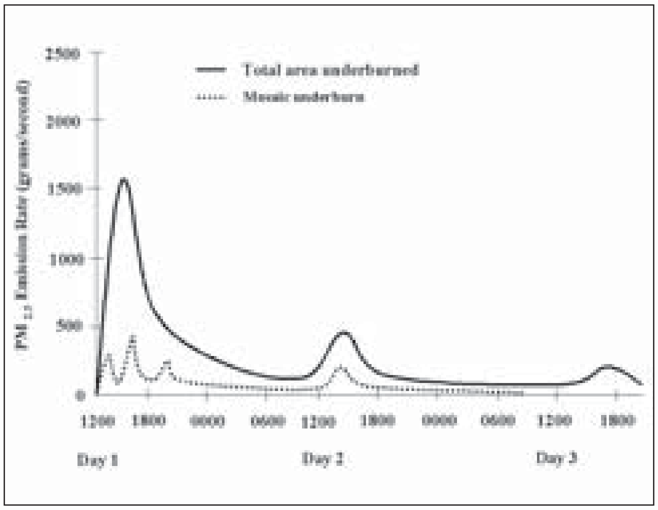

Figure 5.8b. Emission production rate over time for $PM_{2.5}$ during a mosaic burn and a burn where fire covers the entire area within the perimeter.

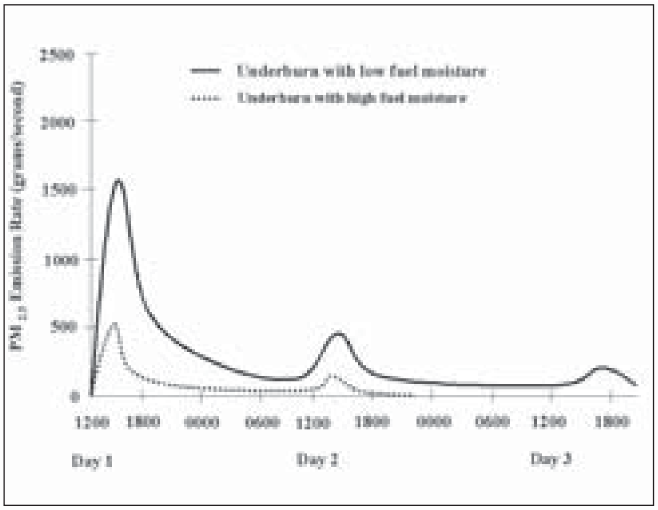

Figure 5.8c. Emission production rate over time for $PM_{2.5}$ during an underburn with low and high fuel moisture content.

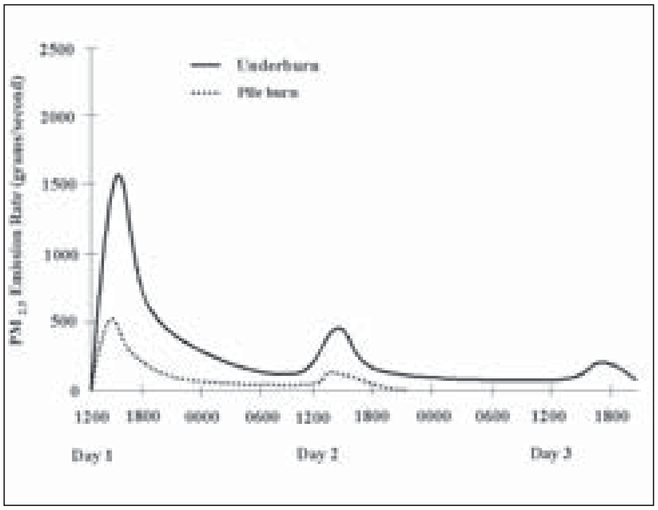

Figure 5.8d. Emission production rate over time for $PM_{2.5}$ during an underburn and a pile burn.

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Chapter 6

FIRE USE PLANNING

Fire Use Planning

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The success of a fire use program is in large part dependent on a solid foundation set in clear and concise planning. The planning process results in specific goals and measurable objectives for fire application, provides a means of setting priorities, and establishes a mechanism for evaluating and refining the process to meet the desired future condition. It is an ongoing process, beginning months or even years in advance of actual fire use, with plans becoming increasingly specific as the day of the burn approaches. Although details differ between fire practitioners, the general planning process is essentially the same.

Land and Resource Management Planning

Fire use planning should begin as a component of the overall land and resource management planning for a site. Consideration of the intentional use of fire to achieve stated resource management goals should be an integral part of this process. In deciding whether or not fire use 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 treatment and include expected negative as well as beneficial outcomes. Care should be exercised to separate statements that are supported by data (preferably local and ecosystem-specific), from those only purported to be true.

Many private landowners do not have written 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. We recommend they put this vision on paper to provide guidance to themselves and their heirs.

The plans should identify any barriers to implementing a treatment judged best from a resource management standpoint, such as regulations, cost, or insufficient resources. If such a treatment is not recommended because of these barriers, the probable ecological ramifications of this decision should be documented. On sites where fire is selected as the best alternative to accomplish the desired resource management objectives, the next step in fire use planning is to develop a fire management plan.

The Fire Management Plan

The fire management plan addresses fire use at the level of the administrative unit, such as a forest, nature preserve, park, ranch or plantation. It ensures that background information about the area has been researched, legal constraints reviewed, and a burn program found to be both justified and technically feasible. It proposes how fire will be applied to the landscape, both spatially and temporally. When managing for multiple resources (e.g., range, wildlife, and timber) on a tract, guidance should be provided regarding the allocation of benefits; i.e., should benefits to the same resource always be maximized on given burn units, or should the focus be rotated among benefits on some, or all burn units over time?

Items commonly addressed in the fire management plan are:

- Background information on the area, such as topography, soils, climate and fuels
- Applicable fire laws and regulations, including any legal constraints
- Landowner policy governing fire use on this tract of land
- Fire history of the area, including the natural fire regime, and recent fire occurrence or use
- Justification for fire management
- Fire management goals for the area, including a description of the desired future condition. (Objectives for specific burns are set in the burn unit plan, see below.)
- Fire management scheduling, qualitatively describing how fire will be applied to the site over time to achieve stated resource objectives. (Quantitative descriptions of fireline intensity, fire severity, and season of burn are set in the burn unit plan, see below.)
- Species of special concern, wildlife habitat issues, invasive species issues
- Definition and descriptions of treatment units or burning blocks
- Air quality and smoke management considerations
- Neighbor and community factors
- Maps illustrating fuels distribution, treatment units, smoke sensitive areas, etc.

When complete, this document should enable the resource manager to gain the support (both internal and external) and identify the resources needed to effectively and efficiently use fire as a management tool.

Community involvement in the fire planning process is crucial to public acceptance of fire use. At what stage 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 full, honest discussion of the potential for such results, and their ramifications, can defuse negative reaction to the occasional bad outcome, especially if the public was involved early in the planning process.

Further guidance for developing a fire management plan is available from a number of federal sources, including *Wildland and Prescribed Fire Management Policy: Implementation Procedures Reference Guide* (USDI and USDA Forest Service 1998), and from The Nature

Conservancy's *Fire Management Manual* (www.tncfire.org/manual).

The Burn Plan

Once the fire management plan is completed and approved, the next step is implementation—not an easy task. Resource managers are usually faced with numerous constraints, such as budget and staff limitations, equipment availability, timing of good burning conditions, and a lack of information on potential effects. A successful prescribed fire program requires the complete dedication of the fire management staff, full cooperation of all personnel and functional areas involved, and unwavering support and commitment throughout the chain of command.

Although the overall resource management goals for an individual burn unit often remain unchanged for long periods, the specific burn objectives for a given unit will likely vary over time, necessitating modifications to the unit plan for each burn. For example, the use of a heading fire during the growing season to promote biodiversity and flowering of ground layer plants may be the current burn objective, while a backing fire during the dormant season may have been used to reduce hazardous fuels loads the last time the unit was burned.

A written burn plan serves several important purposes:

- It makes the planner think about what he/she wants to achieve, and how it will be accomplished.
- It allows the fire manager to prioritize between burn units based on constraints and objectives.
- It functions as the operational plan that details how a burn will be safely and effectively conducted.
- It serves as the standard by which to evaluate the burn.
- It provides a record for use when planning future burns (which makes it essential to document any changes when the burn is conducted, directly on the plan).
- It becomes a legal record of the intended purpose and execution of the burn project.

There is no standard format for a burn unit plan; numerous examples are available which can be consulted for guidance. Sources include state and federal land management agencies, The Nature Conservancy's internet site (www.tncfire.org), or publications such as *A Guide to Prescribed Fire in Southern Forests* (Wade and Lunsford, 1989), which is available online from the Alabama Private Forest Management Team website (www.pfmt.org/standman/prescrib.htm), and from the Florida Division of Forestry (flame.fl-dof.com/Env/Rx/guide/).

Although formats differ, certain components should be included in all burn plans. They should address at least the following 12 topics:

1. **Assessment and Description of the Burn Unit.** The first step in developing a burn plan is to evaluate and document existing conditions. Factors to include depend on the site itself, as well as the complexity of the planned burn. The information recorded here will serve as the baseline from which success of the burn will be determined, so parameters used in the burn objectives should be assessed and described. Include details on the unit size (broken into single-day burn units); date of the last burn; overstory and under-

story vegetation, density and size; fuel type, density and size; soil type and topography; threatened and endangered species present; invasive species present; and current wildlife use.

2. **Maps.** Good maps of the treatment area are a key component of the burn plan. The map scale should be adequate to show pertinent information in meaningful detail. Be careful not to include too much information on a single map, making it difficult to read. The burn plan should include a series of maps showing the following: unit boundaries; adjacent land ownerships, including contact person and phone numbers; topography and manmade obstacles such as canals, ditches, and erosion gullies that would impede equipment or people; natural and constructed fire control lines; areas to be protected or excluded such as sawdust piles, utility poles and sensitive vegetation areas; firing plan; initial placement of equipment and holding personnel, and; escape routes and safety zones. Every crew member should receive a map with the information essential to personnel safety and burn operations.

3. **Measurable Burning Objectives**. Unit-specific treatment objectives identify the desired changes in affected resources from the present to the future condition. Treatment objectives are prepared within the context and intent of all resource management objectives. They are the measures against which the success of a burn is determined. Burn objectives make clear to everyone involved what is expected - including the burners, cooperators, managers, and the public. The objectives should be detailed statements that describe what the treatment is intended to accomplish, and as such, must be specific and quantifiable.

4. **Weather and Fuel Prescription**. The prescription defines the range of conditions under which a fire is ignited and allowed to burn to obtain given objectives. Fuel moisture (by size class) and weather conditions (temperature, humidity, wind, drought, dispersion index) are key factors in achieving objectives because they in large part determine fire behavior (intensity and severity), which in turn, governs ease of fire control and effects. These same parameters also affect smoke production and transport. Considerable care should therefore be taken in defining the window of conditions under which the projected burn may take place. Although there may be an ideal set of conditions that will maximize a single objective, the likelihood of this set of conditions occurring at the right time is typically extremely low. Therefore, a range of fuel and weather conditions are usually specified in the burn prescription that allow the skilled burner to compensate between various parameters to safely and efficiently conduct a successful burn—a burn which meets both the resource and smoke management objectives.

5. **Season and Time of Day**. The season of burn influences many burn parameters. Typically, acceptable burning conditions are more predictable during certain seasons, making it easier to plan and prepare for burns days in advance, but not all burn objectives may be achievable under those weather and fuel conditions. Regional effects are important in decision-making for this factor. For example, in the southeast, dormant season burns are generally more uniform in effects while growing season burns are more likely to be patchy. Backing fires are much easier to conduct during the dormant season when ground layer herbaceous plants are dead and burn readily, rather than green and succulent

thereby retarding fire spread. In the Pacific Northwest, season of burn can be used to reduce emissions. Broadcast burning of slash in the wet spring has been shown to produce 50% fewer emissions when compared to burning periods in the dry fall (Sandberg and Dost 1990). Selecting the correct season to execute a burn will help maximize the probability of achieving the burn objectives.

The timing of ignition determines whether the burn can be completed and mopped up as scheduled during the burning period. Timing is also important when considering factors such as: when solar radiation will break a nighttime inversion or dissipate any dew which formed during the night, when atmospheric conditions will support adequate transport and dissipation of smoke, when surface winds may develop or change speed or direction, or when a sea breeze front may reach the unit. Experienced burners become familiar with the area, and learn how to factor these time-sensitive influences into their burn plans.

6. **Smoke Management**. Planning a fire use project that has the potential to impact areas sensitive to smoke requires assessment of airshed and meteorological conditions 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. Specific regional issues should be addressed, such as mountainous terrain, fog, or sea breeze effects. This information normally will be developed by fire managers using their personal experience and knowledge of fire behavior, smoke transport and dispersion in the area, along with more formal emissions prediction and dispersion modeling.

Sensitive areas downwind of the burn unit should be identified and plotted on a map. Information such as distance and direction from the burn unit, the nature of the sensitivity, and when the area is considered sensitive should be included. Examples of smoke sensitive areas include Class I areas (generally, international parks, and large national parks and national wilderness areas), nonattainment areas, communities or individual residences, airports, highways, and medical facilities. Several procedures for predicting the potential impact of smoke on sensitive areas are discussed in chapter 9.

Smoke dispersion in areas prone to inversions, such as deep, mountainous valleys, is especially problematic in fire use planning. If the smoke remains trapped by the inversion, all of the emissions produced will remain trapped within the airshed.

The following smoke-related questions should be addressed in every plan:

- What quantity of emissions will it take to saturate this airshed?
- Where will the smoke concentrate if it settles under an inversion?
- Do special arrangements need to be made to protect populations impacted by these emissions?
- How many burning projects will it take cumulatively to exceed acceptable levels within this airshed?
- How long will the airshed remain stable and harbor the emissions?

In instances where a burn may affect an area especially sensitive to smoke, the use of air quality monitors may be advisable to ensure that an agreed-upon emission level or limit is not exceeded. Factors to consider in using monitors include placement of the device, personnel to operate the instrument, quality checks, data analysis, and provisions for real-time feedback if data is to be used in making a decision to terminate a burn in progress. Monitors are not commonly accessible and are costly to use, so this option is chiefly available to federal and state agencies. Air quality monitoring for evaluating a fire management program is discussed in Chapter 10.

Smoke impacts to fireline personnel should also be considered in a smoke management plan. The burn planner should consider projected exposure when determining the size of the burn crew and the duration of the work shift. More information on smoke exposure to fireline personnel can be found in Chapter 3.4.

Once an analysis of significant factors is complete, the planner should set specific, measurable smoke management objectives for the burn. These may include, for example, minimum visibility standards for roads or viewsheds, and an emissions limit if air quality monitors are to be used. Objectives provide a common understanding for all individuals involved in or affected by the burn, of what constitutes acceptable smoke impacts. They also provide a tool for the burn boss when deciding whether to terminate a fire because of problematic smoke behavior. If the decision is made to terminate a burn because of smoke problems, it should be remembered that direct suppression often temporarily exacerbates smoke problems. If ignition has been completed, the best strategy may be too let the fire burn out.

The amount of air quality analysis required at all levels of fire planning will be influenced by air quality laws and smoke management regulations. Formal state smoke management programs are becoming increasingly common, but are not yet universal. Some states include only regulatory language regarding “nuisance smoke.” Complying with all applicable laws and regulations is a basic tenet of conscientious land stewardship, but responsible fire use and air quality planning include looking beyond the requirements of the law. Communities likely to be impacted by a fire-use program should be involved in determining what their threshold of acceptance is for smoke from wildland fire. Thorough attention to smoke management planning can prevent future problems.

7. **Notification of Local Authorities and the Public**. Early development of a notification plan will assist in the necessary communication with local authorities and the public. A wide variety of methods have proven successful, including distribution of pamphlets or flyers, public meetings, newspaper and radio announcements, and Internet postings. The public should be notified well in advance of the proposed burn day, and again within a few days of executing the burn. Generally, there is a list of individuals to be notified on the actual burn day. This list is often unit-specific, and should be included along with telephone numbers in the burn plan.

8. **Environmental and Legal Constraints**. If constraints to the burn plan have not already been addressed in a fire management plan for the entire site, they should be addressed here because they can limit or determine how a burn is implemented. These may include environmental, economic, operational, administrative, and legal constraints.

9. **Operations**. The burn plan must describe in detail how fire will be used. This section of the plan may take any number of formats, but the topics to be addressed include:

    - Safety. What provisions will be made to ensure the safety of the crew?
    - Communications. How will the crew communicate with each other, and with dispatch or emergency support?
    - Equipment and Personnel. What resources are needed to effectively accomplish the burn and how will they be deployed?
    - Fire Lines. What is the width and condition of existing fire lines? How many chains of fireline need to be prepared or cleared? How will this be accomplished?
    - Ignition Pattern and Sequence. How will the burn be ignited? Ignition duration and firing patterns play an important role in production and lofting of emissions. Rapid ignition may reduce consumption, therefore emissions, and be successful in lofting a smoke column high into the atmosphere. Backing fires produce fewer emissions than heading fires. More information on using ignition to manage emissions production can be found in Chapter 8, Techniques to Reduce Emissions and Impacts.
    - Holding. How will the fire be kept within its predetermined boundaries? How will snags be dealt with?
    - Mop-up. How will the burn be extinguished? What standard will be used to consider the burn unit safe to leave?

10. **Contingency Planning**. Contingency plans outline procedures for dealing with a burn gone awry. They are a normal part of a burn plan and should include provisions to deal not only with escaped fire, but also with unexpected smoke intrusions during an otherwise controlled burn. Some of the issues to be addressed include safety of the general public and the fire crew, sources of assistance for fire control and smoke-related problems, deployment of resources, actions to be taken to rectify the problem, notification of authorities and the public, and measures to mitigate smoke on roadways. It should be recognized that in some cases where smoke problems dictate shutting down a burn after ignition has been completed, the most prudent action may be to allow the unit to burn out rather than to immediately extinguish it, which can temporarily exacerbate smoke production.

11. **Preburn Checklist**. Every burn plan should include a checklist to be reviewed immediately prior to ignition. The checklist should include the factors essential to safe execution of the burn project, and a list of points to review with the crew during the preburn briefing. The use of the checklist ensures that some detail does not slip by the burn manager’s attention in the busy moments preceding a fire.

12. **Monitoring and Evaluation**. Monitoring and evaluation of the burn are key to learning from the process and making refinements for subsequent burns. Where appropriate and practical, monitoring and post-fire evaluation protocols describing the effects on soil, water, air, vegetation, and wildlife should be included in the burn unit plan. Alternatively, the information can be included in a post-burn evaluation report or form, which is attached to the burn plan after completion.

- Documenting air quality conditions before, during, and after a fire is useful in identifying nuisance smoke thresholds and assuring that air quality standards have not been exceeded. Additionally, monitoring and documenting smoke transport, dilution, or concentrations in each airshed can help develop local knowledge that is the basis of predicting smoke impacts. In addition to environmental effects, the following topics should be addressed: adequacy of preburn treatments, fire behavior, degree to which objectives were achieved, discrepancies between planned fuel and weather components and on site measurements, observations, accidents or near-accidents, slopovers, and recommend changes for future burns. A series of photographs over time at permanent photo points is an excellent inexpensive method to document vegetation changes.

Fire Use Planning for Federal Land Managers

The *Wildland and Prescribed Fire Management Policy: Implementation Procedures Reference Guide* (USDI and USDA Forest Service 1998) represents an effort by Federal wildland fire management agencies to establish standardized procedures to guide implementation of the policy described in the 1995 Federal Wildland Fire Management Policy and Program Review. It uses new terminology and definitions to provide consistency and interpretation to facilitate policy implementation, and describes relationships between planning tiers to fire management objectives, products, and applications.

The federal process generally follows the planning process described above. The flow of information begins with the land and resource management plan, variously called the Forest Management Plan (FS), Integrated Resource Management Plan (BIA), Resource Management Plan (NPS), Comprehensive Conservation Plan (FWS) and the Forest Management Plan (FS). This plan determines the availability of land for resource management, predicts levels of resource use and outputs, and provides for a variety of resource management practices.

The next step is preparation of the Fire Management Plan (FMP). The FMP is the primary tool for translating programmatic direction developed in the land management plan into on-the-ground action. The FMP must satisfy NEPA requirements, or follow direction provided by a Forest Plan that has been developed through the NEPA process. Comparisons between fire use activities and no fire use should be described in the NEPA process. This includes implications of wildland fire and prescribed fire use over extended periods of time.

The most detailed step in the process involves the tactical implementation of strategic objectives for the wildland and prescribed fire management programs. It is at this level where specific plans are prepared to guide implementation of fire-related direction on the ground. This step includes Prescribed Fire Plans, Wildland Fire Implementation Plans, and the Wildland Fire Situation Analysis.

More information on the smoke management requirements and federal planning process is contained in Chapter 4.

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Chapter 7

SMOKE MANAGEMENT METEOROLOGY

Smoke Management Meteorology

Sue A. Ferguson

Once smoke enters the atmosphere, its concentration at any one place or time depends on mechanisms of transport and dispersion. By transport, we mean whatever carries a plume vertically or horizontally in the atmosphere. Dispersion simply is the scattering of smoke.

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 stability and wind that control transport and dispersion, we begin with a few elemental concepts.

Air Pressure

It is helpful to understand air pressure because storms and stagnant air conditions are described in terms of low pressure and high pressure, respectively. Lines of constant pressure are used to illustrate the state of the atmosphere on weather maps, and pressure influences the expansion and contraction of smoke parcels as they travel through the atmosphere. Air pressure is the force per unit area exerted by the weight of the atmosphere above a point on or above the earth’s surface. More simply it can be thought of as the weight of an overlying column of air. Air pressure is greatest near the ground, where the overlying column of air extends the full height of the atmosphere. Pressure decreases with increasing altitude as the distance to the top of the atmosphere shortens.

In a *standard* atmosphere, which represents the horizontal and time-averaged structure of the atmosphere as a function of height only, pressure decreases approximately exponentially with height. With 1,013 millibars (mb) being the standard atmospheric pressure at sea level, the average height of the 850 mb pressure level typically occurs at about 5,000 feet (~1,500 m), the 700 mb pressure level typically occurs at about 10,000 feet (~3,000 m), and the 500 mb height averages around 20,000 feet (~6,000 m). In the lowest part of the atmosphere (less than about 8,000 feet) pressure decreases by approximately 30 mb per 1000 feet. These are useful values to remember when analyzing meteorological data and maps for smoke management. Actual pressure is nearly always within about 30% of standard pressure.

Lapse Rates

Lapse rate is the decrease of temperature with height. Lapse rates help determine whether smoke will rise from a fire or sink back to the surface and are used to estimate atmospheric stability. When air is heated it expands, becomes less dense and more buoyant. This causes it to rise. A parcel of air that is heated at the ground surface by fire or solar radiation becomes warmer than its surroundings, causing it to lift off the surface. As it rises, it encounters lower pressure that causes further expansion. The more air expands, the cooler it becomes. If a parcel of air becomes cooler than its surroundings, it will sink.

Cooling by expansion without an exchange of heat at the parcel boundaries is called adiabatic cooling. In dry air, rising air parcels typically cool at a rate of about 5.5 °F per 1,000 feet (~ 10 °C/km). This is called the dry adiabatic lapse rate (DALR). For example, on a clear day if a heated parcel of air begins at sea level with a temperature of 70 °F (~21 °C), it will cool dry-adiabatically as it rises, reaching a temperature of 53.5 °F (~12 °C) at 3,000 feet (~915 m).

Rising moist air (relative humidity greater than about 70%) is said to undergo a saturation-adiabatic process. The saturated adiabatic lapse rate (SALR) or moist adiabatic lapse rate is a function of temperature and water content. This is because as moist air cools its water vapor condenses, giving off latent heat in the condensation process and causing a saturated parcel to cool more slowly than a dry parcel. Near the ground in mid-latitudes the SALR can be approximated at a rate of about 3 °F per 1,000 feet (~ 5.5 °C/km). For example, on a humid or rainy day, a heated parcel with a 70 °F (~21 °C) initial temperature at sea level, will reach a temperature of 61 °F (~16 °C) at 3,000 feet (~915 m).

Lapse rates are determined by comparing temperatures between different elevations. The temperature from a ridge-top weather station can be subtracted from the temperature at a nearby valley-located weather station to calculate lapse rate. More commonly, radiosonde observations (raobs) are used to determine lapse rates. These balloon-mounted instruments measure temperature, wind, pressure, and humidity at several elevations from the ground surface to thousands of feet. Raobs are available from weather services or at several sites on the Internet twice each day: at 0000 Universal Time Coordinated (UTC)[1] and 1200 UTC.

There are several ways of plotting raob data. Typically a pseudo-adiabatic chart is used. This chart shows measured values of temperature vs. pressure over lines of DALR and SALR. Figure 7.1 illustrates how the above examples would appear on a standard pseudo-adiabatic chart. More recently, skew-T/log-P diagrams (skew-T for short) have become popular. Instead of plotting temperature and pressure on linear, orthogonal axes, skew-T diagrams plot the log of pressure and skew the temperature axis by 45°. The skew-T/log-P view of raob data allows features of the atmosphere to be more obvious than when plotted on a standard pseudo-adiabatic chart. Figure 7.2 illustrates the above examples on a skew-T diagram. On both standard pseudo-adiabatic charts and skew-T diagrams, elevation in meters or feet (corresponding to the pressure of a standard atmosphere) may be shown and wind direction and speed with height is represented parallel to or along the right-hand vertical axis. Many other features also may be included.

Atmospheric Stability

Atmospheric stability is the resistance of the atmosphere to vertical motion and provides an indication of the behavior of a smoke plume. Full characterization of a smoke plume requires a complete estimation of the atmosphere's turbulent structure that depends on the vertical patterns of wind, humidity, and temperature,

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[1] Universal Time Coordinated (UTC) is Standard Time in Greenwich, England. UTC is 9 hours ahead of Alaska Standard Time (AST), where 0000 UTC = 1500 AST and 1200 UTC = 0300 AST. UTC is 5 hours ahead of Eastern Standard Time (EST), where 0000 UTC = 1900 EST and 1200 UTC = 0700 EST.

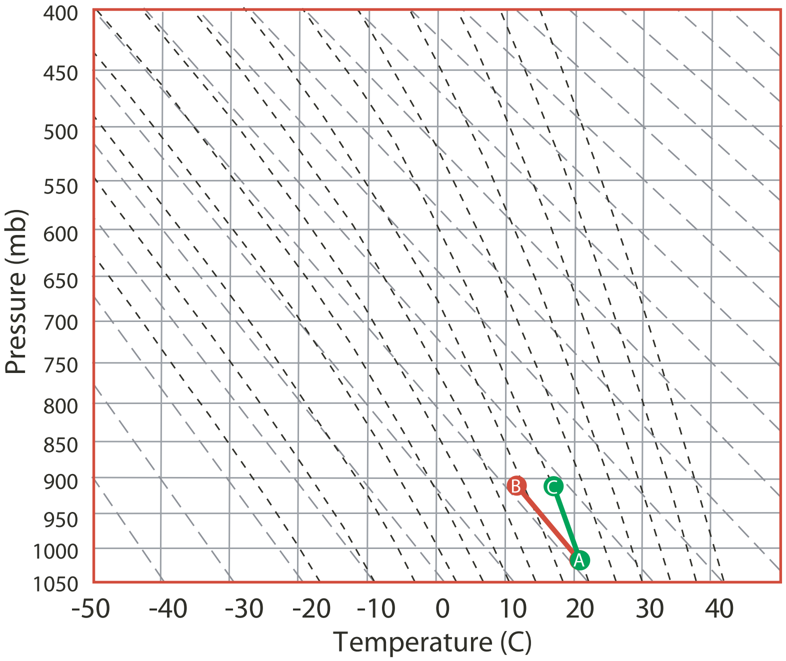

Figure 7.1. Standard pseudo-adiabatic chart. Short-dashed lines show the saturated adiabatic lapse rate (SALR) and long-dashed lines show the dry adiabatic lapse rate (DALR). Point A marks a parcel of air at the surface with a temperature of 21 °C (70 °F). If the atmosphere is dry, the parcel will follow a DALR as it rises and reach point B with a temperature of 12 °C (53.5 °F) at 915m (3000 ft). If the atmosphere is saturated, the parcel will follow a SALR as it rises and reach point C with a temperature of 16°C (61 °F) at 915m (3000 ft).

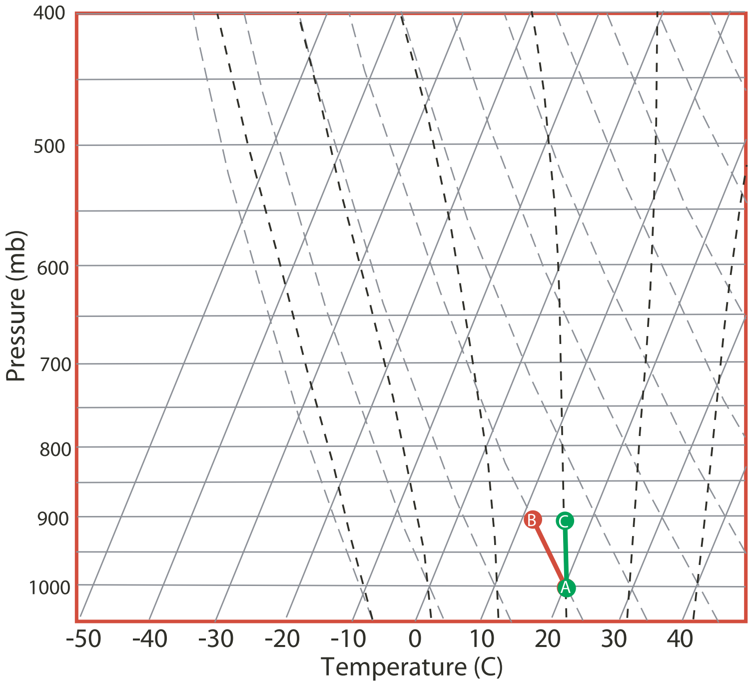

Figure 7.2. Skew-T pseudo-adiabatic chart. Short-dashed lines show the saturated adiabatic lapse rate (SALR) and long-dashed lines show the dry adiabatic lapse rate (DALR). Point A marks a parcel of air at the surface with a temperature of 21 °C (70 °F). If the atmosphere is dry, the parcel will follow a DALR as it rises and reach point B with a temperature of 12 °C (53.5 °F) at 915m (3000 ft). If the atmosphere is saturated, the parcel will follow a SALR as it rises and reach point C with a temperature of 16°C (61 °F) at 915m (3000 ft).

which are highly variable in space and time. Because this can be a complex calculation, it often is approximated by estimates of static stability. The static stability of the atmosphere is determined by comparing the adiabatic lapse rate with ambient, environmental lapse rates (as would be measured from instruments on a rising balloon). By this approximation, an unstable air mass is one in which the temperature of a rising parcel of air remains warmer than its surroundings. In a stable air mass, a rising parcel's temperature is cooler than ambient and a neutral air mass is one in which the ambient temperature is equal to the adiabatic lapse rate.

The most common way of estimating static stability is to note the slope of vertically measured temperature in relation to the slope of the dry (or moist) adiabatic line from a pseudo-adiabatic chart. Figure 7.3 shows raob-measured dry-bulb and dew-point temperatures and the theoretical trajectory of a parcel being lifted from the surface. The parcel trajectory begins at the current surface temperature then follows a DALR until it becomes saturated. The point of saturation is called the lifting condensation level (LCL). Its height in meters can be approximated as 120 x (T_0 – T_d), where T_0 is the temperature at the surface and T_d is the mean dew-point temperature in the surface layers, both in degrees Celsius. From the LCL, the parcel trajectory follows a SALR.

Throughout the depth of the diagram in figure 7.3, the slope of the measured temperature is nearly always steeper than the slope of the adiabatic temperature, suggesting that a lifted parcel always will remain cooler than the ambient temperature, which is a sign of stability. The large distance between the measured temperature and the temperature of the theoretical parcel trajectory also gives an indication of strong

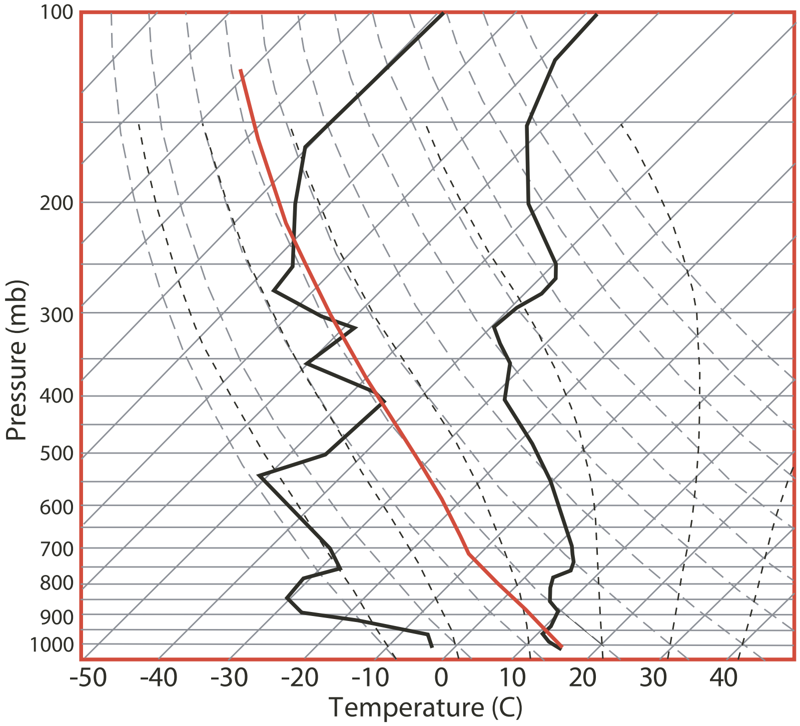

Figure 7.3. Skew-T plot of a stable atmosphere. The thick black line on the right is the measured environmental dry-bulb temperature. The thick black line on the left is the measured environmental dew-point temperature. The red line is a theoretical parcel trajectory. Short-dashed lines are the SALR and long-dashed lines are the DALR.

stability. In a stable atmosphere, smoke emanating from relatively cool fires will stay near the ground. Hot fires may allow plumes to loft somewhat through a relatively stable atmosphere but fumigation of smoke near the ground remains common. Figure 7.4 shows smoke from a vigorous wildfire under a stable atmosphere. Smoke plumes are trying to develop but a strongly stable layer is trapping most smoke just above the ridge tops.

Parcel trajectories in an unstable atmosphere remain warmer than the measured environmental temperatures (figure 7.5). During unstable conditions, smoke can be carried up and away from ground level. Downwind of the source the instability causes smoke plumes to develop a looping appearance (figure 7.6). Obviously there are many variations between stable and unstable atmospheres that cause various patterns of lofting, fanning, coning, looping, and fumigation. Each situation shows characteristic signatures on a pseudo-adiabatic chart but some experience may be required to distinguish the subtle differences.

Because upper-air observations and observations from significantly different elevations are not always available, Pasquill (1961 and 1974) developed a scheme to estimate stability from ground-based observations. Not only is this classification system used to estimate plume characteristics; it also is used in many smoke dispersion models as a proxy for atmospheric turbulence. Table 7.1 shows the Pasquill classification criteria as modified by Gifford (1962) and Turner (1961, 1964, 1970). In this example, surface wind is measured at 10 meters above open terrain. With clear skies, the class of incoming solar radiation is considered strong, moderate, or slight if the solar altitude angle is greater than 60°, between 35° and 60°, or less than 35°, respectively. If more than 50 per cent opaque cloud cover is present and the cloud

Figure 7.4. A smoke plume from a vigorous wildfire during stable atmospheric conditions. Photo by Roger Ottmar.

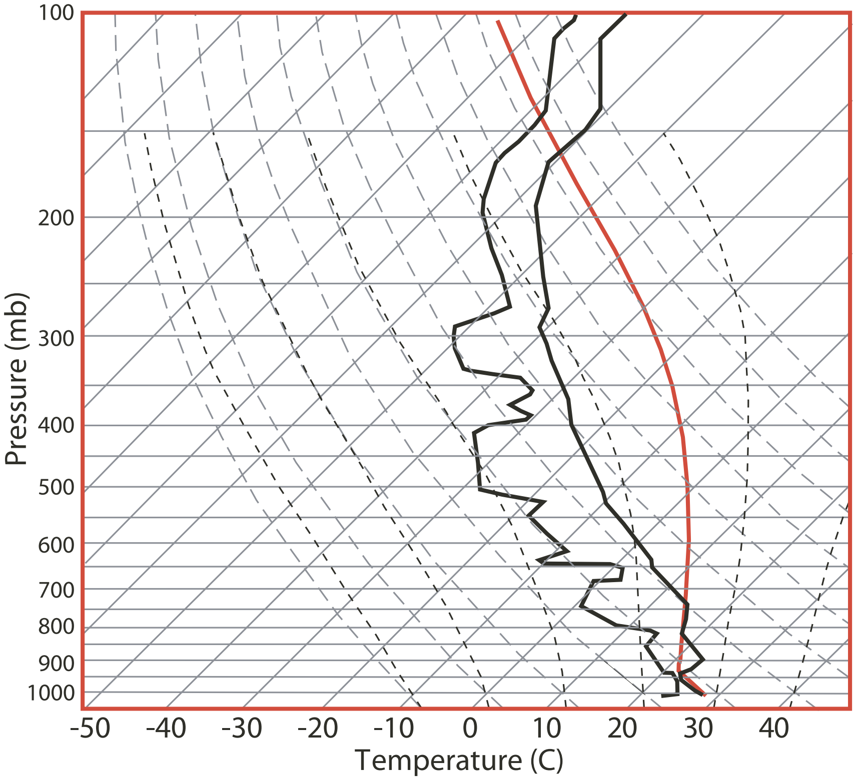

Figure 7.5. Skew-T plot of an unstable atmosphere. The thick black line on the right is the measured environmental dry-bulb temperature. The thick black line on the left is the measured environmental dew-point temperature. The red line is a theoretical parcel trajectory. Short-dashed lines are the SALR and long-dashed lines are the DALR.

Table 7.1. Pasquill stability classification criteria, where A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, and F= moderately stable. See text for an explanation of the incoming solar radiation classes.

Surface Wind (m/s)	Daytime Incoming Solar Radiation			Nighttime Cloudiness	
	Strong	Moderate	Slight	≥ 4/8	≤ 3/8
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Figure 7.6. A smoke plume during unstable atmospheric conditions. Photo by Roger Ottmar.

ceiling height is less than 7,000 feet (~2,100m), the solar class is slight. If ceiling height is between 7,000 feet and 16,000 feet (~4,800m), then the solar class is one step below what it would be in clear sky conditions. At night, classification is based on the amount of sky that is obscured by clouds. An objective way of determining stability classification is shown in Lavdas (1986) and Lavdas (1997).

Mixing Height

Mixing height (also called mixing depth) is the height above ground level through which relatively vigorous vertical mixing occurs. Low mixing heights mean that the air is generally stagnant with very little vertical motion; pollutants usually are trapped near the ground surface. High mixing heights allow vertical mixing within a deep layer of the atmosphere and good dispersion of pollutants. As such, mixing heights sometimes are used to estimate how far smoke will rise. The actual rise of a smoke plume, however, considers complex interactions between atmospheric stability, wind shear, heat release rate of the fire, initial plume size, density differences between the plume and ambient air, and radiant heat loss. Therefore, an estimate of mixing height provides only an initial estimate of plume height.

Mixing heights usually are lowest late at night or early morning and highest during mid to late afternoon. This daily pattern often causes smoke to be concentrated in basins and valleys during the morning and dispersed aloft in the afternoon. Average morning mixing heights range from 300 m (~980 ft) to over 900 m (~2,900 ft) above ground level (Holzworth 1972). The highest morning mixing heights occur in coastal areas that are influenced by moist marine air and cloudiness that inhibit radiation cooling at night. Average afternoon mixing heights are typically higher than morning heights and vary from less than 600 m (~2,000 ft) to over 1400 m (~4,600 ft) 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.

Ferguson and others (2001) generated detailed maps and statistics of mixing heights in the United States.

Smoke plumes during the flaming stage of fires often can penetrate through weak stable layers or the top of mixed layers. Once the plume dynamics are lost, however, the atmosphere retains control of how much mixing occurs. Low-level smoke impacts increase once a convective column collapses.

The depth of the mixed layer depends on complex interactions between the ground surface and the atmosphere in a region called the planetary boundary layer (PBL). As such, it is difficult to measure exactly and there are many ways in which it is calculated. At times, it is possible to estimate the mixing height by noting the tops of cumulus clouds or the presence of an upper-level inversion, which may appear as a deck of strata-form clouds.

Typically, National Weather Service (NWS) smoke management forecast products will estimate the mixing height by the so-called parcel method. This method considers turbulence related only to buoyancy. When a parcel is lifted adiabatically from the surface, the point at which it intersects the ambient temperature profile, or where it becomes cooler than its surroundings, is the mixing height. Usually the maximum daily temperature is used as the parcel's starting temperature and its adiabatic lapse rate is compared with the afternoon (0000 UTC) sounding profile. Conversely, the minimum daily temperature is used to compare with the morning (1200 UTC) raob for calculating morning mixing heights. If an elevated inversion (see next section) occurs before this height is reached, the height of the inversion base would determine the mixing height. If a surface inversion exists, then its top marks the mixing height. For example, the mixing height in figure 7.3 is at the top of the surface-based inversion at about 750 mb (approximately 2,400 meters or 7,800 feet above ground level).

Instead of approximating a mixing depth, physical calculations of the PBL are possible through numerical meteorological models. These calculations are more precise than the parcel method because they consider turbulence generated by wind shear as well as buoyancy. Each prognostic model, however, may calculate the PBL slightly differently as some functions are approximated while others are explicitly derived to enhance computational efficiency and the vertical resolution, which varies between models, affect PBL calculations.

Temperature Inversions

When the ambient temperature increases with height, an inversion is said to be present. It usually marks a layer of strong stability. When a heated air parcel from the surface encounters an inversion, it will stop rising because the ambient air is warming faster than the expanding parcel is cooling. The parcel being cooler than its surroundings will sink. Although the heat from some fires is enough to break through a weak inversion, inversions often are referred to as lids because of their effectiveness in stopping rising air and trapping pollutants beneath it. Smoke trapped under an inversion can substantially increase concentrations of particles and gases, aggravating respiratory problems and reducing visibility at airports and along roadways.

There are three ways that surface-based inversions typically form: (1) valley inversions are very common in basins and valleys during clear nights when radiation heat losses cause air near the ground to rapidly cool: the cold surface air flows from the surrounding slopes and collects in hollows and pockets, allowing warmer air to remain aloft; (2) advective inversions are caused by cold air moving into a region from a nearby lake or ocean, usually during the afternoon when onshore lake and sea breezes tend to form; and (3) subsidence inversions can occur at any time of day or night as cold air from high altitudes subsides or sinks under a region of relatively stagnant high pressure. Valley inversions cause tremendous problems when managing long-duration fires that continue into the night. Advective inversions can surprise smoke managers who are unfamiliar with local lake- and sea-breeze effects, creating poor dispersal conditions in an afternoon when typically good dispersion is expected. Subsidence inversions are difficult to predict even for a well-trained meteorologist. Figure 7.7 shows smoke caught under a valley inversion that is being transported by down-valley winds in the early morning.

Surface inversions also occur in the gaps (passes and gorges) of mountain ranges. Approaching storms usually have an associated center of low pressure that causes a pressure gradient across the range. If cold air is on the opposite side of the range, the gradient in pressure causes the cold air to be drawn through the gap, creating an inversion in the gap. Gap inversions are most common in winter but also are frequent during spring and autumn.

In addition to surface-based inversions, temperature inversions also occur in layers of the atmosphere that are above the ground surface, which sometimes are called thermal belts. Upper-level inversions usually are associated with incoming warm fronts that bring moisture and warmth to high altitudes well ahead of a storm. The inversion lowers to the ground as the front approaches. Upper-level inversions also may be associated with subsidence or surface-based inversions that have been lifted, usually by daytime heating.

Wind

Not only does smoke mix and disperse vertically, the horizontal component of wind readily transports and disperses pollutants. The stron-

Figure 7.7. A plume of smoke flowing out of a mountain valley with down-slope winds during the early morning. Photo by Roger Ottmar.

ger the wind, the more scattered particles become and the less concentrated they will be. Strong winds at the surface, however, can increase fire behavior and associated emission rates. Also, significant surface winds may "lay-down" a plume, keeping smoke close to the ground for long distances.

Friction with the ground causes winds 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. This pattern is complicated in regions of complex terrain, however, and it is common to find stronger surface winds in mountain passes, saddles, and gorges as air is squeezed and funneled through the gap. 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 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, smoldering smoke at night responds to surface winds while daytime smoldering and 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 the upper-level smoke trajectories may be from just above a forest canopy to 10,000 feet (about 3,000 meters) or more. Because flaming heat can create convective columns with strong vertical motion, most smoke during the flaming portion of a fire will be carried to at least the top of the mixing height or an upper-level inversion height before dispersing. In this way, a fire hot enough to pull itself into a single convection column can reduce concentrations near the ground and knowledge of winds at the top of the mixing height or inversion level will determine smoke trajectory and dispersion. Smoldering smoke, on the other hand, has very little forced convection so it often fumigates away from a fire as it rises with daytime buoyancy. Knowledge of wind all the way from the surface to top of the mixing height may be needed to determine smoldering trajectories.

Storm Winds – Storms change the structure of winds entirely. Because storms often bring high instability and good dispersion, it is common to plan fires slightly ahead of an approaching storm. Knowing storm wind patterns can help anticipate associated smoke impacts. Figure 7.8 shows surface wind directions[2] typically associated with a passing cyclonic storm. Because air flows from high pressure to low pressure (like the rush of air from a punctured tire) and storms usually have a center of low pressure at the surface, surface winds ahead of a storm in the northern hemisphere will be from the east or southeast. As the low center approaches, surface winds will become southerly to southwesterly. After the storm passes, surface winds may become more westerly or northwesterly. This pattern can cause smoke to move toward the west to northwest then north to northeast ahead of a cyclonic storm, moving toward the east and southeast following storm passage.

Each cyclonic storm usually contains at least one front (a boundary between two different air masses). A typical storm has a warm front aligned northwest to southeast ahead of the low center, a cold front trailing northeast to southwest near and closely behind the low, and an occluded front (formed when a cold front overtakes a warm front) to the north of the low. Winds change direction most rapidly and become gusty when fronts pass by. Warm fronts can bring increasing stability and cause upper-

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[2] Wind direction is the direction from which the wind is blowing. For example, a west wind is coming from the west and blowing toward the east. If you face east, a west wind will hit your back.

level inversions, while cold fronts usually are associated with strong instability. The stronger the front, the more dramatic the wind shift and the stronger the gusts. Cold frontal passage typically improves dispersion of smoke with stronger winds and an unstable air mass that can scour away existing inversions. Smoke trajectories should be expected to change direction with the passage of a storm front and storms can cause significant changes in fire behavior and resulting emission rates. Storm fronts are not always typical, however, and the number, strength, and orientation of fronts are quite variable.

Strong winds above the influence of the earth's surface experience forces associated with the earth's rotation in addition to pressure gradient and other forces. This causes winds in the upper atmosphere to follow lines of constant pressure instead of moving across lines of constant pressure as surface or lower-speed winds do when air flows from high pressure to low pressure. In the upper atmosphere the pressure pattern of a typical storm is shaped like a trough (figure 7.9). As air follows the pressure contours around the trough, southwesterly upper-level winds occur 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 most moving fronts, causing smoke trajectories aloft to change directions sometime after trajectories at the surface have changed following a storm passage.

Thunderstorms, which are the result of strong convection, create much different wind patterns

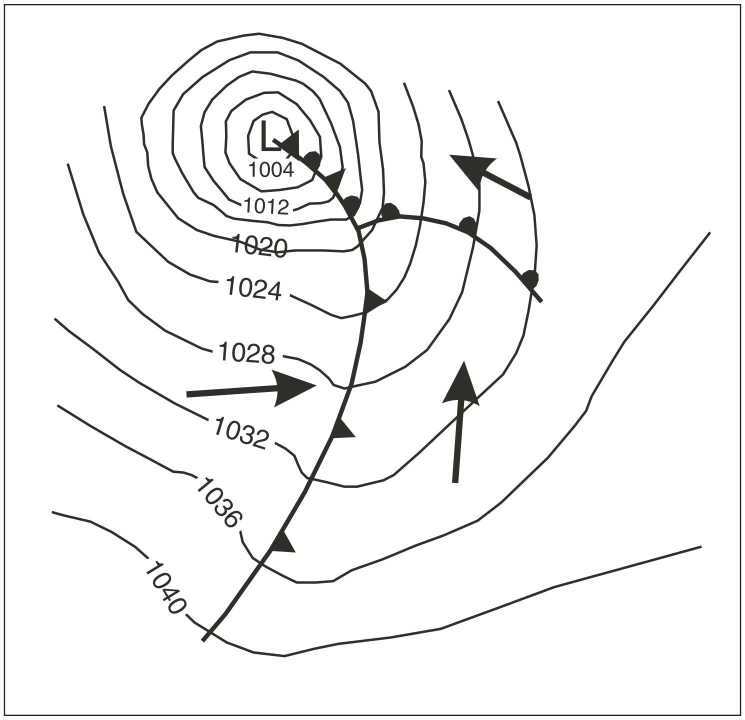

Figure 7.8. Schematic of surface winds associated with a typical cyclonic storm in the Northern Hemisphere. The letter, L, marks position of the surface low pressure center. Thin lines represent isobars (constant pressure contours that are labeled in millibars) at sea level. The thick line marked with barbs represents a surface cold front, marked with half-circles is a warm front, and marked with both is an occluded front. East to southeast surface winds are common ahead of a warm front, south to southwest winds are common ahead of a cold front, and west to northwest winds are common following a cold front.

than cyclonic storms. Gusty, shifty winds are common at times of strong convection. Strong down bursts of wind in a direction away from the thunder cell may occur several minutes ahead the storm, while winds around the cell may be oriented towards it. Although mixing heights usually are quite high during thunderstorms, allowing for well-lofted plumes, the shifting wind directions and strong gusts can cause variable and unpredictable smoke trajectories and fire behavior in close proximity to thunderstorms.

Diurnal Winds – In the absence of storms, diurnal wind patterns dominate trajectories of smoke near the ground. Diurnal patterns are caused by differences between radiational cooling at night and solar heating during the day, and by different thermal properties of land and sea surfaces that cause them to heat and cool at different rates. The differential heating causes changes in surface pressure patterns that control air movement. Slope winds and sea and lake breezes, all of which are common in wildland smoke management situations, typify diurnal patterns.

Slope 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

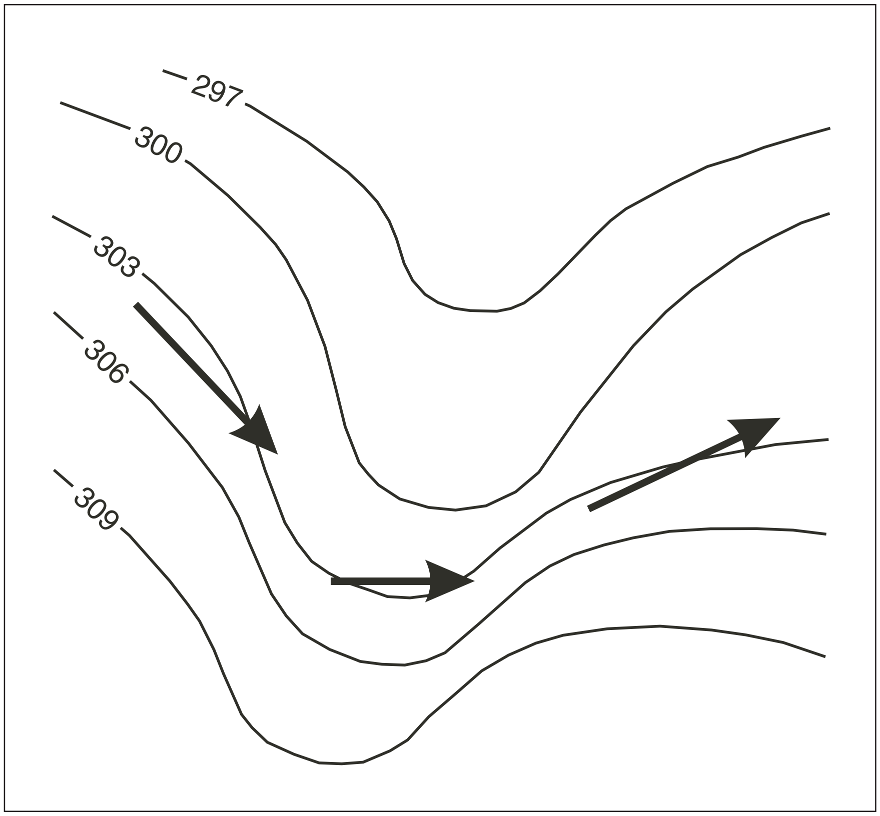

Figure 7.9. Schematic of upper-level (700 mb) winds associated with a typical stormy trough pattern in the Northern Hemisphere. Thin lines represent pressure height contours that are labeled in tens of meters. South to southwest upper-level winds are common ahead of a 700 mb trough, westerly winds are common as the trough passes, and northwesterly winds are common following an upper-level trough.

than its surroundings, usually hugs the terrain in such a way that smoke following a drainage wind will follow 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, the 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. 1988), 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 before sunrise.

Sea and lake breezes 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. The sea or lake breeze not only can change smoke trajectories but the incoming cool air can cause surface based inversions that will trap smoke at low levels near the ground. Also, strong sea breezes can knock plumes down, causing increasing smoke concentrations near the ground.

Terrain-Influenced Wind – Surface winds are 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 upper-level winds are oriented perpendicular to a terrain barrier, surface winds on the lee side of the barrier often are light and variable. Upper-level winds oriented in the same direction as a valley will enhance upvalley or downvalley winds. Cross-valley winds will be 90° different than those in the valley itself.

The combination of wind and atmospheric stability determine whether smoke will collect on the windward side of a terrain barrier, move up, over and away, or traverse the barrier only to accumulate on the leeward side. Weak winds and a stable atmosphere will enhance blocking and windward accumulations of smoke. Stronger winds in a stable atmosphere may allow accumulations of smoke in leeward valleys and basins. An unstable atmosphere allows smoke to be lifted over and above the terrain. 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.

Often very small-scale undulations in topography can affect smoke trajectories, especially at night when atmospheric stability keeps smoke close to the ground. Gentle saddles in ridges may offer outflow of smoke from a valley. Small streambeds can collect and transport significant amounts of smoke even with only shallow or weak downslope winds. A simple band of trees or brush may provide enough barrier to block or deflect smoke. As the urban-wildland interface becomes increasingly complex, the role of subtle topographic influences becomes increasingly important.

Higher in the atmosphere, away from the earth's surface, topography plays a decreasing role in controlling wind speed and direction. Upper-level winds above the influence of underlying terrain are referred to as "free-air" winds and tend to change slowly from one place to another, except around fronts and thunderstorms.

The Role of Inversions on Wind – Temperature inversions significantly influence wind direction and speed. Under many inversions there is little or no transport wind and smoke tends to smear out in all directions. Some inversions, such as advected inversions that are associated with sea breezes and valley inversions, may have significant surface wind but it usually is in a different direction to winds aloft. In these cases, surface smoke may be transported rapidly under the inversion in one direction while lofted smoke may be transported in an opposite direction.

Wind Observations – Because surface winds are strongly influenced by small undulations in terrain, vegetation cover, and proximity to 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 will give a poor indication of 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 representative of burn-site conditions than one that is farther away if the distant station is in a location that better matches terrain effects expected at the burn site.

There are four principle sources of surface wind data: (1) on-site measurements with a portable RAWS or hand-held anemometer, (2) observations that estimate winds using the Beaufort wind scale[3] or wind sock,[4] (3) local measurements with a standard RAWS, and (4) measurements from NWS observing stations. Because stations vary in their surroundings, from small clearings on forested slopes to open fields, and different types of anemometers are used that are mounted at different heights, wind data is very difficult to compare between one site and another. Therefore, it is useful to become familiar with measurements and observations from reliable sites and understand local effects that make data from that 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. Frequently light and variable wind measurements actually are 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, often it is possible to use an upper-level observation from some point well away from the burn site to estimate upper-level smoke trajectories. Also, surface RAWS that are mounted on the tops of ridges or mountains may compare well with free-air winds at a similar elevation. If clouds are in the area, upper-level winds 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 5 km and 13 km (about 16,000 to 45,000 feet) their movement can indicate wind at those high levels. Mid-level clouds may have shades of gray or bulbous edges with bases ranging from 2 km to 7 km (about 6,6000 to 24,000 feet). Mid-level clouds often have a strata-form or layered appearance, which may indicate the presence of an inversion.

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[3] 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).

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

Therefore, movement of these types of clouds may closely approximate steering winds for a rising smoke plume.

In addition to observations, it is becoming increasingly common to have available the output from wind models. These data do not provide the detail of a point observation the way 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 850 mb, 700 mb, and 500 mb heights, either from a state, federal, or private meteorological service, or a variety of Internet sites. For surface winds, standard NWS analyses are helpful in regions of flat or gently rolling terrain but mesoscale meteorological models typically are needed to resolve surface wind fields in regions of complex topography. Several regions throughout the country are beginning to employ mesoscale models (e.g., MM5, RAMS, and MASS) producing wind maps with less than 15 km horizontal spacing. Local universities, research labs, state offices, and consortia of local, state, and federal agencies have undertaken mesoscale modeling efforts. Output usually can be found on a local Internet site through the NWS forecast office, a fire weather office, university, state regulator, EPA office, or regional smoke manager. Also, many smoke dispersion models have built-in wind models to generate surface winds at very fine spatial resolutions (less than 5 km grid spacings) from inputs of surface and upper-air observations or data from coarser meteorological models. Smoke dispersion models and their related wind models may be available through a regional smoke manager or EPA office (see Chapter 9—Smoke Dispersion Prediction Systems).

Atmospheric Moisture

Because water vapor in the atmosphere reduces visibility, if smoke is added to an already humid environment, visibility can be severely degraded. Also, if the air is saturated with water vapor, particles from smoke may act as condensation nuclei causing water droplets to form. This promotes the formation of clouds or fog, which further degrades visibility. Often a deadly combination occurs during the darkness of night as smoldering smoke drains down-valley to encounter high humidities from condensing cold air under a valley inversion. The effect can be fatal, especially along transportation corridors (Achtemeier and others 1998).

Favorable conditions for fog occur when the dew point temperature is within a few degrees of the dry bulb temperature, wind is less than a few meters per second, and there is a high content of moisture in the soil. Fog is most common at night when temperatures often drop to near the dew point value and winds are most likely to be 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 typically are produced twice each day and become available within 3 to 6 hours after 0000 UTC and 1200 UTC observations are complete. This is because prognostic models require input data from the 0000 UTC and 1200 UTC upper-air observations and a few hours of run-time on a super computer. Prognostic models (progs) form the basis of most forecast products. For example, the first forecast of the day should be available by 7 am to 10 am local daylight time from Anchorage and by 10 am to 1 pm local standard time from Miami. Earlier forecasts or forecasts updated throughout the day are possible if the most recently available upper-air observations and prognostic model outputs 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 specified times and locations.

Even though there are increasing numbers of numerical guidance tools, weather forecasting still is 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 National Weather Service. Their rigorous training, fire weather program, and state-of-the art equipment and analysis tools help maintain a unique expertise. Most NWS fire weather forecast offices now issue special dispersion and transport forecasts. In addition to NWS forecasters, many states maintain a smoke management program with highly skilled meteorologists. Also, the number of inter-agency fire weather offices and private meteorological services is growing and can provide reliable forecast products specifically designed for smoke management. 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, and prognostic model output products now available on the World Wide Web. In this way, apparent trends and local influences can be determined and the need for last minute changes can be recognized more quickly. For example, increasing afternoon cloudiness in the forecast may have indicated an approaching storm that was predicted for the following morning. If clouds do 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 as time to an event shortens. For example, it is possible to provide an indication of storminess within 30 to 90 days. A storm passage, however, may not be predicted until about 14 days in advance 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 usually are available 24 to 48 hours in advance of a scheduled burn. This allows a smoke manager to anticipate a potential burning window well in advance. Specific timing, however, should not be made before 2 days in advance if the situation is highly dependent on an accurate weather forecast.

Our increasing knowledge of air-sea interactions is making it possible to predict some aspects of weather up to a year in advance as certain regions of the country respond to the El Niño Southern Oscillation (ENSO). Precipitation and temperature during winter and spring are most strongly related to ENSO. Relating key factors for smoke management such as wind and mixing height or stability is more difficult, especially during summer. Nevertheless, an ENSO-based seasonal prediction gives prescribed burners 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 prevailing weather of an area. 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 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 desired to reduce smoke impacts on cities and towns.

It is possible to infer climate just by local proximity to oceans, lakes, rivers, and mountains. 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 transpiring moisture, both of which help to modify heating and cooling of the ground surface. This can reduce daytime mixing heights and keep nighttime heights relatively high, with respect to deserts. Also, the structural deformation of trees often indicates high winds, where the direction of branches or flagging point away from prevailing wind directions.

Quantitative summaries of climate can be obtained from the state climatologist or Regional Climate Center (RCC), many of whom also maintain informative Internet sites and can be reached through the National Climatic Data Center (NCDC) <www.ncdc.noaa.gov>. It is most common to find temperature and precipitation 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 recently generated climate database by Ferguson and others (2001) provides information on twice-daily variations in surface wind, mixing height, and ventilation index over a 30-year period.

We know that 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 acquire 30 to 50 years of weather observation data for any reliable climate summary.

Summary

Managing smoke in ways that prevent serious impact to sensitive areas from single burns or multiple burns occurring simultaneously 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 prior to and during the burn with regional, local, and on-site observations. On-site observations are helpful because air movement, and therefore smoke movement, is influenced by small variations in terrain and vegetation cover, and proximity to lakes and oceans, 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 wildland areas and its effect on biomass fires, refer to the Fire Weather handbook (Schroeder and Buck 1970).

In using weather observations, forecasts, and climate summaries effectively for smoke management there are 3 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 needs.

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Chapter 8

SMOKE MANAGEMENT TECHNIQUES

Smoke Management: Techniques to Reduce or Redistribute Emissions

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Introduction

A land manager’s decision to use a specific burning technique is influenced by many considerations, only one of which is a goal to reduce smoke emissions. Other important considerations include ensuring public and firefighter safety, maintaining control of the fire and keeping it within a given perimeter, complying with numerous environmental regulations, minimizing nuisance and hazard smoke, minimizing operational costs, and maximizing the likelihood of achieving the land management objective of the burn. Often these other considerations preclude the use of techniques that reduce emissions. In some cases, however, smoke emission reductions are of great importance and are achieved by compromising other goals. Emission reduction techniques vary widely in their applicability and effectiveness by vegetation type, burning objective, region of the country, and whether fuels are natural or activity-generated.

Emission reduction techniques (or best available control measures–BACM) are not without potential negatives and must be prescribed and used with careful professional judgment and full awareness of possible tradeoffs. Fire behavior is directly related to both fire effects and fire emissions. Emission reduction techniques alter fire behavior and fire effects and can impair or prevent accomplishment of land management objectives. In addition, emission reduction techniques do not necessarily reduce smoke impacts and some may, under certain circumstances, actually increase the likelihood that smoke will impact the public. Emission reduction techniques can cause negative effects on other valuable resources such as through soil compaction, loss of nutrients, impaired water quality, and increased tree mortality; or they may be dangerous or expensive to implement.

Land managers are concerned about the repeated application of any resource treatment technique that does not replicate the ecological role that fire plays in the environment. Such applications may result in unintended resource damage, which may only be known far in the future. Some examples of resource damage that could occur from the use of emission reduction techniques include the loss of nutrients to the soil if too much woody debris is removed from the site, or the effects of soil compaction associated with mechanical processing (chipping, shredding, or yarding) of fuels. The application of herbicides and other chemicals and/or the effects on soils of the intense heat achieved during mass ignition are also of concern. These issues are difficult to quantify but are of universal importance to land managers, who must weigh the impact of their decisions on long-term ecosystem productivity.

Multiple resource values must be weighted along with air quality benefits before emission reduction techniques are prescribed. Flexibility is key to appropriate application of emission reduction techniques and use of particular techniques should be decided on a case-by-case basis. Emission reduction goals may be targeted but the appropriate mix of emission reduction techniques to achieve those goals will require a careful analysis of the short and long term ecological and social costs and benefits. Air quality managers and land managers should work together to better understand the effectiveness, options, difficulties, applicability, and tradeoffs of emission reduction techniques.

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

1. *Use techniques that reduce the emissions produced for a given area treated.*
2. *Redistribute the emissions through meteorological scheduling and by sharing the airshed.*

Although each method can be discussed independently, fire practitioners often choose lighting and fuels manipulation techniques that complement, or are consistent with, meteorological scheduling for maximum smoke dispersion and favorable plume transport. Meteorological scheduling is often the most effective way to prevent direct smoke impacts to the public and some emission reduction techniques may actually increase the likelihood of smoke impacts by decreasing the energy in the plume resulting in more smoke close to the ground. A few of the potential negative consequences of specific emission reduction techniques are mentioned in this chapter although this topic is not addressed comprehensively.

Use of Smoke Management Techniques

Much of the information presented in this chapter was gathered from fire practitioners at three national workshops held during the fall of 1999. Practitioners were asked to describe how (or if) they apply emission reduction techniques in the field, how frequently these methods are used, how effective they are, and what constraints limit their wider use. The information gained at each of the workshops was then synthesized into a draft report that was distributed to the participants for further review and comment. Twenty-nine emission reduction and emission redistribution methods within seven major classifications were identified as currently in use to reduce emissions and impacts from prescribed burning.

The emission reduction methods described in this document may be used independently or in combination with other methods on any given burn. In addition, a number of different firing methods potentially can be applied to any given parcel of land depending on the objectives and judgments made by 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 have occurred since EPA's release of the first document describing best available control measures (BACM) for prescribed burning (EPA 1992). Some of these changes have dramatically impacted when and how emission reduction methods for prescribed fire can be applied. On federally managed lands, the following constraints apply to many of the emission reduction techniques: National Environmental Policy Act (NEPA), Threatened and Endangered Species (T&E) considerations, water quality and impacts on riparian areas, administrative constraints imposed by Congress (eg, roadless and wilderness area designations), impacts on archaeological resources, smoke management program requirements, and other state environmental or forestry regulations.

The following emission reduction and emission redistribution techniques are a comprehensive compilation of the current state of the knowledge. Any one of these may or may not be applicable in a given situation depending upon specifics of the fire use objectives, project locations, time and cost constraints, weather and fuel conditions, and public and firefighter safety considerations.

Reducing the Amount of Emissions

Emissions from wildland fire are complex and contain many pollutants and toxic compounds. Emission factors for over 25 compounds have been identified and described in the literature (Ward and Hardy 1991; Ward and others 1993). A simplifying finding from this research is that all pollutants except nitrous oxide (NO_x) are negatively correlated with combustion efficiency, so actions that reduce one pollutant results in the reduction of all (expect NOx). Nitrous oxide and CO_2 (not considered a pollutant) can increase if the emission reduction technique increases combustion efficiency.

Emission reduction techniques may reduce emissions from a given prescribed burn area by as much as about 60 percent to as little as virtually zero[1]. Considering all burning nationally, if emission reduction techniques were optimally used, emissions could probably be reduced by approximately 20-25 percent assuming all other factors (vegetation types, acres, etc.) were held constant and land management goals were still met[1]. Individual states or regions may be able to achieve greater emission reductions than this or much less depending on the state's or region's biological decomposition capability or ability to utilize available biomass.

In the context of air quality regulatory programs, current or future emissions are typically measured against those that occurred during a baseline period (annual, 24-hour, and seasonal) to determine if reductions have or will occur in the future. Within this framework, land managers need to know their baseline emissions to determine the degree of emission reduction that a method described here will provide in order to conform to a State Implementation Plan, State Smoke Management Program, or local nuisance standards.

Because of all these variables, wildland fire emission models such as the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997), Consume 2.1 (Ottmar and others [in

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[1] Peterson, J. and B. Leenhouts. 1997. What wildland fire conditions minimize emissions and hazardous air pollutants and can land management goals still be met? An unpublished technical support document to the EPA Interim Air Quality Policy on Wildland and Prescribed Fires. August 15, 1997. (Available from the authors or online at http://www.epa.gov/ttncaaa1/faca/pbdirs/emissi.pdf

preparation]), and Emissions Production Model (EPM) (Sandberg and Peterson 1984) can be used to estimate particulate, gaseous and hazardous pollutant emissions based on the specifics of each burn. There are seven general categories that encompass all of the techniques described in this document. Each is described below.

1. Reduce the Area Burned

Perhaps the most obvious method to reduce wildland fire emissions is to reduce the area burned. Area burned can be reduced by not burning at all or by burning a subset of the area within a designated perimeter. Caution must be applied though, and programs to reduce the area burned must not ultimately result in just a delay in the release of emissions either through prescribed burning at a later date or as the result of a wildland fire. Reducing the area burned should be accomplished by methods that truly result in reduced emissions over time rather than a deferral of emissions to some future date.

This technique can have detrimental effects on ecosystem function in fire-adapted vegetation community types and is least applicable when fire is needed for ecosystem or habitat management, or forest health enhancement. In some areas and some vegetation types, when fire is used to eliminate an undesirable species or dispose of biomass waste, alternative methods can be used to accomplish effects similar to what burning would accomplish. Examples of specific techniques include:

- **Burn Concentrations.** Sometimes concentrations of fuels can be burned rather than using fire on 100 percent of an area requiring treatment. The fuel loading of the areas burned using this technique tend to be high. The total area burned under these circumstances can be very difficult to quantify.

- **Isolate fuels.** Large logs, snags, deep pockets of duff, sawdust piles, squirrel middens, or other fuel concentrations that have the potential to smolder for long periods of time can be isolated from burning. This can be accomplished by several techniques including: 1) constructing a fireline around the fuels of concern; 2) not lighting individual or concentrated fuels; 3) using natural barriers or snow; 4) scattering the fuels; and 5) spraying with foam or other fire retardant material. Eliminating these fuels from burning is often faster, safer, and less costly than mop-up, and allows targeted fuels to remain following the prescribed burn.

- **Mosaic burning**. Landscapes often contain a variety of fuel types that are non-continuous and vary in fuel moisture content. Prescribed fire prescriptions and lighting patterns can be assigned to use this fuel and fuel moisture non-homogeneity to mimic a natural wildfire and create patches of burned and non-burned areas or 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 8.1). Depressional wetlands, swamps, and hardwood stringers can be excluded by burning when soil moisture is abundant. Furthermore, if the burn prescription calls for low humidity and high live fuel moisture, continuous burning in the dead fuels may occur while the live fuels exceed the moisture of extinction. In both cases, the unburned live fuels may be available for future burning in a prescribed or wildland fire during droughts or dormant seasons.

2. Reduce Fuel Load.

Some or all of the fuel can be permanently removed from the site, biologically decomposed, and/or prevented from being produced. 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 category and can include such techniques as mechanical removal of logging debris from clearcuts, onsite chipping of woody material and/or brush for offsite utilization, and mechanical removal of fuels which may or may not be followed by offsite burning in a more controlled environment. Sometimes mechanical treatments (such as whole-tree harvesting or yarding of unmerchantable material [YUM]) may result in sufficient treatment so that burning is not needed. Mechanical treatments are applicable on lands where this activity is allowable (i.e., non-wilderness, etc.), 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 fuel types and has some limited applicability in shrub and grass fuel types. A portion of the emission reduction gains 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 undue soil disturbance or compaction, stimulate alien 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 decomposed (figure 8.2). If the biomass is spread across the ground as additional litter fuels, emission reductions are not achieved if the litter is consumed either in a prescribed or wildland fire. Use of this technique may eliminate the need to burn.
- **Firewood sales**. Firewood sales may result in sufficient removal of woody debris making onsite burning unnecessary. This technique is particularly effective for piled material where the public has easy access. This technique is generally applicable in forest types with large diameter, woody biomass. The emissions from wildland fuels when burned for residential heating are not assessed as wildland fire emissions but as residential heating emissions. The impact of these emissions on the human environment is not attributed to wildland fire in the national or state emissions inventories.
- **Biomass for electrical generation**. Woody biomass can also be removed and used to provide electricity in regions with cogeneration facilities. Combustion efficiency in electricity production is greater than open burning and emissions from biomass fuel used offset fossil fuel emissions. Although this method of reducing fuel loading is cost-effective where there is a market for wood chips, there are significant administrative, logistical, and legal barriers that limit its use.
- **Biomass utilization**. Woody material can be used for many miscellaneous purposes including pulp for paper, methanol production, wood pellets, garden bedding, and specialty forest products. Demand for these products varies widely from place to

Figure 8.1. Mosaic burning creates patches of burned and unburned areas resulting in reduced emissions.

Figure 8.2. Mechanical processing of biomass.

place and year to year. Biomass utilization is most applicable in forest and shrub types that include large diameter woody biomass and where fuel density and accessibility makes biomass utilization economically viable.

- **Ungulates**. Grazing and browsing live grassy or brushy fuels by sheep, cattle, or goats can reduce fuels prior to burning or reduce the burn frequency. Goats will sometimes consume 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 composition and long-term ecological processes on an area, eventually converting grass dominated areas to brush. On moderate to steep slopes, high populations of ungulates contribute to increased soil erosion.

3. Reduce Fuel Production.

Management techniques can be used to shift species composition to vegetation types that produce less biomass per acre per year, or produce biomass that is less likely to burn or burns more efficiently with less smoke.

- **Chemical treatments**. Broad spectrum and selective herbicides can be used to reduce or remove live vegetation, or alter species diversity respectively. This often reduces or eliminates the need to use fire. Chemical production and application have their own emissions, environmental, and public relations problems. A NEPA (National Environmental Policy Act) analysis is generally required prior to any chemical use on public lands and states often require similar analyses prior to chemical use on state or private lands.
- **Site conversion**. Natural site productivity can be decreased by changing the vegetation composition. 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 less total fuel but also with more grass and herbs. Grass and herbs tend to burn cleaner than shrubs. Total fuel loading can also be reduced through conversion to species that are less productive.
- **Land use change**. Changing wildlands to another land use category may result in elimination of the need to burn. Conversion of a wildland site to agriculture or an urbanized use significantly alters the ecological structure and function and presents numerous legal and philisophical issues. This alternative is probably not an option on Federally managed lands.

4. Reduce Fuel Consumed.

Emission reductions can be achieved when significant amounts of fuel are at or above the moisture of extinction, and therefore unavailable for combustion. Burning when fuels are wet may leave significant amounts of fuel in the treated area only to be burned in the future. This may not result in a real reduction in emissions then, but rather a delay of emissions to a later date. Real emission reductions are achieved only if the fuels left behind will biologically decompose or be otherwise sequestered at a time of subsequent burning. Even though wet fuels burn less efficiently and produce greater emissions relative to the amount of fuel consumed, emissions from a given event are significantly reduced because so much less fuel is consumed.

In the appropriate fuel types, the ability to target and burn 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 diameter fuels may be sufficient. The opportunity to limit large fuel and organic layer consumption can significantly reduce emissions.

- **High moisture in large woody fuels**. Burning when large-diameter woody fuels (3+ inches in diameter or greater) 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 8.3). The large logs therefore consume less in total, they do not smolder as much, and they do not cause as 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 area 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 fuel consumption is needed, burning under high moisture conditions is not a viable alternative.

Figure 8.3. Burning when large fuel moisture is high can result in less total fuel consumption.

- **Moist litter and/or duff**. The organic layer that forms from decayed and partially decayed material on the forest floor often burns during the inefficient smoldering phase. Consequently, reducing the consumption of this material can be very effective at reducing emissions. Consumption of this litter and/or duff layer can be greatly reduced if the material is quite moist. The surface fuels can be burned and the organic layer left virtually intact. The appropriate conditions 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 non-fire adapted forest and brush types. This technique may not be appropriate in areas where removal of the organic layer is desired. Burning litter and/or duff to expose mineral soil is often necessary in fire adapted ecosystems for plant regeneration.

- **Burn before precipitation.** Scheduling a prescribed fire before a precipitation event will often limit the consumption of large woody material, snags, stumps, and organic ground matter, thus reducing the potential for a long smoldering period and reducing the fire average emission factor. Sucessful 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, which take a number of months to dry after harvest. If an area can be burned within 3-4 drying months of timber harvest, many of the large fuels will still contain a significant amount of live fuel moisture. This technique is generally restricted to activity-generated fuels in forest-types.

5. Schedule Burning Before New Fuels Appear.

Burning can sometimes be scheduled for times of the year before new fuels appear. This may interfere with land management goals if burning is forced into seasons and moisture conditions where increased mortality of desirable species can result.

- **Burn before litter fall**. When decidous trees and shrubs drop their leaves this ground litter contributes extra volume to the fuel bed. If burning takes place prior to litter fall there is less available fuel and therefore less fuel consumed and fewer emissions.
- **Burn before green-up**. Burning in cover types with a grass and/or herbaceous fuelbed component can produce fewer emissions if burning takes place before these fuels green-up for the year. Less fuel is available therefore fewer emissions are produced.

6. Increase Combustion Efficiency.

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

- **Burn piles or windrows**. Fuels concentrated into clean and dry piles or windrows generate greater heat and burn more efficiently (figure 8.4). A greater amount of the consumption occurs in the flaming phase and the emission factor is lower. This technique is primarily effective in forest fuel types but may have some applicability in brush types also. Concentrating fuels into piles or windrows generally requires the use of heavy equipment, which can negatively impact soils and water quality. Piles and windrows also cause temperature extremes in the soils directly underneath and can result in areas of soil sterilization. If fuels in piles or windrows are wet or mixed with dirt, extended smoldering of the debris can result in residual smoke problems.
- **Backing fires**. Flaming combustion is cleaner than smoldering combustion. A backing fire takes advantage of this relationship by causing more fuel consumption to take place in the flaming phase than

Figure 8.4. Fuels burned in dry, clean piles burn more efficiently and generate less emissions

would occur if a heading fire were used (figure 8.5). In applicable vegetation types where fuels are continuous and dry, the flaming front backs more slowly through the fuelbed and by the time it passes, most available fuel is consumed so the fire quickly dies out with very little smoldering. In a heading fire, the flaming front passes quickly and the ignited fuels continue to smolder until consumed. The opportunity to use backing fires is not always an option and often increase operational costs.

- **Dry conditions**. Burning under dry conditions increases combustion efficiency and less emissions may be produced. However, dryer conditions makes fuel that was not available to burn (at or above the moisture of extinction) available to burn. The emissions from additional fuel burned generally more than offsets emission reduction advantages gained by greater combustion efficiency. This technique is effective only if all fuels will consume under either wet or dry conditions.

- **Rapid mop-up**. Rapidly extinguishing a fire can reduce fuel consumption and smoldering emissions somewhat although this technique is not particularly effective at reducing total emissions and can be very costly (figure 8.6). Rapid mop-up primarily effects 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.

- **Aerial ignition / mass ignition**. "Mass" ignition can occur through a combination of dry fine-fuels and very rapid ignition, which can be achieved through a technique such as a helitorch (figure 8.7). Mass ignition can shorten the duration of the smoldering phase of a fire and reduce the total amount of fuel consumed. When properly applied, mass ignition causes rapid consumption of dry, surface fuels and creates a very strong plume or convec-

Figure 8.5. Backing fires in uniform, noncomplex fuelbeds consume fuels more efficiently than during a head fire resulting in fewer emissions.

Figure 8.6. Quickly extinguishing a smoldering fire is a costly but effective technique for reducing smoldering emissions and impacts.

Figure 8.7. Mass ignition can shorten the duration of the smoldering phase and reduce total consumption resulting in fewer emissions

tion column which draws much of the heat away from the fuelbed and prevents drying and preheating of larger, moister fuels. This strong plume may result in improved smoke dispersal. The fire dies out shortly after the fine fuels fully consume and there is little smoldering or consumption of the larger fuels and duff. The conditions necessary to create a true mass ignition situation include rapid ignition of a large, open area with continuous, dry fuels (Hall 1991).

- **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 8.8). These devices are commonly used to burn land clearing, highway right-of-ways, or demolition debris in areas sensitive to smoke and may be required by air quality agency regulations in some areas.

Redistributing the Emissions

Emissions can be spatially and temporally redistributed by burning during periods of good atmospheric dispersion (dilution) and when prevailing winds will transport smoke away from sensitive areas (avoidance) so that air quality standards are not violated. Redistribution of emissions does not necessarily reduce overall emissions.

1. Burn when dispersion is good.

Smoke concentrations can be reduced by diluting the smoke through a greater volume of air, either by burning during good dispersion conditions when the atmosphere is unstable or burning at slower rates. If burning progresses too slowly, smoke accumulation due to evening atmospheric stability can occur.

2. Share the airshed.

Establishing a smoke management program that links both local and interstate jurisdictions will create opportunities to share the airshed and reduce the likelihood of smoke impacts.

Figure 8.8. Air curtain incinerators result in very hot and efficient fires that produce little smoke.

3. Avoid sensitive areas.

The most obvious way to avoid smoke impacts is to burn when the wind is blowing away from all smoke-sensitive areas such as highways, airports, populated areas, and scenic vistas. Wind direction must be considered during all phases of burning. For example, the prevailing winds during the day time may move the smoke away from a major highway; however, at night, drainage winds can carry the smoke toward the highway.

4. Burn smaller units.

Short term emissions and impacts can be reduced by burning subsets of a large unit over multiple days. Total emissions are not reduced if the entire area is eventually burned.

5. Burn more frequently.

Burning more frequently does not allow fuels to accumulate, thus there are less emissions with each burn. Frequent, low intensity fires can prevent unwanted vegetation from becoming established. If longer fire rotations are used, the vegetation has time to grow resulting in the production of extra biomass and extra fuel loading at the time of burning. This technique generally has positive effects on land management goals since it results in fire regimes that more closely mimic the frequency of natural fire in many ecosystems.

The Use and Effectiveness of Emission Reduction and Redistribution Techniques

The overall potential for emission reductions from prescribed fire depends on the frequency of use of emission reduction techniques and the amount of emission reduction that each method offers. This section provides information on the overall potential for emission reduction and redistribution from prescribed fire based on (a) the frequency of use of each emission reduction and emission redistribution technique 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 regional workshops (as described previously). The information provided can, and should, be improved upon by local managers who will have better information about specific, local burning situations.

The use of each smoke management technique is organized by U.S. region as shown in figure 8.9. They are the Pacific Northwest including Alaska (PNW), Interior West (INT), Southwest (SW), Northeast (NE), Midwest (MW), and Southeast including Hawaii (SE) regions. Each region has its own vegetation cover types, climatology, and terrain characteristics, all of which influence the land manager's decision to burn and the appropriateness of various emission reduction techniques.

Manager use of emission reduction techniques is influenced by numerous factors including land management objectives, the type and amount of vegetation being burned, safety considerations, costs, laws and regulations, geography, etc. The effect of some of these many influencing factors can be assessed through general knowledge of the frequency of use of a particular technique in a specific region. Table 8.1 provides general information about frequency of use of each smoke management technique by region of the country, grouped as shown in figure 8.9.

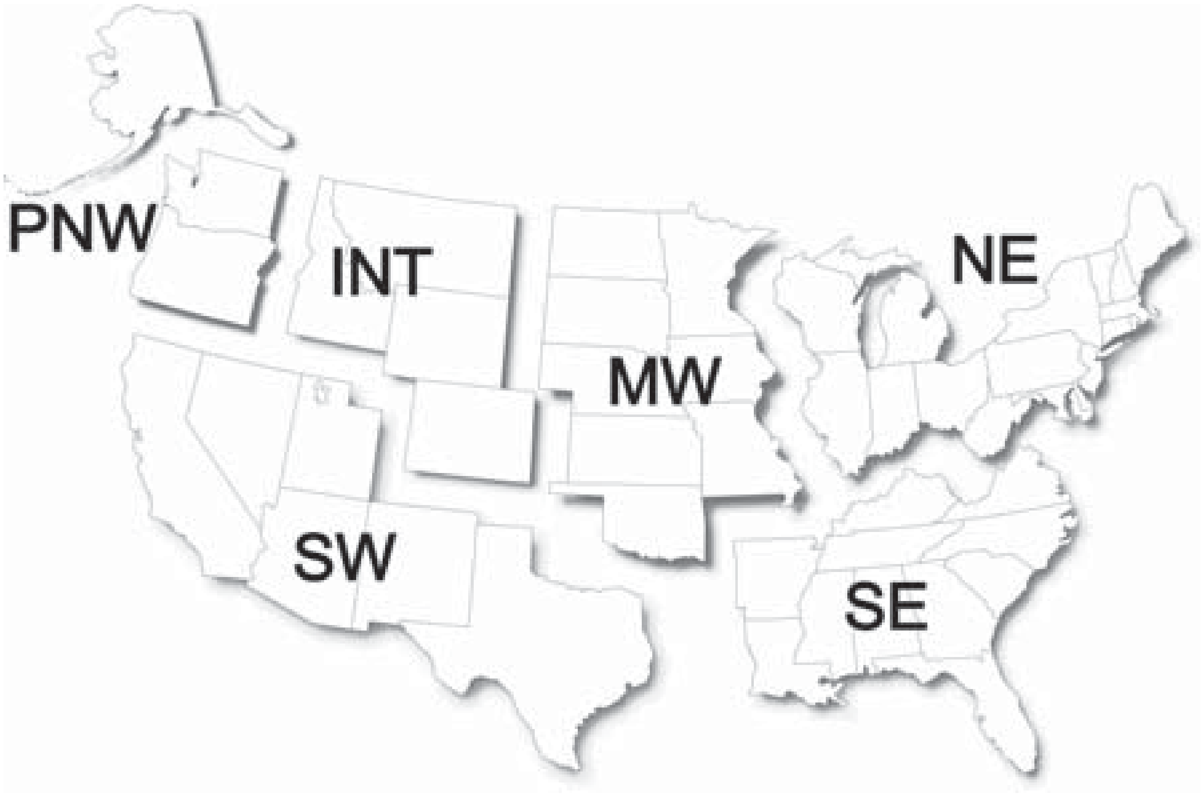

Figure 8.9. Prescribed burning regions including Pacific Northwest including Alaska (PNW), Intermountain (INT), Midwest (MW), Southwest (SW), Southeast including Hawaii (SE), and Northeast (NE).

Information in table 8.1 summarizes regional applicability of each of the twenty-nine smoke management methods. Interviews with fire practitioners demonstrate that, on a national scale, several smoke management techniques are rarely used. These include biomass for electrical generation, biomass utilization, site conversion, land use change, 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 also seldom used. The methods most commonly applied include aerial ignition/mass ignition, burning when dispersion is good, sharing the airshed, and avoiding sensitive areas.

The general effectiveness of the emission reduction and redistribution techniques is described in table 8.2 based on input from managers at the workshops. Local managers will have better information about specific situations and can improve upon the information in the tables. Each technique was assigned a general rank of “High” for those techniques most effective at reducing emissions or “Low” for those techniques that are less effective. Some emission reduction techniques also 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

Table 8.1. Frequency of smoke management method use by region. Alaska is included in the Pacific Northwest (PNW) region, and Hawaii is included in the southeast region (SE)

Smoke Management Method	**- - - - - - - - - -Frequency of Use by Region - - - - - - - - - -**		
	Rarely	**Occasionally**	**Commonly**
1. Reduce the Area Burned			
• Burn Concentrations	SE	NE, MW, SW, PNW	INT
• Isolate Fuels		NE, SE, MW, SW	INT, PNW
• Mosaic Burning	NE, SE, MW		INT, SW, PNW
2. Reduce Fuel Load			
• Mechanical Removal	NE, MW	SE	INT, SW, PNW
• Mechanical Processing	SW	NE, SE, MW, INT, PNW	
• Firewood Sales	NE, SE, MW, INT, PNW	SW	
• Biomass for Electrical Generation	All Regions		
• Biomass Utilization	All Regions		
• Ungulates		NE, SE, MW	INT, SW, PNW
3. Reduce Fuel Production			
• Chemical Treatment	NE, MW, INT, SW, PNW	SE	
• Site Conversion	All Regions		
• Land Use Change	All Regions		
4. Reduce Fuel Consumed			
• High Moisture in Large Fuels		NE, MW, INT, SW	SE, PNW
• Moist Litter &/or Duff	SW	NE, MW, INT	SE, PNW
• Burn Before Precipitation		All Regions	
• Burn Before Large Fuels Cure	SE, INT, SW		NE, MW, PNW
5. Schedule Burning Before New Fuels Appear			
• Burn Before Litter Fall	All Regions		
• Burn Before Green Up		INT, PNW	NE, SE, MW, SW
6. Increase Combustion Efficiency			
• Burn Piles or Windrows	SE	NE, MW	INT, SW, PNW
• Backing Fires	INT	PNW	NE, SE, MW, SW
• Dry Conditions	All Regions		
• Rapid Mop-up		SE, INT, SW	NE, MW, PNW
• Aerial Ignition/Mass Ignition			All Regions
• Air Curtain Incinerators	All Regions		
7. Redistribute Emissions			
• Burn when dispersion is good			All Regions
• Share the airshed			All Regions
• Avoid sensitive areas			All Regions
• Burn smaller units	All Regions		
• Burn more frequently	NE, MW, SW, PNW	INT	SE

Table 8.2. Relative effectiveness of various smoke management techniques.

Smoke Management Technique	**General Emission Reduction Potential**	**Can Eliminate or Delay Need to Burn**	**Effective for Local Smoke Impact Reduction (if burned)**
1. Reduce the Area Burned			
• Burn Concentrations	High		✓
• Isolate Fuels	High		✓
• Mosaic Burning	High		
2. Reduce Fuel Load			
• Mechanical Removal	High	✓	
• Mechanical Processing	Low	✓	
• Firewood Sales	Low	✓	
• Biomass For Electrical Generation	High	✓	
• Biomass Utilization	Low	✓	
• Ungulates	High	✓	
3. Reduce Fuel Production			
• Chemical Treatment	Moderate	✓	
• Site Conversion	High	✓	✓
• Land Use Change	High	✓	
4. Reduce Fuel Consumed			
• High Moisture In Large Woody Fuels	High		✓
• Moist Litter & Duff	High		✓
• Burn Before Precipitation	High		✓
• Burn Before Large Fuels Cure	High		✓
5. Schedule Burning Before New Fuels Appear			
• Burn Before Litter Fall	Low		
• Burn Before Green-up	Low		
6. Increase Combustion Efficiency			
• Burn Piles & Windrows	Low		✓
• Backing Fires	Moderate		✓
• Dry Conditions	Low		
• Rapid Mop-up	Low		✓
• Aerial Ignition / Mass Ignition	Low		✓
• Air Curtain Incinerators	High		✓
7. Redistribute Emissions			
• Burn When Dispersion Is Good	None		✓
• Share The Airshed	None		✓
• Avoid Sensitive Areas	None		✓
• Burn Smaller Units	None		✓
• Burn More Frequently	None		✓

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 8.2.

Table 8.3 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 would probably be used more frequently if specific constraints could be overcome.

Smoke management techniques that, in the opinion of workshop participants, show particular promise for wider use in the future are listed below:

1. **Mosaic Burning:** Since this method reduces the area burned and replicates the natural role of fire, it is being increasingly used for forest health restoration burning on a landscape scale.
2. **Mechanical Removal:** In areas where slope and access are not a problem and fuels have economic value, the wider use of whole tree yarding, YUM yarding, cut-to-length logging practices and other methods that remove fuel from the unit prior to burning (if the unit is burned at all) may have potential for wider application if economic markets for the removed fuels can be found.
3. **High Moisture in Large Woody Fuels, and/or Moist Litter and Duff:** In situations where the objective is not to maximize the consumption of large woody debris, litter, and/or duff, this option is favored by fire practitioners as an effective means of reducing emissions, smoldering combustion, and smoke impacts.
4. **Pile and Windrow Burning:** Pile burning, although already widely used in all regions, is gaining popularity among land managers because of the flexibility offered in scheduling burning and the resultant lower impacts on smoke sensitive locations. Lower impacts may not result if piles or windrows are wet or mixed with dirt.
5. **Aerial/Mass Ignition**: Little clear information currently exists as to the extent to which aerial ignition achieves true mass ignition and associated emission reduction benefits. More effort to achieve true mass ignition using aerial techniques may yield significant emission reduction benefits.
6. **Burn More Frequently:** Fire managers generally favor more frequent burning practices to reduce fuel loading on second and subsequent entry, thereby reducing emissions over long time periods. This will increase daily or seasonal emissions.

Estimated Emission Reductions

While the qualitative assessment of emission reduction technique effectiveness shown in table 8.2 is a useful way to gauge how relatively successful a particular technique may be in reducing emissions, it is also useful to model potential quantitative emission reduction. Table 8.4 summarizes potential emission reductions that may be achieved by employing various techniques as estimated by the fuel consumption and emissions model Consume 2.1 (Ottmar and others [in preparation]). For example, use of mosaic burning techniques in natural, mixed conifer fuels in which one-half of a 200-acre project is burned is projected to reduce $PM_{2.5}$ emissions from 14.8 to 7.4 tons for a 50% reduction in emissions. A 33% reduction in

Table 8.3. Constraints to the use of emission reduction and redistribution techniques as reported by regional workshop participants.

Smoke Management Method	**Constraints**				
	Administrative	**Physical**	**Legal**	**Cost**	**Other**
1. Reduce the 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
• Land Use Change	Very High	Few	Very High	Very High	Ecosystem impacts
4. Reduce Fuel Consumed					
• High Moisture in Large Woody Fuels	Few	Few	Few	Few	Incompatible fuels in some regions
• Moist Litter and Duff	Few	Few	Few	Few	Not used in the SW 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 and 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	
7. Redistribute Emissions					
• Burn When Dispersion is Good	Few	Moderate	Few	Moderate	Increased escape potential
• Share the Airshed	High	Few	High	High	
• Avoid Sensitive Areas	Few	Moderate	Few	High	
• Burn Smaller Units	High	Few	Few	High	
• Burn More Frequently	Few	Few	Few	Moderate	Smoke management windows and cost

Table 8.4. Approximate emission reduction effectiveness for various emission reduction techniques in certain vegetation types. (Values generated with Consume 2.1 [Ottmar and others, in preparation]).

Emission Reduction Technique	**Vegetation Type**	**Total Fuel Loading** (tons/acre)	**Fuel Type**[1]	**Size** (acres)	**Ignition Time**[2] (minutes)	**Large Fuel Moisture**[3] (percent)	**Duff Moisture**[4] (percent)	**Total Fuel Consumption** (tons)	**Total PM_{10} Emissions** (tons)	**PM10 Emission Reduction** (percent)	**Total $PM_{2.5}$ Emissions** (tons)	**$PM_{2.5}$ Emission Reduction** (percent)
Mosaic Burning	Southern pine	10.9	Natural	100	180	N/A	120	296	3.09	50	2.95	50
Non-mosaic Burning	Southern pine	10.9	Natural	200	180	N/A	120	593	6.19		5.91	
Mechanical removal	North central red and white pine	19.4	Activity	100	180	30	N/A	1,659	15.65	40	14.82	42
No Mechanical removal	North central red and white pine	32.4	Activity	100	180	30	N/A	2,531	26.42		25.56	
Ungulates	Midwest grassland	1.0	Natural	100	N/A	N/A	120	17	0.17	70	0.06	67
No Ungulates	Midwest grassland	1.4	Natural	100	N/A	N/A	120	57	0.57		0.18	
High Moisture in Large Fuels	Interior mixed conifer	96.9	Activity	100	180	40	N/A	3,924	34.92	44	32.65	43
Low Moisture in Large Fuels	Interior mixed conifer	96.9	Activity	100	180	15	N/A	7,270	62.33		57.67	
Moist Litter and/or Duff	Alaska black spruce	30.8	Natural	100	N/A	N/A	120	1,492	13.19	26	12.39	26
Dry Litter and/or Duff	Alaska black spruce	30.8	Natural	100	N/A	N/A	40	1,909	17.83		16.85	
Burn Before Large Fuels Cure	Pacific Northwest Douglas-fir/hemlock	118.6	Activity	100	180	100	N/A	3,165	24.82	45	22.47	44
Burn After Large Fuels Cure	Pacific Northwest Douglas-fir/hemlock	118.6	Activity	100	180	30	N/A	6,194	45.21		40.10	
Piled Fuels	Southwest Ponderosa pine	43.2	Piled	100	N/A	N/A	N/A	8,549	31.16	9	27.14	13
Non-piled Fuels	Southwest Ponderosa pine	44.6	Activity	100	180	30	N/A	2,672	34.16		31.34	
Mass Ignition	Pacific Northwest Douglas-fir/hemlock	118.6	Activity	100	30	40	N/A	5,597	40.77	10	36.13	10
No Mass Ignition	Pacific Northwest Douglas-fir/hemlock	118.6	Activity	100	180	40	N/A	6,195	45.21		40.10	
Burn More Frequently	California chaparral	6.7	Natural	100	N/A	N/A	120	469	3.87	83	3.17	83
Burn Less Frequently	California chaparral	39.7	Natural	100	N/A	N/A	120	2,779	22.93		18.76	

[1] Activity fuels are woody debris resulting from management activity such as logging.

[2] A tractor piled unit does not require ignition time for Consume 2.1.

[3] A natural fuel unit or piled unit does not require large woody fuel moisture content input for Consume 2.1.

[4] An activity fuel units or piled unit does not require duff moisture content input for Consume 2.1

$PM_{2.5}$ emissions can be achieved by pile burning mixed conifer fuels under the conditions noted in the table. Specific simplifying assumptions were made in each case to produce the estimates of emission reduction potential seen in table 8.4. Other models using the same field assumptions would yield similar trends.

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. Although fire suppression efforts may only delay the emissions rather then eliminate them altogether. Allowing fires to burn without suppression early in the fire season to prevent more severe fires in drier periods would reduce fuel consumption and reduce emissions. 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, we should remember that there is an inextricable link between fuels management, prescribed fire, wildfire severity, and emission production.

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Chapter 9

DISPERSION PREDICTION SYSTEMS

Smoke Dispersion Prediction Systems

Sue A. Ferguson

Smoke dispersion prediction systems are becoming increasingly valuable tools in smoke management. There are a variety of potential applications that can help current management issues. These include screening, where methods and models are used to develop "worst-case" scenarios that help determine if alternative burn plans are warranted or if more in-depth modeling is required. Such tools also help in planning, where dispersion predictions aid in visualizing what fuel and weather conditions are best suited for burning or when supporting data are needed to report potential environmental impacts. Also, prediction systems can be used as communication aids to help describe potential impacts to clients and managers. For regulating, some states use dispersion prediction systems to help determine approval of burn permits, especially if ignition patterns or fuel complexes are unusual. Other states require dispersion model output in each burn permit application as supporting proof that a burn activity will not violate clean air thresholds.

There are a variety of tools that can be applied to screening and some planning applications. The easiest of these are simple approximations of dispersion potential, emission production, and proximity to sensitive receptors. The approximations are based on common experience with threshold criteria that consider worst-case conditions or regulatory requirements. More detailed planning and many regulatory situations require numerical modeling techniques. While numerical models output a calculated physical approximation of dispersion features, they can be adjusted to predict worst-case scenarios by altering such things as emission production or trajectory winds. Often the easily applied numerical models are used for screening. Typically, more rigorous applications require the use of complex models by trained personnel.

Methods of Approximation

A first level of approximation can simply determine whether the atmosphere has the capacity to effectively disperse smoke by using indexes of ventilation or dispersion. These indexes are becoming widely used and may be a regular feature of fire weather or air quality forecasts in your area. Usually the ventilation index is a product of the mixing height times the average wind within the mixed layer. For example, a mixing height of 600 meters (~2,000 feet) above the ground surface with average winds of 4 m/s (~7.8 knots or ~8.9 mph) produces a ventilation index of 2,400 m^2/sec (~15,600 knots-feet). With similar wind speeds, the ventilation index would increase to 12,000 m^2/sec (~78,000 knots-feet) if the mixing height rose to 3,000 meters (~10,000 feet). Ventilation indexes calculated from model output may use the product of the planetary boundary layer (PBL) and lowest level winds (e.g., 10 to 40 meters above ground level). Others calculate the index by multiplying the mixing height by a determined transport wind speed,[1] which might be near the top of the mixed layer. Because of different methods of calculating ventilation index, the scales used for burning recommendations may vary.

It helps to gain experience with a ventilation index before making management decisions based on its value. Defining a uniform method for calculating the index and comparing it frequently with observed smoke dispersal conditions can do this. Ferguson et al. (2001) developed a national historical database of ventilation index based on model generated 10-meter winds and interpolated mixing height observations. It is useful in illustrating the spatial and temporal variability of potential ventilation all across the country. In South Carolina the index is divided into 5 categories that correspond to specific prescribed burning recommendations, where no burning is recommended if the index is less than 4,500 m^2/sec (28,999 knots-feet) and restrictions apply if it is between 4,500 and 7,000 m^2/sec (29,000-49,999 knots-feet) (South Carolina Forestry Commission, 1996). In Utah the ventilation index is referred to as a “clearing index” and is defined as the mixing depth in feet times the average wind in knots divided by 100. In this way, a clearing index of less than 200 would indicate poor dispersion and likely pollution; an index between 200 and 500 indicates fair dispersion, while indexes greater than 500 represent good to excellent dispersion. Commonly, the clearing index must be greater than 400 before burning is recommended. In the northwestern U.S., where a mesoscale weather model is used to predict ventilation index, the South Carolina scale has been slightly adjusted to match local burning habits and to accommodate for the slightly different way of computing the index. Table 9.1 gives common values of the ventilation index (VI) and associated smoke conditions.

Ventilation indexes have no value when there is no mixing height, which is common at night. Also, if the atmosphere is very stable within the mixed layer, the ventilation index may be too optimistic about the ultimate potential of dispersing a smoke plume. Therefore, to help

Table 9.1. Common values of the ventilation index (VI) and associated smoke conditions. The Index is calculated by multiplying mixing height (MH) or planetary boundary layer (PBL) times trajectory winds (Traj.), average winds through the depth of the mixed layer (Avg.), or winds at 40 meters above ground level (40m).

VI (knots-ft) MH x Traj.	**VI (knots-ft)/100 MH x Avg.**	**VI (m^2/sec) PBL x 40m**	**Smoke Condition**
0-28,999	< 200	< 2,350	Poor
29,000-37,999	200-400	2,350-4,700	Marginal
38,000-49,999	400-500	4,700-7,050	Fair
50,000-94,999	>500	>7,050	Good
> 95,000			Excellent dispersion - but burn with caution

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[1] Transport winds are those considered most likely to carry smoke away from a fire, usually near mid-level of the horizontal portion of a spreading plume.

determine the atmosphere’s capacity to disperse smoke during all atmospheric conditions, Lavdas (1986) developed an Atmospheric Dispersion Index (ADI) that combines Pasquill’s stability classes (see table 7.1) and ventilation indexes with a simple dispersion model. National Weather Service (NWS) fire weather offices are beginning to include the ADI as a regular part of their smoke management forecast. See table 9.2 for an explanation of the ADI categories. Commonly the ADI must be greater than 30 before burning is recommended.

Another way to approximate smoke impacts is through a geometric screening process that is outlined in “A Guide for Prescribed Fire in Southern Forests” (Wade 1989) and “Southern Forestry Smoke Management Guidebook” (USDA-Forest Service, Southern Forest Experiment Station 1976). The recommended steps include: 1) plotting the direction of the smoke plume, 2) identifying common areas of smoke sensitivity (receptors) such as airports, highways, hospitals, wildernesses, schools, and residential areas, 3) identifying critical areas that already have an air pollution or visibility problem (non-attainment areas), 4) estimating smoke production, and 5) minimizing risk.

It is suggested that the direction of the smoke plume during the day be estimated by considering the size of the fire and assuming a dispersion of 30° on either side of the centerline trajectory if wind direction is planned or measured and 45° if forecasted winds are used. At night, the guide suggests that smoke follows down-valley winds and spreads out to cover valley bottoms. Fuel type, condition, and loading are used to help estimate the amount of smoke that will be produced. In minimizing risk, it is suggested to consider mixing height, transport wind speed, background visibility, dispersion index, and various methods of altering ignition and mop-up patterns.

Because the guidebooks for southern forestry estimate emissions based on fuel types specific to the southeastern U.S., other methods of

Table 9.2. Atmospheric Dispersion Index (ADI) with its current interpretation (Lavdas 1986).

ADI	Interpretation
1-6	Very poor dispersion (common during nighttime)
7-12	Poor dispersion
13-20	Generally poor dispersion
21-40	Fair dispersion (but stagnation may occur if wind speeds are low)
41-60	Generally good dispersion (common in afternoon of U.S. interior)
61-100	Good dispersion (commonly related to good burning weather)
> 100	Very good dispersion (but may relate to high fire hazard)

estimating emissions are needed to employ geometric screening applications elsewhere. Existing models such as FOFEM (Reinhardt and others 1997) and CONSUME (Ottmar and others 1993) are designed for this purpose.

Schaaf and others (1999) describe a similar screening process for deciding the level of analysis for each project. The screening steps include: 1) determining fire size, 2) estimating fuel load, 3) identifying distance to sensitive areas, and 4) calculating emission production. Unlike the southern forestry screening method, which estimates downwind impacts from simple geometry, Schaaf and others (1999) recommend running a numerical dispersion model to help calculate smoke concentrations if initial screening thresholds are met. Further analysis or efforts to reduce potential impacts are then recommended only if predicted concentrations exceed specified standards.

Before relying on simple screening methods to determine if additional modeling may be required or if alternatives are necessary, it is helpful to define appropriate threshold criteria by consulting regulations, surrounding community opinions, and management concerns. For example, the criteria of sensitive receptor proximity may range from fractions of a mile to several miles. On the other hand, some places may base criteria on total tonnage of emissions, no matter how close or far from a sensitive area. Most often criteria are combinations of proximity to receptors and fire size, which vary from place to place.

Numerical Models

Most of the available dispersion prediction systems are in the form of deterministic numerical models and there are three types designed to estimate the timing and location of pollutant concentrations; dispersion, box, and three-dimensional grid models. Dispersion models are used to estimate smoke and gas concentrations along the trajectory of a smoke plume. Box models do not calculate trajectories of particles but assume smoke fills a box, such as a confined basin or valley, and concentrations vary over time as smoke enters and leaves the box. Grid models are like expanded box models in that every grid cell acts as a confined box. Because trajectories are not explicitly computed, box or grid models may include other enhancements, such as complex computations of chemical interactions. Currently, only dispersion and box models have been adapted for wildland smoke management applications. Work is underway to adapt grid models to smoke problems and this will help in estimates of regional haze because grid models can simulate large domains and usually include critical photochemical interactions. The following summary of numerical models currently used by smoke managers is updated from an earlier review by Breyfogle and Ferguson (1996).

Dispersion Models – Dispersion models track trajectories of individual particles or assume a pattern of diffusion to simplify trajectory calculations. Particle models typically are the most accurate way to determine smoke trajectories. They are labor intensive, however, and more often used when minute changes in concentrations are critical, such as when nuclear or toxic components exist, or when flow conditions are well bounded or of limited extent (e.g., PB-Piedmont by Achtemeier 1994, 1999, 2000). Diffusion models commonly assume that concentrations crosswind of the plume disperse in a bell-shape (Gaussian) distribution pattern. Both plume (figure 9.1a) and puff (figure 9.1b) patterns are modeled. The plume method assumes that the smoke travels in a straight line under steady-state conditions (the speed and direction of particles do not change during the period of model simulation). SASEM (Sestak and Riebau 1988), VSMOKE (Lavdas, 1996), and VSMOKE-GIS (Harms and Lavdas 1997) are examples of plume models. Plume models most commonly are applied in regions of flat or gently rolling terrain but can be used whenever a plume is expected to rise above the influence of underlying terrain. The puff method simulates a continuous plume by rapidly generating a series of puffs (e.g., NFSpuff: Harrison 1995; Citpuff: in TSARS+ by Hummel and Rafsnider 1995; and CALPUFF: Scire and others 2000a). Therefore, like particle models, puff models can be used at times when trajectory winds change, such as during changeable weather conditions or in regions where underlying terrain controls smoke trajectory patterns. Because particle trajectory models and Gaussian diffusion models use coordinate systems that essentially follow particles/parcels as they move (Lagrangian coordinates), sometimes they are referred to as Lagrangian dispersion models.

Particle and puff models must have high spatial and temporal resolution weather data to model changing dispersion patterns. This requires at least hourly weather information at spatial resolutions that capture important terrain features (usually less than 1km). For this reason, particle and puff models currently used for smoke management include a weather module that scales observations or input from external meteorological information, to appropriate spatial and temporal resolutions. For example, TSARS+ is designed to link with the meteorological model NUATMOS (Ross and others 1988) while CALPUFF is linked to CALMET (Scire and others 2000b). NFSpuff (Harrison 1995) and PB-Piedmont (Achtemeier 1994, 1999, 2000) contain internal algorithms that are similar to CALMET and NUATMOS. Most weather modules that are attached to particle and puff models solve equations that conserve mass around terrain obstacles and some have additional features that estimate diurnal slope winds and breezes associated with lakes and oceans at very fine scales.

Unlike most particle or puff models, plume models assume that mixing heights and trajectory winds are constant for the duration of the burn. Therefore, they do not require detailed weather inputs and are very useful when meteorological information is scarce. Plume models, however, will not identify changing trajectories or related concentrations if weather conditions fluctuate during a burn period. Also, when smoke extends beyond a distance that is reasonable for steady-state assumptions, which typically is about 50 km (30 miles), plume approximations become invalid. When terrain or water bodies interact with the plume, steady-state assumptions become difficult to justify, no matter how close to the source. Despite the limitation of plume models in complex terrain, they can be useful if plumes are expected to rise above the influence of terrain or if plumes are confined in a straight line that follows a wide valley when dispersion does not extend beyond the valley walls.

Box and Grid Models – The box method of estimating smoke concentrations assumes instantaneous mixing within a confined area, such as a confined basin or valley (figure 9.1c). This type of model usually is restricted to weather conditions that include low wind speeds and a strong temperature inversion that confines the mixing height to within valley walls (e.g., Sestak and others, unpublished; Lavdas 1982). The valley walls, valley bottom, and top of the inversion layer define the box edges. The end segments of each box typically coincide with terrain features of the valley, like a turn or sudden elevation change. Flow is assumed to be down-valley and smoke is assumed to instantaneously fill each box segment. The coordinates used to calculate box dispersions are fixed in space and time and thus called Eulerian coordinates. The box method provides a useful alternative to Gaussian diffu-

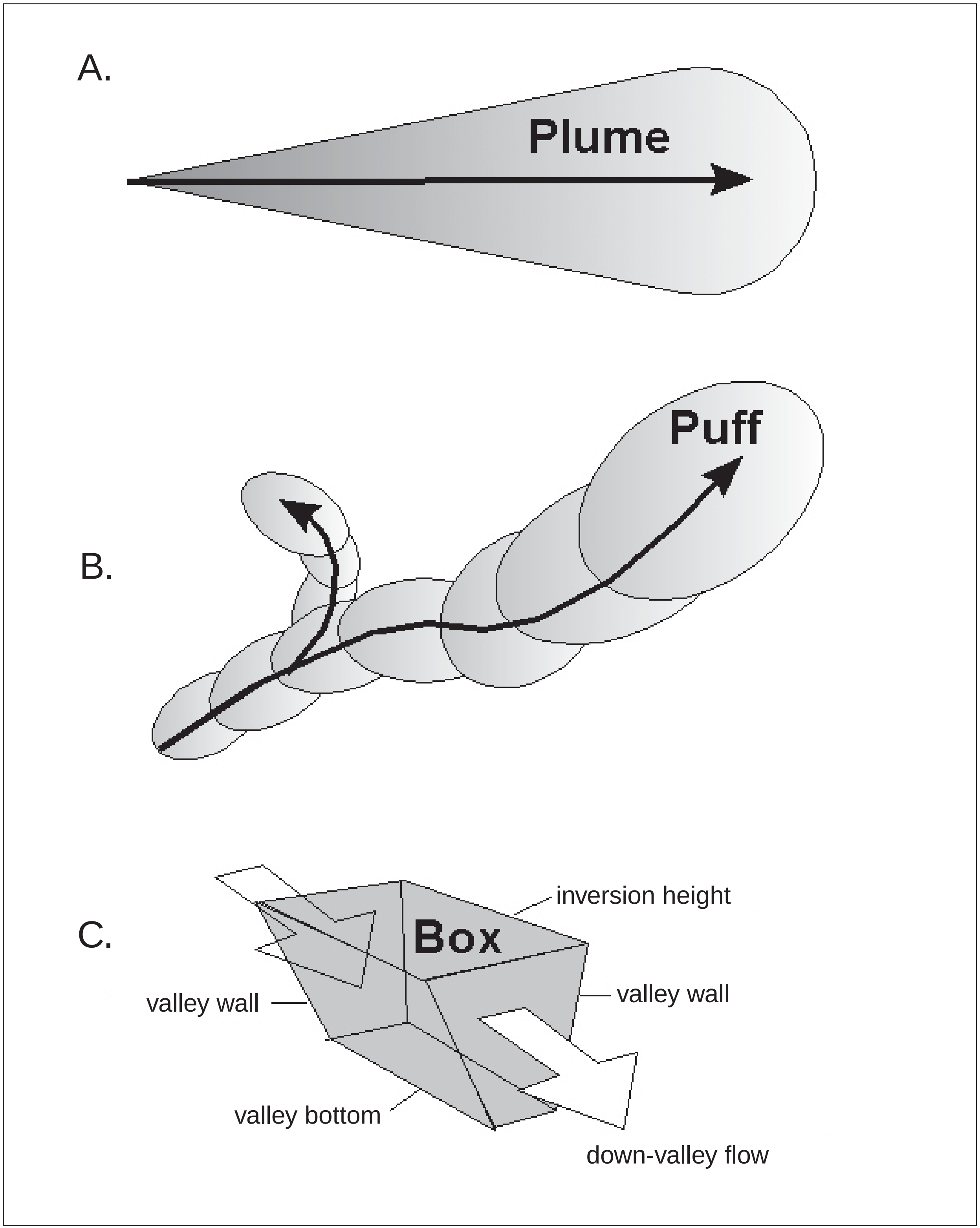

Figure 9.1. Schematic diagrams of numerical dispersion models; (A) Gaussian plume, (B) Gaussian puff, and (C) box.

sion models when understanding patterns of smoke concentrations in an isolated valley become critical.

Many grid models are called Eulerian grids because of their fixed coordinate system. The fixed coordinates make it difficult for grid models to track the impact of individual plumes but allows for easier evaluation of cumulative impacts from several plumes or chemical interactions of particles and gases within plumes. This makes grid models especially useful for evaluating the impact of smoke on regional haze. Work is underway to adapt at least two grid models (REMSAD: Systems Applications International 1998; and CMAQ: Byun and Ching 1999) for wildland fire applications. REMSAD has very simple chemistry thus is desirable for use in large domains or over long time periods. The CMAQ model is more fully physical and part of the EPA's Models 3 project, which is a "one-atmosphere" air quality modeling framework designed to evaluate all potential impacts from all known sources. At this time grid models require experienced modelers to initialize and run. Smoke managers, however, may be asked to provide input for grid models and could begin seeing results that influence application of regional haze rules.

Uncertainty

All prediction systems include some level of uncertainty, which may occur from the meteorological inputs, diffusion assumptions, plume dynamics, or emission production. Many dispersion models and methods have been compared to observations of plumes from point sources, such as industrial stacks, or tightly controlled experiments (e.g., Achtemeier 2000). In these cases, the greatest error usually occurs because of inaccuracies in the weather inputs; either from a poor forecast or an insufficient number of data points. If trajectories can be determined correctly then dispersion and resulting down-wind concentrations from point sources are relatively straightforward calculations. This is because emission rates and subsequent energy transmitted to the plume from industrial stacks, or controlled experiments, usually are constant and can be known exactly.

It is expected that the largest source of uncertainty in modeling smoke concentrations from wildland fires is in estimating the magnitude and rate of emissions. Highly variable ignition patterns and the condition and distribution of fuels in wildland fires create complex patterns of source strength. This causes plumes with simultaneous or alternating buoyant and non-buoyant parts, multiple plumes, and emission rates that are dependent on fuel availability and moisture content. Few comparisons of observations from real wildland fires to dispersion model output are available. Those that do exist are qualitative in nature and from the active phase of broadcast-slash burns (e.g., Hardy and others 1993), which tend to generate relatively well-behaved plumes.

To calculate the complex nature of source strength, components of heat and fuel (particle and gas species) must be known. For simulating wildland fires, additional information is required on: 1) the pattern of ignition, 2) fuel moisture by size of fuel, 3) fuel loading by size, 4) fuel distribution, and 5) local weather that influences combustion rates. Much of this information is routinely gathered when developing burn plans. Peterson (1987) noted that 83% of the error in calculating emissions is due to inaccurate fuel load values. Therefore, even the best burn plan data will introduce a large amount of uncertainty in predicted dispersion patterns.

The shift from burning harvest slash to using fire in natural fuel complexes for understory renovation and stand replacements has introduced another degree of uncertainty by the existence of decaying fuel and isolated concentrations of deep duff that have previously been neglected in pre-burn inventories. This has prevented emission models from accurately estimating the contribution of smoldering combustion, which is common in the porous elements of rotten wood and deep duff. Until this omission is corrected, users must manipulate source-strength models into expecting smoldering by inputting very long ignition periods and low fuel loads, which simulate the independent smoldering combustion that occurs in porous material.

Currently variable-rate emissions are determined by approximating steady-state conditions in relatively homogeneous burning segments of a fire (e.g., Sandberg and Peterson 1984; Ferguson and Hardy 1994; Lavdas 1996; Sestak and Riebau 1988) or by allowing individual fuel elements to control combustion rates (e.g., Albini and others 1995; Albini and Reinhardt 1995; Albini and Reinhardt 1997). The steady-state method has been adapted for many of the currently available puff, plume, and box models and is most useful when the pattern and duration of ignition are known ahead of time, either through planning or prediction. The fuel-element approach shows promise for calculating emissions simultaneously with ignition rates (fire spread) and may become particularly useful for coupled fire-atmosphere-smoke models, which currently are being developed.

Principal components (plume rise, trajectory, and diffusion) of all numerical dispersion models assume functions that are consistent with standard, EPA approved, industrial stack emission models. The models themselves, however, may or may not have passed an EPA approval process. Primary differences in the physics between the models appear to be the degree to which they fully derive equations. All models include some empirical coefficients, approximations, or parameterized equations when insufficient input data are expected or when faster computations are desired. The degree to which this is done varies between models and between components of each model. Note that it is not clear whether fully physical calculations of plume rise and dispersion are more accurate than approximate calculations in biomass burning because of the considerable uncertainty in the distribution and magnitude of available fuels in wildland areas.

Output

Useful output products for smoke managers are those that relate to regulatory standards, show impact to sensitive receptors, and illustrate patterns of potential impact. Regulatory standards require 24-hour averaged and 24-hour maximum surface concentrations of respirable particles at sensitive receptors. In addition, surface concentrations of carbon monoxide (CO), lead, sulfur oxides (SOx), ozone (O_3), nitrous oxides (NOx), and hydrocarbons (e.g., methane, ethane, acetylene, propene, butanes, benzene, toluene, isoprene) are needed to conform to health regulations. Quantifying the impact on regional haze is becoming necessary, which requires an estimate of fine particles, carbon gases, NOx, O_3, relative humidity, and background concentrations. Safety considerations require estimates of visibility, especially along roads (Achtemeier et al. 1998) and at airports. In addition to quantitative output, it is helpful to map information for demonstrating the areal extent of potential impact because even the smallest amount of smoke can affect human values, especially when people with respiratory or heart problems are in its path. For example, studies have shown that only 30 to 60 $\mu g/m^3$ in daily averaged PM_{10} (particulate matter that is less than 10 micrometers in diameter) can cause increases in hospital visits for asthma (Schwartz et al. 1993; Lipsett et al. 1997). These values are less than 1/3 of the national ambient air quality standard (U.S. Environmental Protection Agency 1997). Sometimes the mere presence of smoke, regardless of its concentration, is enough to force alteration of a burn plan.

The old adage, "you can't get out what you don't put in," aptly describes the output of dispersion prediction systems. In a geometric screening system (Wade 1989), only place of impact can be approximated because elemental constituents of the source emissions are not considered. The value in screening processes of this type, however, is that they allow an objective, first-guess estimate of smoke impacts so alternative measures can be taken if needed. Also, the process can be done on a map that illustrates potential receptors and estimated trajectory for others to see and discuss. Depending on the state or tribal implementation plan, a geometric screening may be all that is needed to conform to regulatory standards.

Numerical models disperse gases and particulates that are available from a source-strength model, which uses measured ratios of emissions to amount of fuel consumed (emission factors). Emission factors vary depending on fuel type, type of fire (e.g., broadcast slash, pile, or undisturbed) and phase of the fire (e.g., flaming or smoldering). Currently, emission factors available for wildland fire include total particulate matter (PM), particulate matter that is less than 10 micrometers (μm) in diameter (PM_{10}), particulate matter that is less than 2.5 μm in diameter ($PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and non-methane hydrocarbons (NMHC). Emission factor tables (AP-42) are maintained by the U.S. Environmental Protection Agency (1995).

At this time, emissions of lead and SOx from biomass fires are considered negligible. Emission factors of NOx are uncertain and have not been quantified to a satisfactory level. It is assumed that ozone is not created at the source but develops downwind of the source as the plume is impacted by solar radiation. Currently, aside from grid models, only one dispersion model (CALPUFF: Scire and others 2000a) includes simple photochemical reactions for calculation of down-wind ozone.

Desired attributes within a dispersion prediction system vary in complexity by several orders of magnitude. To help potential users determine which systems may best apply to their specific need, three levels of complexity were estimated for each desired attribute as shown in table 9.3. The 1st level is the simplest; usually producing generalized approximations. At the 3rd level, attributes are determined with the best available science and often include a number of perspectives or options for output.

Using the estimated levels of complexity from table 9.3, it becomes possible to rank dispersion prediction systems for each potential application. For example, if graphical output is available, the location of impact can be determined. If surface concentrations of particles and gases are available, then the system can be used to determine health and visibility impacts. A quick estimate of visibility may require only a 1st level of complexity, while precise visibility determinations may require more complex approaches. A summary of attributes for each dispersion prediction system is provided in table 9.4. The numbers in the attribute columns refer to an estimated level of complexity from 1 to 3 as summarized in table 9.3. Ease of use is a subjective determination based on the work of Breyfogle and Ferguson (1996). It considers the number and type of inputs, the availability of inputs, required user knowledge, and effort needed to produce useful results. Because calculating a ventilation or clearing index is simply a product of two numbers, dispersion indexes typically are computed by others, and both commonly are available through fire weather or air quality forecasts, they are considered very easy to use.

Several methods/models can show cumulative impacts from a number of fires by generalizing the atmosphere's capacity to hold the total emissions (index values) or by displaying multiple plumes at once (VSmoke-GIS if separate projects are used as overlays, NFSpuff, TSARS+, and CALPUFF). The ability to numerically determine the cumulative impact, however, requires concentrations of intersecting plumes to be added together. Currently CALPUFF (Scire and others 2000a) is capable of additive concentrations.

Only two of the currently available models are specific to a geographic area. They are NFSpuff (Harrison 1995) and PB-Piedmont (Achtemeier 1994, 1999, 2000) that were built for ultimate ease by including digital elevation data so the user would not have to find it or adjust for different formats. Early versions of the NFSpuff model contain only elevation data from Washington and Oregon while later versions include all of the western states. The PB-Peidmont model includes data for the piedmont regions of

Table 9.3. Desired attributes of dispersion prediction systems are compared to estimated levels of complexity.

Attribute	1st Level	2nd Level	3rd Level
Communication Aids	Tables	Mapped concentrations	Mapped concentrations as time-sequence loops
Location of impact	At defined receptors	Maps of plume patterns	Maps of plume patterns overlain with sensitive receptor/area locations
Heath Effects	PM surface concentrations	Surface concentrations of $PM_{2.5}$ & CO	Surface concentrations of $PM_{2.5}$, CO, CH_4, NMHC
Visibility in Plume	TSP[a], relative humidity	TSP, relative humidity, $PM_{2.5}$, carbon, background	TSP, relative humidity, $PM_{2.5}$, O_3, carbon, background, NO_2
Regional Haze	Wind, mixing height, emissions	Wind, mixing height, emissions, background, TSP, relative humidity	Wind, mixing height, emissions, background, TSP, relative humidity, $PM_{2.5}$, O_3, carbon, NO_2
Complex Terrain	Generalized or specific to individual valley or basin	Spatial topography	Spatial topography, land-water, vegetation cover

[a] TSP – total suspended particles

Table 9.4. Dispersion prediction systems designed for wildland fire applications. Attributes are ranked by their level of complexity, with 1 being simplest and 3 being most complex, where a dash indicates that the attribute is unavailable. Ease of use is ranked from 1 being the easiest to 10 being the most difficult.

Type	**Method/Model**	**Comm. Aid**	**Impact location**	**Health**	**Visibility in plume**	**Haze**	**Complex terrain**	**Ease of use**
Approx.	Ventilation Index [a]	--	--	--	--	1	1	1
	Dispersion Index	--	--	--	--	1	1	1
	Geom. Screen	2	1	--	--	--	1	3
Box	ValBox	2	1	1	[b]	-	1	5
Plume	Sasem [a]	1	1	2	1	--	--	4
	Vsmoke	1	1	2	1	--	--	5
	Vsmoke-GIS	2	3	2	1	--	--	6
Puff	NFSpuff	3	2	2	[b]	--	2	5
	Citpuff/TSARS+	2	2	2	[b]	--	2	9
	CALPUFF [a]	3	3	3	2	--	3	8
Particle	PB-Piedmont	2	2	-	-	-	1	5

[a] Most likely to meet regulatory requirements (varies from state to state and tribe to tribe)

[b] Although not a direct output of the model, visibility may be approximated from concentration (Wade 1988)

southeastern United States. Other models do not require elevation data (e.g., SASEM and VSmoke) or allow the input of elevation data from anywhere as long as it fits the model-specified format (e.g., VSmoke-GIS, TSARS+, and CALPUFF). While there is some concern that version 1.02 of the Emission Production Model (EPM: Sandberg and Peterson 1984) is specific to vegetation types in Washington and Oregon, it has been adapted for use in the southeastern U.S. through VSmoke (Lavdas 1986) and can be adjusted to function elsewhere in the country (e.g., SASEM: Sestak and Riebau 1988). Newer versions of EPM (Sandberg 2000) and the BurnUp emissions model (Albini and Reinhardt 1997) are not geocentric but to date neither has been incorporated into any available dispersion prediction system.

Summary

For many projects a simple model often provides as good information as a more complex model. Regulations, however, may dictate the level of modeling required for each project. Other times, community values will determine the level of effort needed to demonstrate compliance or alternatives. Also, skills available to set up and run models or the availability of required input data may affect whether a prediction system is necessary and which one is most appropriate.

Because regulations vary from state to state and tribe to tribe and because expectations vary from project to project there is no simple way to determine what dispersion prediction system is best. It is hoped that the information in tables 9.3 and 9.4 can be used to help assess the value of available methods and models. For example, if a simple indication of visibility impacts is required, plume models can be used or visual indexes can be approximated from concentrations out of box, plume, or puff models. If more detailed visibility impacts are required, a sophisticated puff model should be used. Whatever the situation, whether smoke dispersion prediction systems are used for screening, planning, regulating, or simply game playing, it is helpful to remember their strengths and weaknesses.

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Chapter 10

AIR QUALITY MONITORING

Air Quality Monitoring for Smoke

John E. Core

Janice L. Peterson

Introduction

There are several reasons why wildland fire managers may want to conduct an ambient air quality-monitoring program. These include:

- smoke management program evaluation purposes,
- to fulfill a public information need,
- to verify assumptions used in Environmental Assessments,
- to assess potential human health affects in communities impacted by smoke,
- and to evaluate wildland burning smoke impacts on State and Federal air quality laws and regulations.

Both visibility data and $PM_{10}/PM_{2.5}$ concentration data are useful to smoke management program coordinators for assessing air quality conditions if the information is provided in real-time. Fire managers may also be interested in monitoring impacts on visibility in Class I areas. Whatever the objective may be, care must be taken to match monitoring objectives to the right monitoring method. Monitoring locations, sampling schedules, quality assurance, and monitoring costs are elements that must also be considered.

Particulate Monitoring Techniques

Particulate monitoring instruments generally use one of two particle concentration measurement techniques: gravimetric or optical. Gravimetric or filter-based instruments collect particulates on ventilated filters. The filters are later weighed at special laboratory facilities to determine the mass concentration of particulate collected. Gravimetric monitoring techniques have been used for years to quantify mass concentration levels of airborne particulate matter. Filter-based 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. Results may not be available for days or weeks. Also, airflow rates and elapsed sampling time must be carefully monitored and recorded to ensure accurate results. Filter-based techniques integrate samples over a long period of time, usually 24-hours, to obtain the required minimum mass for analysis. Gravimetric monitoring is best for projects where high-accuracy is needed and the time delay in receiving the data is not a problem. State monitoring networks designed to detect violations of air quality standards rely largely on gravimetric monitors. Specific monitoring devices must be approved by EPA for this task and are called Federal Reference Monitors (FRM’s).

Optical instruments measure light-scattering (nephelometers) or light-absorbing (aethalometers) characteristics of the atmosphere. This measurement can then be converted to obtain an estimate of the concentration of airborne particulates. Optical instruments offer several advantages over gravimetric methods, including real-time readings, portability, low power consumption, and relatively low cost. Optical instruments have the disadvantage of being generally less accurate than gravimetric instruments at estimating particulate mass concentration. Optical instruments are best for projects where real-time or near-real time data is needed, where a high degree of accuracy is not a requirement, and if instrument portability and ruggedness is desirable.

Proper conversion of the light scattering measurement collected by nephelometers to an estimate of particle concentration requires development of customized conversion equations. The light scattering value measured depends on particle size distribution and optical properties of the specific aerosol mix in the area of interest. The light scattering value measured varies as a function of the relative proportions of fine particles (including smoke) and coarse particles (such as soil dust). As a result, optical instruments should be calibrated against a co-located FRM in the same area, and pollutant mix, in which they will eventually operate. A formula is then developed to properly convert scattering to a particulate mass per unit volume ($\mu g/m^3$) estimate.

In a recent monitoring instrument evaluation study, sixty-six laboratory measurements were made with the MIE DataRam, the Radiance Research nephelometer, and an EPA FRM sampler where the instruments were exposed to pine needle smoke (Trent and others 1999). Results from these tests concluded that both nephelometers overestimated mass concentrations of smoke when using the scattering to mass conversion factors provided by the manufacturer. A follow-up study (Trent and others 2000) compared optical instruments from various manufacturers (Radiance, MIE, Met One, Optec, and Andersen) to FRM instruments both in the field and laboratory and developed preliminary custom calibration equations (figure 10.1). The report provides an estimate of a conversion equation for each instrument tested

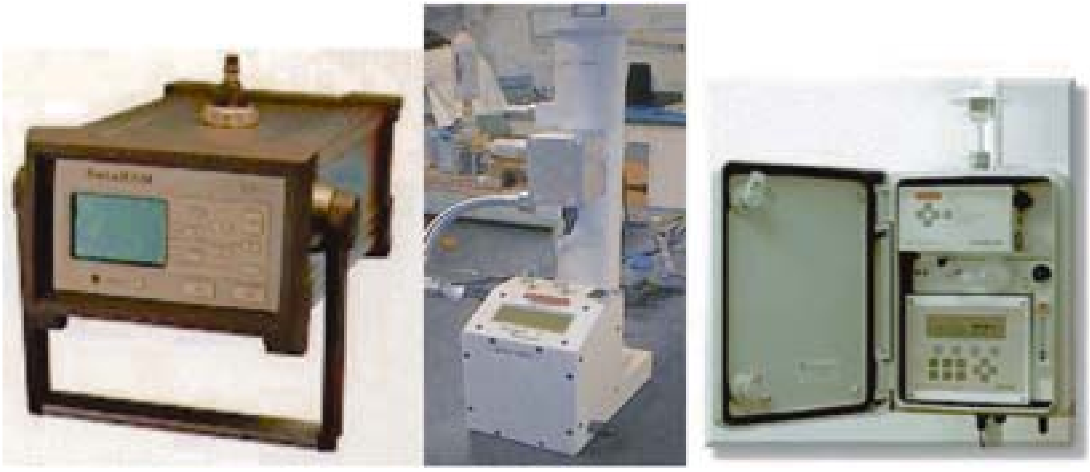

Figure 10.1. Three of the nephelometers tested during the Trent and others (2000) study include the MIE DataRam, the Radiance Research nephelometer, and the Met One GT-640.

but also recommends that optical instruments be field calibrated for a type of fire event, and that meteorological conditions and existing levels of ambient particles be included. Specific conditions to consider during calibration are age of the smoke, type of fire (flaming or smoldering), fuel moisture, relative humidity, and background particle concentration without smoke from the fire. Figure 10.2 shows the correlation found between $PM_{2.5}$ measurements made with an EPA FRM gravimetric instrument vs. results from an MIE DataRam nephelometer (Trent and others 2000).

Wildland Fire Smoke Monitoring Objectives

Gathering PM_{10}/$PM_{2.5}$ air quality data downwind from a prescribed burn or wildfire is an important fire manager goal in some areas. This data may be used as an input to smoke management decision-making, and may or may not involve immediate public release of estimated pollutant levels and health warnings. This monitoring can be conducted at a few sensitive locations within a relatively small area during specific events such as a planned large-scale understory burn, or used as a permanent part of smoke management effectiveness monitoring. Real-time data access, ease of use, and ruggedness are all generally required so optical instruments are most appropriate (table 10.1). Monitors are often equipped with data loggers and modems to permit downloading of the data over a telephone line or via radio modem. In the near future, technology will be available to make air quality monitoring data from remote sites accessible over the Internet. The USDA Forest Service, Missoula Technology and Development Program with Applied Digital Security, Inc have developed a satellite-based data retrieval system. Appropriately outfitted

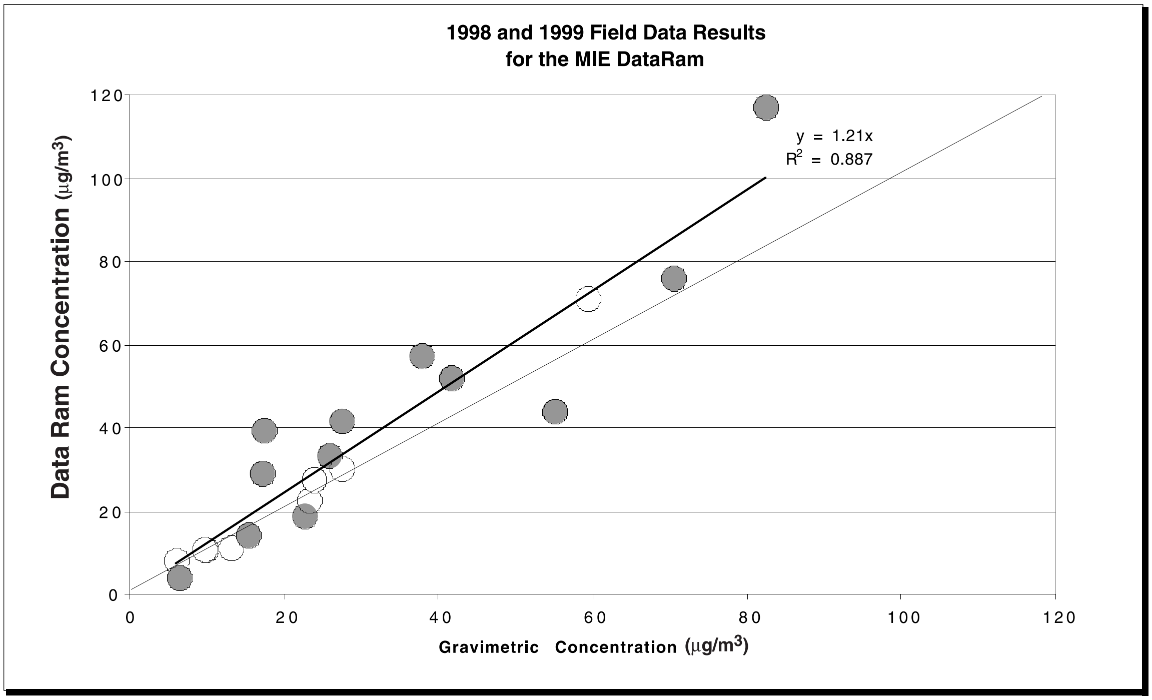

Figure 10.2. Comparison of $PM_{2.5}$ measurements made with a gravimetric Federal Reference Monitor vs. an MIE DataRam nephelometer (Trent and others 2000).

Table 10.1. Equipment appropriate for smoke monitoring differs by program objective.

Program objective	**Temporal requirement**	**Spatial scale or extent**	**Applicable monitoring equipment**
Smoke impact monitoring	Real-time, short-term or event-based	Localized, neighborhood-to-urban scale	▪ Radiance nephelometer[a] ▪ MIE DataRAM nephelometer[b] ▪ Laser photometers[c] ▪ TEOM[d] ▪ BAM[e]
NAAQS monitoring	Long-term	Urban to broad airshed scale	▪ MiniVols[f] ▪ Dichots[g] ▪ Other EPA FRM Monitor[h]
Visibility monitoring	Long-term and real-time	Regional	▪ IMPROVE Sampler[i] ▪ Optec Nephelometer[j] ▪ 35mm Camera[k] ▪ Digital Camera System[l]

[a] A small, lightweight, battery powered integrating nephelometer is manufactured by Radiance Research. Like all light scattering devices, the extinction measurements made by this instrument may be used to estimate PM10/PM2.5 mass by applying an appropriate conversion formula to the light scattering measurements. Units cost about $4,800.

[b] The MIE DataRam nephelometer internally estimates mass concentration via a default or user-specified conversion formula. Units cost about $11,000.

[c] Laser photometers are small, battery powered light scattering devices that provide real-time estimates of light extinction, which can then be converted to PM10/PM2.5 mass given the appropriate conversion formula. Manufacturers include Met One Instruments Inc. and TSI. Units cost about $5,300.

[d] Tapered Element Oscillating Microbalance (TEOM). Manufactured by Rupprecht & Patashnick. The TEOM is an EPA Equivalent Method designated for PM_{10}. Cost is about $17,000.

[e] The Beta Attenuation Monitor (BAM) is also known as a Beta Gauge Monitor. Manufactured by Thermo Environmental, Graseby Andersen, and Dasibi Environmental Corporation. These are EPA Equivalent Methods designated for PM_{10}. Costs range from $14,000 to $20,000.

[f] The MiniVol Portable Air Sampler is a filter-based instrument that utilizes rechargeable batteries, a small air pump, and a programmable timer. Manufactured by Airmetrics, Inc., units cost about $2,300.

[g] The dichotomous sampler (dichot) is a filter-based system manufactured by Graseby Andersen that collects both coarse (2.5-10 µm) and fine particles (<2.5 µm) for speciation analysis. Units cost about $8,500.

[h] EPA federal reference method (FRM) samplers for PM10 and PM2.5 include the Rupprecht & Patashnick Partisol and Partisol-Plus Sequential Sampler; the BGI portable PM10 sampler, the Andersen Instruments RAAS FRM PM2.5 sampler and others. See the EPA AMTIC web page for current information.

[i] The IMPROVE Modular Aerosol Sampler ($35,000) is a filter-based unit manufactured by Air Resource Specialists. It consists of PM10 and PM2.5 sampling heads which capture aerosols on Teflon and quartz filters for chemical analysis (speciation). Costs range from $6,500 to $26,000 depending on configuration.

[j] For true ambient light scattering measurements, the NGN-2 nephelometer manufactured by Optec ($25,000) and used in the IMPROVE network is the standard instrument for visibility monitoring.

[k] A 35mm camera with auto winder, data back and enclosure used for scene monitoring costs about $3,300.

[l] One digital image acquisition system is available from Air Resource Specialists, Inc. and includes a digital camera, weatherproof enclosure, and image capture computer. The system costs approximately $4,800.

instruments will send packets of 5-minute average particulate concentrations each hour by satellite to a stored database to be viewed and retrieved through a Web site.[1]

A second smoke monitoring objective may be to gather data on prescribed fire smoke impacts at sensitive locations over a much longer period for purposes of comparison with ambient air quality standards (NAAQS). In these cases, immediate data access is of secondary importance to gathering data that approximates or is equivalent to the high-accuracy official Federal Reference Method (FRM) instruments used by air regulatory agencies. A popular option is the small, portable, battery powered MiniVol sampler although these are not official EPA FRM designated monitors. The lag-time limitation may be overcome by using one of two EPA-approved continuous air monitoring devices (TEOM or Beta Attenuation Monitors [BAM]) but this equipment is costly and requires a high degree of technical skill to operate (table 10.1).

Visibility protection is another monitoring objective for fire managers when wildland burning smoke may impact nearby Class I areas. For visibility monitoring, information is not only needed on $PM_{10}/PM_{2.5}$ concentrations but aerosol chemical composition and particle light scattering and absorption as well. Since aerosol chemical analysis (speciation) monitoring requires filter-based methods and extinction measurements require in-situ real-time methods, a combination of techniques are used. Monitoring is typically conducted throughout the year over long time periods to establish trends. In as much as data consistency with the national visibility programs is also important, specialized instruments designed and deployed by the Interagency Monitoring of Protected Visual Environments (IMPROVE) Network (Malm

Figure 10.3. A typical IMPROVE monitor installation.

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[1] MTDC Air Program News Issue 1. August 2001. Available at: http://fsweb.mtdc.wo.fs.fed.us/programs/wsa/air_news/issue1.htm

2000) should be used whenever possible (figure 10.3). Monitoring the visual quality of a vista, called scene monitoring, is often done at the same time using 35mm cameras. Digital camera systems can be used at sites where real-time web access to the scene is desirable (table 10.1).

Further monitoring guidance is available on the Internet at the EPA Air Monitoring Technology Information Center (AMTIC) web site (http://www.epa.gov/ttn/amtic) and the EPA Visibility Improvement site (http://www.epa.gov/oar/vis/index.html).

Monitoring Locations & Siting

Samplers used for smoke impact monitoring are normally placed at smoke sensitive locations that have the greatest likelihood of impact.[2] This may be a private residence, within a nearby community, or at a county fair. Care must be taken to ensure that the instrument is located in an open, exposed location removed from local pollution sources such as dirt roads, burn barrels, or woodstoves that would influence the data. The sampler should be located two or more meters above ground at a secure location. Power availability and access are often controlling considerations (CH2MHill 1997).

Visibility monitoring sites must be representative of the Class I area of interest and are therefore best located within the area's boundary or, in the case of wilderness areas, as close to the boundary as possible. Since visibility data is used to represent conditions over sub-regional spatial scales, special care is needed in siting to avoid local source influences. The IMPROVE network has recently been expanded with representative monitors for each of the 156 Class I areas in the country. Siting of the instruments was accomplished with state and Federal Land Manager input.

Sampling Schedules

The timing, duration, and frequency of sampling depend on the program objective. Continuous, hourly data is needed to monitor smoke impacts from several days prior to burn ignition to a day or two after the event. In contrast, PM_{10} NAAQS compliance monitoring using filter-based instruments is conducted once every six days in attainment areas. In a nonattainment area, daily sampling is required for cities with more than a million people and every three days otherwise. Filter-based measurements made as part of the IMPROVE visibility monitoring network are made every third day to reduce costs and operational requirements. Continuous monitoring instruments always operate 24 hours per day. Although sampling duration and frequency decisions are often based largely on operating costs and technician time requirements, measurements made as part of the IMPROVE network or for NAAQS compliance determinations must follow the protocols outlined in EPA regulations found on the AMTIC web site.

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[2] For NAAQS compliance monitoring, refer to the EPA Monitoring Network Siting Guidance found on the EPA AMTIC web site at: http://www.epa.gov/ttn/amtic.

Quality Assurance

Data integrity is essential in any monitoring program. Every monitoring project should have a documented quality assurance plan. In addition to the maintenance and calibration measures outlined by the manufacturer of the instruments being used, additional quality assurance measures may also be included in the plan if the monitoring data are of an especially important nature. These include auditing procedures conducted by the state/local air quality agency to verify proper instrument siting, calibration and data capture as well as traceability of measurement standards to the National Bureau of Standards (NBS) (EPA 1984). Methods of calculation and data processing should also be audited. Fire managers may wish to confer with their state/local air agency to assure that monitoring results are valid.

Monitoring Costs

Monitoring is expensive. In addition to 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 also be included. On-going annual operating costs for technician time to service the instruments is a major expense that often drives the monitoring system design.

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Chapter 11

EMISSION INVENTORIES

Emission Inventories

Janice L. Peterson

An inventory or estimate of total statewide (or some other geographically distinct unit) annual emissions of criteria pollutants is a necessary part of understanding the burden on the air resource in an area and taking appropriate control actions. Emission inventories are a basic requirement of state air resource management programs and are a required element of State Implementation Plans. Emission inventories help explain the contribution of source categories to pollution events, provide background information for air resource management, provide the means to verify progress toward emission reduction goals, and provide a scientific basis for state air programs. An accurate emissions inventory provides a measured, rather than perceived, estimate of pollutant production as the basis for regulation, management action, and program compliance. Emission inventories should include all important source categories including mobile, area, and stationary and are not complete unless difficult-to-quantify sources like agricultural burning, backyard burning, rangeland burning, and wildland and prescribed burning are each addressed.

Wildland and prescribed fires are extremely diverse and dynamic air pollution sources and their emissions can be difficult to quantify. Design and development of an emission inventory system is primarily the responsibility of state air regulatory agencies. But cooperation and collaboration between air regulatory agencies and fire managers is required to design an effective and appropriate emission inventory system. Wildland fire managers should have the knowledge and data necessary to calculate emissions from their burn programs and be prepared to work with the state in developing emission inventory systems for wildland fire.

At the most basic level, estimation of wildfire emissions requires knowledge of area burned, fuel consumed, and a fuel-appropriate emission factor. The estimate of emissions is made through simple multiplication of area burned (acres or hectares) times fuel consumed (tons per acre or kilograms per hectare) times an emission factor assigned with knowledge of the fuel type (lbs/ton or g/kg) (figure 11.1). Resulting emissions are in tons or kilograms.

Greater accuracy, precision, and complexity can be achieved through increasingly detailed knowledge of these basic parameters. For example, area burned is estimated pre-burn in many existing reporting systems; if area burned is reassessed post-burn the accuracy of the emission inventory will increase. Accuracy and precision will also be improved if fuel consumed can be estimated with knowledge of pre-burn loading and consumption of fuels in each of many possible categories based on fuel type, size, and arrangement; and with knowledge of fuel moisture conditions, weather parameters, and application of emission reduction techniques. A more precise emission factor can be assigned with knowledge of burning conditions that can shift fuel consumption from the less efficient smoldering combustion phase into the more efficient flaming phase (figure 11.2).

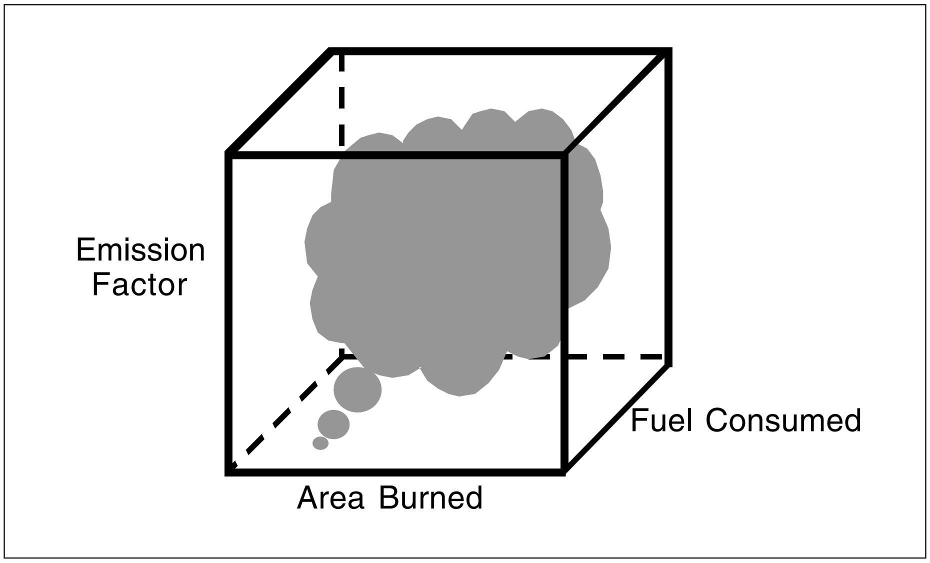

Figure 11.1. Basic information components needed to estimate the quantity of emissions from an individual wildland burn and compile an emissions inventory.

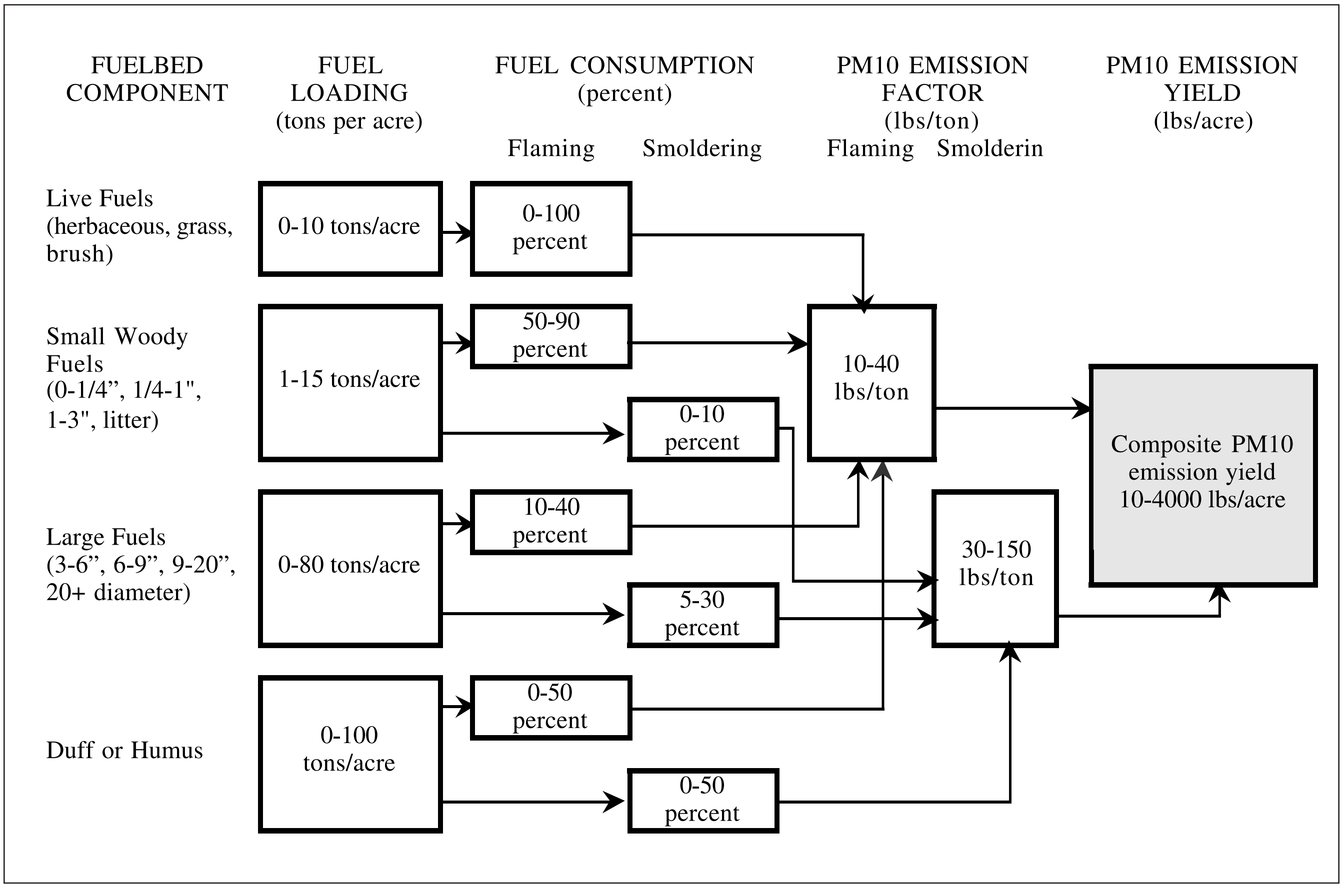

Figure 11.2. Detailed information about fuel loading and consumption by size class plus information to predict consumption by phase of combustion can increase the accuracy and precision of estimates of emissions from prescribed wildland fire for an emissions inventory (Modified from Sandberg [1988]). The ranges given in the figure cover the majority of fuel loading and consumption situations in wildland fuels but do not define the extremes. Numerous exceptions could likely be found in practice.

Sources of Prescribed Burning Activity Level Information

States with incomplete or no centralized burn reporting requirements will need to go to the burners themselves to quantify activity level. Federal agencies generally keep fairly accurate records of burning accomplished in a given time period and can also provide estimates of wildfire acres. Federal agencies that may need to be contacted in a given state or area include the Bureau of Land Management, Bureau of Indian Affairs or individual Tribes, National Park Service, Forest Service, and Fish and Wildlife Service. In some areas other federal agencies may need to be contacted. Such as the Department of Energy, Department of Defense, Natural Resources Conservation Service, Agricultural Research Service, U.S. Geological Survey, or the Department of Reclamation along with managers of National Preserves and National Monuments.

Specific state agencies with a forestry, wildlife, conservation, or natural resource management mandate are another source of activity level information. They may use prescribed burning themselves and may compile burning statistics for state lands and sometimes also for private lands. Private land owners, especially those managing timber-lands should be contacted as should The Nature Conservancy and the Audubon Society.

In some areas, especially where prescribed wildland burning is infrequent, the only source for activity level information may be a gross estimate for all prescribed fires for an entire state or area. This can sometimes be obtained from a single federal or state agency, or sometimes from an academic institution.

Type of Burn

Prescribed burning can be divided into categories depending on the arrangement of the fuels. Fuel arrangement can help predict total fuel consumption and the proportion consumed in the flaming vs. smoldering phases. Broadcast burning refers to fuels burned in place. This term can be used to describe natural woody fuels scattered under a stand of trees, woody debris scattered at random after a timber sale, brush burned in place, or grass. Fuels can also be concentrated into piles before burning. In addition to pile and broadcast burning, other general prescribed-fire-type categories that may be used include range, windrow, right-of-way, spot, black line, jack-pot, and concentration. Knowledge of the type of burn is valuable for estimating emissions as it can affect the accuracy and correct interpretation of estimates of area burned, fuel consumed, and assignment of an appropriate emission factor.

Area Burned

Area burned is generally the easiest parameter to obtain from fire managers. One caution is that area burned is often estimated prior to prescribed burning and not updated with the results of the burn, which may be smaller or larger (in the case of an escaped fire) than originally estimated. Also, area burned may reflect the area treated or the area within the wildland fire perimeter, rather than the area actually blackened by fire. The wildland fire perimeter may be considerably larger than the area actually blackened by fire. For example, a study of the Yellowstone fires of 1988 found that about 65% of the wildfire perimeter area within the park was actually blackened (Despain and others 1989), the remaining 35% was in unburned islands. In the case of prescribed fire, land managers may consider a larger area to have been treated or to have benefited by the fire than was actually blackened by flames. Compiling an accurate emission inventory requires actual acres (or hectares) blackened for an accurate estimate of emissions. Caution should be used with estimates of area burned, as this parameter is more prone to systematic overestimation than any other component of emissions estimation.

Fuel Consumed

Fuel consumed is generally estimated via a two-step process; first fuel loading is estimated, then a percent consumption is applied to calculate fuel consumed. At the most basic level, a single value for both total fuel loading and consumption can be used (for example 20 tons of fuel of which 50 percent consumed). In reality, a fuelbed is a complex mix of various sizes of woody fuels (tree boles, branches, and twigs), needle and/or leaf litter, decayed and partly decayed organic matter and rotten material (generally called duff or rot), and live fuels like brush, forbs, and grass. Each of these fuelbed components contributes to the total loading and is consumed to a greater or lesser extent. For example 100 percent of woody fuels less than 1 inch in diameter may burn whereas just 30 percent of those greater than 3 inches in diameter burn. In addition, some emission reduction techniques are specific by fuelbed component. Use of a single estimate of total fuel loading and consumption will fail to capture this. To gain accuracy in the emissions inventory and the ability to track the use and effectiveness of emission reduction techniques, further detail concerning fuel loadings by fuelbed component would ideally be tracked.

One simple method for obtaining a gross estimate of fuel loading is through the use of standardized fuel models. The most widely used example is the array of National Fire Danger Rating System (NFDRS) fuel models (Deeming and others 1977). These 20 models are standardized descriptions of different fuel types that can be used with some applicability to virtually all wildlands in the US. The NFDRS fuel models were designed as predictors of fire danger rather than to characterize the wide range of potential wildland fuel loadings as would be ideal for compilation of an emissions inventory. Another commonly used set of fuel models is based on predicting fire behavior. Thirteen fire behavior fuel models are described in Anderson (1982). Since both the NFDRS and fire behavior fuel models were designed for purposes other than accurate fuel loading estimation, these models should be used with caution. In addition, the use of standardized fuel models to estimate fuel loading means that efforts to reduce fuel loading for emission reduction purposes prior to prescribed burning cannot be tracked or reflected in the emissions inventory.

Other more detailed standardized fuel models called fuel characteristic classes (FCC's) are under development (Sandberg and others 2001) that are expected to greatly improve fuel loading estimates when they reach widespread use. It is estimated that there will be a core set of 48 to 64 FCC's in common usage with as many as 10,000 available in total describing the vast range of fuel types and conditions that can exist in wildlands across the country.

The most accurate method of estimating fuel loading is to have fire managers measure it in the field. Field estimation also enables reflection of the effect of emission reduction techniques on fuel loading. The most accurate method of estimating fuel consumption is through modeling (field measurement being unreasonably difficult in virtually all cases). In the west, two fuel consumption models are commonly used for this: the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997) and Consume (Ottmar and others 1993). These two models can provide very good estimates of fuel consumption if some basic knowledge of factors influencing fuel loading and moisture are known.

Estimating fuel loading and consumption for wildfire is much more difficult than for prescribed fire. For one thing, large wildfires often burn through many different fuel types where fuel loading can range from just a couple of tons per acre to over 100 tons per acre. Also, the science of predicting fuel consumption and emissions from a fire burning in tree crowns is extremely weak. The fuel type available from wildfire report forms is generally for the point of ignition rather than a reflection of fuel on the majority of acres burned.

Emission Factors

Wildland and prescribed-fire emission factors are contained in the EPA document AP-42 (EPA 1995) and in table 5.1 in the Smoke Source Characteristics chapter. Accuracy may be gained in an emissions inventory through knowledge of the portion of fuel consumed in the two primary consumption phases: flaming and smoldering. Flaming consumption emits far less emissions per unit of fuel consumed than smoldering consumption. Estimation of the flaming vs. smoldering ratio can be obtained through fuel consumption modeling and with knowledge of some influencing factors such as rate of ignition, fuel moisture conditions, and days since rain.

Federal Agency Reporting

The Forest Service, Bureau of Land Management, Fish and Wildlife Service, National Park Service, and Bureau of Indian Affairs all have mandatory reporting requirements for wildland and prescribed fires although at present, they are all somewhat different. These reports contain some of the basic information needed to compile an emissions inventory. Within the next couple of years, all federal agencies will be moving toward a consolidated fire reporting database through implementation of the Federal Fire Policy.

Record keeping by state and private landowners is much more variable and may or may not be available to states wishing to compile an emissions inventory.

Forest Service

Forest Service forms FS-5100-29 (wildland fire) and FS-5100–29T (prescribed fire) require some of the basic inputs needed to compile an emissions inventory. The wildland fire report form requires reporting of acres burned within the fire perimeter regardless of landowner plus National Fire Danger Rating System (NFDRS) fuel model. It is significant to note that the instructions for estimating acres (USDA Forest Service 1999) specify reporting of all acres within the fire perimeter, unfortunately this value is not likely to equal acres blackened by fire. The number of acres blackened will always be less than the number of acres within the fire perimeter so use of this value without some adjustment will result in a serious systematic overestimation of acres actually burned and therefore of smoke produced. The NFDRS fuel model reported is the one in which the fire was burning at the time and place where another required element, the fire intensity level, was observed so it may or may not be representative of the majority of acres burned. Individual fire reports are collected throughout the year and can be analyzed through an electronic system called FIRESTAT (USDA Forest Service 1999).

Data collected by the Forest Service about prescribed burning that is useful for compiling an emissions inventory includes the prevailing NFDRS fuel model; the total acres plus the percent of acres burned; the preburn loading of dead fuels 0-3 inches in diameter; 3+ inches in diameter, and live; and the percent of these fuels that consumed. The prescribed fire report allows more accurate estimation of emissions since the percent of acres burned is reported and fuel loading and consumption is estimated in three categories. The Forest Service reporting system does not include estimates of duff consumption which can contribute as much as 50 percent of the emissions from a prescribed burn in certain areas under dry conditions, though is generally much less than that.

Fish and Wildlife Service

The Fish and Wildlife Service also has mandatory fire reporting requirements and uses a system called the Fire Reporting System (FRS) for data collection. The FRS requires reporting of project area size plus the actual burned area or acres blackened for both wildland and prescribed fire. It also allows multiple entries for NFDRS fuel model and links a specific area burned to each. Fuel loading is assigned based on NDFRS defaults in seven categories: dead woody fuels of diameter 0-1/4”, 1/4-1", 1-3", 3+; herbaceous; live woody; and duff. Users then specify percent consumption for each fuelbed category. Custom fuel models may also be defined. Data collected as part of the FRS provides very good information for estimating emissions from both wildland and prescribed fire on Fish and Wildlife Service burns though this is a very small part of total burning in most areas of the country with notable exceptions in the Southeastern states and Alaska.

Bureau of Land Management

The BLM reporting requirements include estimation of area burned for wildland and prescribed fire, less any unaltered areas as an estimate of acres blackened. The fire behavior fuel model that best represents the fuels in the burn area is required as is the NFDRS fuel model in the vicinity of the fire origin. The model representing fuels in the burn area is more appropriate for emissions estimation. In addition, for prescribed fire up to two fire-behavior fuel models can be selected and the percent of the burned area assigned. Fuel loading (tons per acre) and consumption (percent) can be reported in each of six fuel size classes: 0-1", 1.1-3", 3.1-9", greater than 9", shrub and herb, and litter and duff. If actual field data for fuel loading and consumption is not available, the most appropriate standard fuel loading and consumption range can be selected. Fuel loads can be assigned as light, average, or heavy for the fire behavior fuel model type and fuel consumption can be assigned as light, average, or heavy making some customization of the standard fuel models possible. The BLM reporting system also accommodates the unique requirements of estimating loading and consumption of prescribed burning of debris piles.

National Park Service

The NPS has mandatory fire reporting requirements but the information collected is of little use for emissions estimation, especially for wildland fire. For wildland fires, acres burned is required but the instructions don't specify whether perimeter acres or acres blackened is to be reported. The only required description of vegetation assigns one of three categories: commercial forest land, non-commercial forest land, or non-forest watershed which provides little or no information for estimating fuel loading and consumption. There is an optional field for input of NFDRS fuel model but how often this is used is unknown. Prescribed fire and wildland fire for resource benefit requires input of both NFDRS fuel model and a fire behavior fuel model.

Bureau of Indian Affairs

Fire reporting requirements for the BIA are similar to those for the NPS (see discussion above). One minor difference exists in the reporting of prescribed and wildland fire for resource benefits, where a fire behavior model may be input (but is not required). Further, a fire danger rating (NFDR) fuel model cannot be input.

Choosing the Appropriate Accuracy and Precision in an Emissions Inventory

The appropriate accuracy and precision for a state emissions inventory should be designed through analysis of the importance of the source in the affected area (sub-state, state, or multi-state area). Variables influencing the importance of prescribed burning as a source can be assessed through addressing issues such as:

- whether there are current impacts from prescribed fire or wildfire smoke,
- the aggressiveness of state goals for emission reduction and air quality improvement,
- the trend in burning in the local area and the rate of increase or decrease,
- a professional or financial motivation by burners to track and/or reduce emissions,
- the need to associate wildland fire emissions with specific air pollution episodes.

Tables 11.1 and 11.2 summarize information needed for a prescribed burning emissions inventory and for a wildland fire emissions inventory. Each table lists the categories of information needed to inventory emissions, proposes a minimum requirement for a basic inventory, and lists options for increasing the accuracy and precision of the inventory which may be desirable if wildland fire in the area of interest is of concern or controversial.[1]

Data requirements for producing an emissions inventory for either prescribed burning or wildland burning are very similar. They both require information about the time period of the burn, the location, the area actually burned, a description of the fuelbed, how much fuel burned, and site specific information for assigning an emission factor. A prescribed burning

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[1] Sandberg, David, V.; Peterson, Janice. 1997. Emission inventories for SIP development. An unpublished technical support document to the EPA Interim Air Quality Policy on Wildland and Prescribed Fires. August 15, 1997. (Available from the authors or online at http://www.epa.gov/ttncaaa1/faca/pbdirs/eisfor6.pdf).

Table 11.1. Summary of information needed to compile a prescribed fire emissions inventory and options for increasing accuracy.

Information Needed	Units	Minimum Requirement	Overview of Options for Increasing Precision	Comments
1. Time period	time	year	season, month, day	
2. Location	n/a	administrative area	county, latitude and longitude, legal description	Latitude and longitude, and legal descriptions may be the burn start-point or mid point. All burners should be consistent.
3. Area actually burned	acres	acres	stratify by fuelbed description, area burned by time intervals (hourly or longer)	Should be retrospective to get an accurate estimate. Time interval estimates would be necessary for accurate dispersion modeling.
4. Fuelbed description	type or tons per acre	grass/brush/ forest floor/ forest crowns or slash	vegetative type, fuel model, fuel model by loading category (high/medium/low), inventoried fuel loadings	Critical for accurately estimating fuel loading and assigning an emission factor but may also be used for estimating fuel consumed. Use of BACM techniques may be detected with refined information.
5. Fuel consumed	percent or tons/acre	expert estimate	site specific information for driving predictive models	Critical variables for gaining precision will vary with fuel type and area, fuel moisture is nearly universal. Use of BACM techniques may be detected with refined information.
6. Emission factor	lbs/ton	burn average based on fuelbed description	site specific information to allow consumption to be apportioned into flaming vs. smoldering phases	Assigned based on AP-42.
7. Type of burn or fuelbed	category	none	broadcast, pile, right-of way, spot burning	Can increase accuracy of consumption estimates and emission factor assignment.
8. Purpose of Burn	category	none	ecosystem management, waste disposal, habitat enhancement, etc.	Can be useful if SIP strategies or permitting differs by purpose of burn.

Table 11.2. Summary of information needed to compile a wildland fire emissions inventory and options for increasing accuracy

Information Needed	Units	Minimum Requirement	Overview of Options for Increasing Precision	Comments
1. Time period	time	year	season; month; wildfire start, major spread, control, and declared-out dates; activity by day	Finest time resolution for which the inventory results will be used.
2. Location	n/a	administrative area	county; latitude and longitude	
3. Area actually burned	acres	acres	acres black stratified by other categories of information such as date, fuelbed, area burned in severe, moderate and low intensity, etc.	Currently, reported wildfire area burned is generally perimeter area which results in a systematic overestimation of area burned by as much as one third.
4. Fuelbed description	type or tons per acre	grass/brush/ forest floor/ forest crowns or slash	vegetative type, fuel model, fuel model by loading category (high/medium/low), percent of area burned by fuelbed description	Critical for estimating fuel loading and assigning an emission factor but may also be used for estimating fuel consumed. Unfortunately “cover type at point of ignition” is generally what is indicated on fire reports. Minimally, acres burned are to be stratified by grass, brush, forest floor, timber crowns, or slash. This is the most critically lacking variable in most current fire reports, and some approach to augmenting the information should be considered.
5. Fuel consumed	percent or tons/acre	expert estimate	more research is needed to develop algorithms to predict wildfire fuel consumption	Very difficult to estimate accurately and likely varies widely throughout a wildfire area.
6. Emission factor	lbs/ton	average value from table	see fuelbed description	Assigned based on AP-42.
7. Control strategy	category	none	full suppression, modified, limited	May be used in some SIP strategies in order to identify sources that are allowed to burn to achieve resource benefits or economic efficiency.

emissions inventory includes extra information about the type of burn or fuelbed arrangement plus the purpose of the burn. These are optional data items that may be useful in some cases. A wildland burning emissions inventory includes information about the control strategy used to fight the fire.

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Chapter 12

ADMINISTRATION AND ASSESSMENT

Smoke Management Program Administration and Evaluation

Peter Lahm

Smoke management program administration can range from activities conducted at the local burn program level to a multi-state coordinated effort to manage smoke. The EPA Interim Air Quality Policy on Wildland and Prescribed Fires (Interim Policy) (EPA 1998) recommends that smoke management programs be administered by a central authority with clear decision-making capability. As smoke management programs range from voluntary efforts to mandatory regulatory driven programs, the administration will vary accordingly[1]. On the more local level, the programs may be administered by a group of land managers or private landholders seeking to coordinate burning efforts to avoid excessive smoke impacts. Mandatory regulatory driven smoke management programs tend to be administered by tribal/state/district air quality regulatory agencies or state forestry entities. The administration of smoke management programs allows for a number of different approaches to meet EPA objectives and to maintain cooperative and interactive efforts to manage the dual objectives of good air quality and land stewardship.

The Interim Policy also recommends periodic evaluation of smoke management programs to ensure that air quality objectives are being met. From the land management point of view, these same reviews are critical to assessing whether land management objectives are being met under the smoke management program. EPA also recommended periodic evaluation of smoke management rule or regulation effectiveness as part of its Interim Policy. For programs that are under scrutiny by a concerned public or are growing rapidly, continuous evaluation should also be considered. All smoke management efforts—from formal interagency smoke management plans to less structured efforts to address smoke from individual fire operations—can benefit from continuous and periodic evaluation. If a smoke management program changes size, jurisdiction, or regulatory responsibilities, the level of effort applied to managing smoke should also change. To keep a program ahead of growing air quality concerns, a continuous effort to evaluate smoke management effectiveness is useful. This evaluation is also critical for local unit programs that are under formal state or tribal smoke management plans. The evaluation process has applicability to all types of fire, including wildland fire under suppression, wildland fire use and prescribed fire.

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[1] Examples of specific state smoke management programs are provided in chapter 4, section 4.2.

Smoke Management Program Administration

Administration of a smoke management program is frequently a function of the size of the burn program using a metric such as acres burned or emissions generated, coupled with the complexity of the local air quality issues. Fire programs located in areas that are not rife with Class I areas, PM_{10} non-attainment areas, or smoke-sensitive transportation corridors are commonly under voluntary smoke management programs and may be locally administered. These types of programs may be focused on concerns of local area impacts such as nuisance or transportation safety and can be well addressed through local level coordination among burners. State forestry agencies and their respective districts are frequently central points for dissemination of information; many examples of this type of program can be found in the southeastern states.

As air quality complexity rises with potential smoke impacts on non-attainment areas or Class I areas, legal requirements also rise, and frequently trigger a more centralized regulatory-based smoke management program. Attendant with the increased program requirements is the commensurate increased cost of the program. Direct costs of smoke management program administration are frequently recovered through the charging of fees to burners. Fees are frequently based on emissions production or tonnage of material to be consumed and are used to offset an authority's program administration costs. The increased indirect cost of frequent reporting requirements and other permitting tasks such as modeling of impacts and smoke management plan preparation are frequently overlooked. The most common centralized program approach is administered by the state or tribal air quality authority and can be found in such states as Colorado. States such as Florida and Oregon have opted to use their forestry agencies to help directly manage their smoke management programs. Oversight by the respective air quality regulatory authority is usually a part of such a program. There is an option for interagency approaches to smoke management program administration. This approach blends the lines between air quality regulatory agencies and land managers. Personnel from a land management agency may be out-stationed to the respective air quality regulatory authority to assist in the smoke management program administration. The states of Utah and Arizona use this approach respectively and have avoided program management fees in this fashion. This approach can also foster good inter-agency communication and development of joint air quality and land management objectives for smoke management programs.

The future of smoke management program administration will be a reflection of the implementation of the Regional Haze Rule (40 CFR Part 51), which creates a paradigm in which air quality impacts are viewed in a regional sense rather than by locality or state. Tribal smoke management programs are being rapidly developed and will help support this regional approach. The establishment of multi-state smoke management jurisdictions is rapidly becoming a reality with a joint effort by Idaho and Montana being a recent example. The $PM_{2.5}$ and ozone standards will also support this type of approach as the impacts of smoke are viewed as a long-range transport issue. The inclusion of all sources of fire emissions, such as agricultural burning and wildland burning, into a singular smoke management program is also a future direction in these programs, and can already be found in the Title 17 Rule in California.

Evaluation of Smoke Management Programs

Size of Program — In lieu of any other parameter that can describe the activity level of a burn program, the number of acres can be used to trigger level of effort for smoke management and subsequent evaluation of smoke effects. As mentioned elsewhere, the representation of fire activity in terms of emissions is more effective for air quality purposes. In lieu of emissions, fire size and fuel type can be used for triggering different smoke management requirements. Small burns located in remote areas with low emissions may not dictate any evaluation greater than tracking the activity level and date of burn. However, more complex situations such as a burn of several days' duration with heavy emissions located in the wildland/urban interface should be tracked more extensively for smoke management effectiveness. This same complex situation may track the effectiveness of emission reduction practices. It may be beneficial if the criteria are established in consultation with the local or state air regulatory agency. For federal agencies, these criteria can also be linked to the management plan's monitoring program. A post burn analysis of the smoke management plan and the burn's smoke effects can be extremely valuable to all concerned parties.

Intensity and Duration of Smoke Effects — The intensity and duration of smoke impacts are critical parameters that can represent a variety of smoke management effectiveness measures. Duration of smoke impacts upon the public, a non-attainment area, a transportation corridor or Class I area can be tracked and assessed through direct air quality monitoring.[2] The public can be tolerant of one day of heavy levels of smoke, however consecutive day impacts may lead to a rash of complaints. The criteria for evaluating a program may be to assess the number of consecutive days/hours of impact to a specific area. The intensity level of smoke impact also plays a role, as short bursts of high levels of smoke punctuated by clear air is frequently tolerable by receptors. An application of this type of criteria exists in Oregon where number and intensity of smoke intrusions is tracked annually. This type of criteria is applicable to individual incidents as well.

Methods of tracking the intensity and duration of smoke impact include:

- Number and type of public complaints (citizen, doctor, hospital, etc.);
- Intrusion of smoke into designated smoke sensitive areas through specific air quality measurement;
- Violations or percent increase of criteria pollutants attributable to smoke;
- Visibility impacts (local and regional).

As the National Ambient Air Quality Standards (NAAQS) include both short term and annual standards, the full impact of smoke on the NAAQS may not be readily determined until well after the burn season is completed, which further supports the importance of incorporating evaluation into a smoke management program. Impacts on visibility were previously viewed on an annual basis, however that has changed to tracking impacts on Class I areas to determine effects on the 20% clearest and 20% dirtiest days. These methods for tracking and evaluation should be established prior to the event or as part of the overall smoke management program as they can take significant planning or coordination. Pre-planning for the air quality element of the Wildland Fire Situation Analysis used by federal agencies for wildland fires

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(USDI and USDA Forest Service 1998) can also be beneficial as the public, air quality regulatory community, and land management entity has the opportunity to increase acceptance of smoke effects.

The evaluation criteria should be as quantitative as possible in light of the complexity of the burn or program and the air quality concerns of the area. Proximity to non-attainment or Class I areas should automatically trigger some programmatic evaluation. Visibility should be considered in terms of plume blight, regional haze and impacts on safety (transportation). Conversely, a small incident with a small quantity or short duration of emissions in an area with few air quality concerns should not warrant extensive programmatic or individual incident evaluation effort. Again, advance coordination with concerned parties can help determine this varying level of effort.

If an incident or program results in a smoke intrusion above a pre-defined level such as number of complaints or presence of smoke in an avoidance area, the cause should be evaluated as soon as possible. The breakdown of the smoke management plan for an incident is equivalent to the breakdown of the fire behavior prescription for the burn. Smoke management contingency programs are another element of a smoke management program included in the Interim Policy (EPA 1998). Factors such as weather/smoke dispersion forecasting or fuel condition changes can lead to such a smoke intrusion and need to be evaluated quickly following a failure of the system in order to be addressed in a proactive fashion. Determination of what caused the adverse air quality impact allows for growth of the program through implementation of changes to avoid future recurrence. If a program or incident was conducted such that no smoke criteria were exceeded, evaluation of the factors which led to success are also valuable in building confidence among cooperating parties. The development of an annual report which outlines the air quality effects of a burning program or the smoke management program demonstrates the commitment to addressing both land management and air quality objectives and can show significant and useful trends to concerned parties. The knowledge that smoke impacts are being addressed effectively in terms of specific criteria is valuable when working with the concerned public and media.

Sources for Evaluation — Evaluation can be the assessment of air quality monitoring data collected by the land manager or utilization of existing air quality networks as operated by a regulatory agency (state/district/county/EPA/tribe). The meteorological conditions under which burns occur is another criteria that can be evaluated to help assess the smoke management program. For complex smoke areas, the use of digital camera points could allow distribution of the real-time images over the Internet to concerned parties, including the public. The concerned public can also be directly queried as to the level of smoke levels and duration of effects.

Annual Evaluation — One of the most effective means of evaluating the smoke management program is to hold periodic meetings amongst the concerned parties such as the burners, regulators and potentially-concerned public. The frequency of such reviews should depend on the air quality complexity and smoke impacts. Many statewide smoke management programs meet annually to review the years' activities, successes and problems. These meetings could include review of activity/emissions of burners, record-keeping efforts, effects tracked through the previously mentioned methods, and discussion of program logistics and costs. This same review meeting is also an opportune time to plan for future changes, discuss emerging issues, and conduct training if needed. The Interim Policy (EPA 1998) also urges such an evaluation process occur annually. These annual sessions may be an effective way of addressing an Interim Policy goal of assessing the adequacy of the rules and regulations pertaining to smoke management for a respective state, tribe or other managing entity. Reflecting the state of the smoke management program, whether statewide or at the land manager level, through the issuance of an annual program report on smoke management can be another technique for assessing the program and informing the public of the investment into smoke management.

Continuous Evaluation — If a specific incident were to have significant adverse effects, it might trigger immediate review to prevent a repeat occurrence. This immediate incident assessment can be an effective way of addressing pressing public concerns that may have arisen due to the impacts. During a wildland fire use incident, daily conference calls amongst the land manager and the regulatory agencies which discuss acres/fuels/emissions or qualitative smoke behavior can be very effective at addressing smoke concerns. This real-time evaluation can prevent conflict over smoke impacts and can ensure accurate information be provided to the public as well as incorporated into the message transmitted to the media by the respective agencies.

Incident debriefings should consider air quality effects and how they were addressed. In wildland fire use, there is a continuous evaluation of air quality as part of the Wildland Fire Situation Analysis (USDI and USDA Forest Service 1998). Establishment of criteria for evaluation of air quality effects prior to the actual event or implementation of a program can allow for greater buy-in by potentially affected parties when the fire occurs. Criteria for evaluation should also include indicators of success.

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APPENDIX

Appendix A

Glossary of Fire and Smoke Management Terminology

The terms listed below were either taken from existing glossaries or developed specifically for this Guide. Where terms were taken from an existing glossary or document, the source reference is indexed in brackets (e.g. [source number]), with full reference citations provided at the end of the glossary. Note: Although the referenced definitions in this glossary were taken from other sources, the editors have revised or changed many of them from their original version.

Absorption coefficient	A measure of the ability of particles or gases to absorb photons; a number that is proportional to the number of photons removed from the sight path by absorption per unit length. (See Extinction coefficient). [2]
Activity fuel	Debris resulting from such human activities as road construction, logging, pruning, thinning, or brush cutting. It includes logs, chunks, bark, branches, litter, stumps, and broken understory trees or brush.
Activity level	Fuels resulting from, or altered by, forestry practices such as timber harvest or thinning, as opposed to naturally created fuels. [1]
Adiabatic lapse rate	Rate of decrease of temperature with increasing height of a rising air parcel without an exchange of heat at the parcel boundaries. (See Dry adiabatic lapse rate, Saturated adiabatic lapse rate, and Atmospheric stability).
Advection	The transfer of atmospheric properties by the horizontal movement of air, usually in reference to the transfer of warmer or cooler air, but may also refer to moisture. [1]
Aerial ignition	Ignition of fuels by dropping incendiary devices or materials from aircraft. [1]
Aerosol	A suspension of microscopic solid or liquid particles in a gaseous medium, such as smoke and fog. [2]

Air mass	An extensive body of air having similar properties of temperature and moisture. [1]
Air pollution	The general term referring to the undesirable concentration of substances (gases, liquids, or solid particles) to the atmosphere that are foreign to the natural atmosphere or are present in quantities exceeding natural concentrations. [1]
Air quality	The composition of air with respect to quantities of pollution therein; used most frequently in connection with “standards” of maximum acceptable pollutant concentrations. [1]
Allowable emissions	The emissions rate that represents a limit on the emissions that can occur from an emissions unit. This limit may be based on a federal, state, or local regulatory emission limit determined from state or local regulations and/or 40 Code of Federal Regulations (CFR) Parts 60, 61, and 63. [3]
Ambient air	Any unconfined portion of the atmosphere: open air, surrounding air. [4]
Ambient standards	Specific target threshold concentrations and exposure durations of pollutants based on criteria gauged to protect human health and the welfare of the environment. Ambient standards are not emissions limitations on sources, but usually result in such limits being placed on source operation as part of a control strategy to achieve or maintain an ambient standard. [3]
Anthropogenic	Produced by human activities. [2]
Area sources	A source category of air pollution that generally extends over a large area. Prescribed burning, field burning, home heating, and open burning are examples of area sources. [1]
Atmospheric inversion	(1) Departure from the usual increase or decrease with altitude of the value of an atmospheric property (in fire management usage, nearly always refers to an increase in temperature with increasing height). (2) The layer through which this departure occurs (also called inversion layer). The lowest altitude at which the departure is found is called the base of the inversion. (See Atmospheric stability; Temperature inversion; Mixing height; Mixing layer; Stable atmosphere; Unstable atmosphere; Subsidence inversion) [1]

Atmospheric pressure	The force exerted by the weight of the atmosphere, per unit area. At sea level the atmospheric pressure fluctuates around 1013 millibars (mb). At 5,000 feet (~1,500 m) above sea level the atmospheric pressure fluctuates around 850 mb. (See Standard atmosphere).
Atmospheric stability	The degree to which vertical motion in the atmosphere is enhanced or suppressed. (See Atmospheric inversion; Temperature inversion; Mixing height; Mixing layer; Stable atmosphere; Unstable atmosphere). [1]
Attainment Area	An area considered having air quality as good as or better than the National Ambient Air Quality Standards (NAAQS) as defined in the Clean Air Act. Note that an area may be in attainment for one or more pollutants but be a nonattainment area for one or more other pollutants. (See Non-attainment area). [3]
Avoidance	A smoke emission control strategy that considers meteorological conditions when scheduling prescribed fires in order to avoid incursions into smoke sensitive areas. [1]
Background level	In air pollution control, the concentration of air pollutants in a definite area during a fixed period of time prior to the starting up, or the stoppage, of a source of emission under control. In toxic substances monitoring, the average presence in the environment, originally referring to naturally occurring phenomena. [1]
Best Available Control Measures (BACM)	An emission limitation action based on the maximum degree of emission reduction (considering energy, environmental, and economic impacts) achievable through application of production processes and available methods, systems, and techniques. [4]
Burn severity	A qualitative assessment of the heat pulse directed toward the ground during a fire. Burn severity relates to soil heating, large fuel and duff consumption, consumption of the litter and organic layer beneath trees and isolated shrubs, and mortality of buried plant parts. [1]
Carbon dioxide (CO_2)	A colorless, odorless, nonpoisonous gas, which results from fuel combustion and is normally a part of the ambient air. [1]
Carbon monoxide (CO)	A colorless, odorless, poisonous gas produced by incomplete fuel combustion. Carbon monoxide is a criteria pollutant and is measured in parts per million. (See Criteria pollutants).

Carcinogen	Any substance that can cause or contribute to the production of cancer. [1]
Clean Air Act	A federal law enacted to ensure that air quality standards are attained and maintained. Initially passed by Congress in 1963, it has been amended several times. [1]
Combustion efficiency	The amount of products of incomplete combustion released relative to amounts produced from theoretically perfect combustion, expressed as a dimensionless percentage. Because perfect combustion produces only CO_2 and water, its combustion efficiency is 1.0. In combustion of wildland fuels, combustion efficiency can roughly range from as high as 0.95 (for flaming combustion) to as low as 0.65 (for smoldering combustion).
Condensation nuclei	The small nuclei or particles with which gaseous constituents in the atmosphere (e.g., water vapor) collide and adhere. [2]
Consumption	The amount of a specified fuel type or strata that is removed through the fire process, often expressed as a percentage of the preburn weight. [1]
Convection column	The rising column of gases, smoke, fly ash, particulates, and other debris produced by a fire. The column has a strong vertical component indicating that buoyant forces override the ambient surface wind. [1]
Convergence	The term for horizontal air currents merging together or approaching a single point, such as at the center of a low-pressure area producing a net inflow of air. The excess air is removed by rising air currents. Expansion of the rising air above a convergence zone results in cooling, which in turn often gives condensation (clouds) and sometimes precipitation. [1]
Criteria Pollutants	Pollutants deemed most harmful to public health and welfare and that can be monitored effectively. They include carbon monoxide (CO), lead (Pb), nitrogen oxides (NOx), sulfur dioxide (SO_2), Ozone (O_3), particulate matter (PM) of aerodynamic diameter less than or equal to 10 micrometers (PM_{10}) and particulate matter of aerodynamic diameter less than or equal to 2.5 micrometers ($PM_{2.5}$). [3]
Deciview	A unit of visibility proportional to the logarithm of the atmospheric extinction. (See Extinction coefficient; Visibility; Visual range). [2]

De minimis level	A level of emission or impact that is too small to be considered of concern. From the Latin phrase “de minimis non curat lex,” meaning the law is not concerned with trifles.
Dew point	Temperature to which a specified parcel of air must cool, at constant pressure and water-vapor content, in order for saturation to occur. The dew point is always lower than the wet-bulb temperature, which is always lower than the dry-bulb temperature, except when the air is saturated and all three values are equal. Fog may form when temperature drops to equal the dew point. (See Dry-bulb temperature; Wet-bulb temperature). [1]
Dormant season burning	Prescribed burning conducted during the time of year when vegetation is not actively growing. In some parts of the country, dormant season burns are typically less intense than growing season burns.
Drift smoke	Smoke that has drifted from its point of origin and is no longer dominated by convective motion. May give false impression of a fire in the general area where the smoke has drifted. [1]
Dry adiabatic lapse rate (DALR)	Adiabatic cooling in a dry atmosphere. Usually about -5.5 degrees Fahrenheit per 1,000 feet (~-10 degrees centigrade per kilometer). (See Adiabatic lapse rate; Saturated adiabatic lapse rate).
Dry-bulb temperature	Originally, the temperature measured with a mercury thermometer whose bulb is dry. Commonly it is a measure of the atmospheric temperature without the influence of moisture. (See Wet-bulb temperature; Dew point).
Duff	The partially decomposed organic material above mineral soil that lies beneath the freshly fallen twigs, needles, and leaves and is often referred to as the F (fermentation) and H (humus) layers. Duff often consumes during the less efficient smoldering stage and has the potential to produce more than 50 percent of the smoke from a fire.
Ecosystem health	A condition where the parts and functions of an ecosystem are sustained over time and where the system’s capacity for self- repair is maintained, allowing goals for uses, values, and services of the ecosystem to be met.

Ecosystem maintenance burn	A prescribed fire or wildland fire managed for resource benefits that is utilized to mimic the natural role of fire in an ecosystem that is currently in an ecologically functional and fire resilient condition. [5]
Ecosystem Processes	The actions or events that link organisms and their environment, such as predation, mutualism, successional development, nutrient cycling, carbon sequestration, primary productivity, and decay. Natural disturbance processes often occur with some periodicity
Ecosystem Restoration	The re-establishment of natural vegetation and ecological processes that may be accomplished through the reduction of unwanted and/or unnatural levels of biomass. Prescribed fires, wildland fires managed for resource benefits and mechanical treatments may be utilized to restore an ecosystem to an ecologically functional and fire resilient condition. [5]
Extinction coefficient	A measure of the ability of particles or gases to absorb and scatter photons from a beam of light; a number that is proportional to the number of photons removed from the sight path per unit length. (See Absorption coefficient; Deciview; Visibility; Visual range). [2]
Effective windspeed	The mid-flame windspeed adjusted for the effect of slope on fire spread. [1]
Emission factor (EFp)	The mass of particulate matter produced per unit mass of fuel consumed (pounds per ton, grams per kilogram). [1]
Emission inventory	A listing, by source, of the amount of air pollutants discharged into the atmosphere of a community. [3]
Emission rate	The amount of an emission produced per unit of time (lb./min or g/sec). [1]
Emission reduction	A strategy for controlling smoke from prescribed fires that minimizes the amount of smoke output per unit area treated. [1]
Emission Standards	A general type of standard that limit the mass of a pollutant that may be emitted by a source. The most straightforward emissions standard is a simple limitation on mass of pollutant per unit time (e.g., pounds of pollutant per hour). [3]

Extinction	The attenuation of light due to scattering and absorption as it passes through a medium. [2]
Federal Class I area	In 1977, Congress identified 156 national parks, wilderness areas, international parks and other areas that were to receive the most stringent protection from increases in air pollution. It also set a visibility goal for these areas to protect them from future human-caused haze, and to eliminate existing human-caused haze, and required reasonable progress toward that goal. [5]
Fine fuel moisture	The moisture content of fast-drying fuels that respond to changes in moisture within 1 hour or less; such as, grass, leaves, ferns, tree moss, pine needles, and small twigs (0-1/4" or 0.0-0.6 cm). (See Fuel moisture content; One-hour timelag fuels). [1]
Fire-adapted ecosystem	An ecosystem with the ability to survive and regenerate in a fire-prone environment.
Fire-dependent ecosystem	An ecosystem that cannot survive without periodic fire.
Fire exclusion	The policy and practice of eliminating fire from an area to the greatest extent possible, through suppression of wildland fires and a lack of fire use.
Fire regime	Periodicity and pattern of naturally occurring fires in a particular area or vegetative type, described in terms of frequency, biological severity, and area extent. [1]
Fire regime groups	Classes of fire regimes grouped by categories of frequency (expressed as mean fire return interval) and severity. Refers specifically to five groups used in Federal policy and planning: 0-35 years, low severity; 0-35 years, stand replacement; 35-100 years, mixed severity; 35-100 years, stand replacement; 200+ years, stand replacement. (See Fire return interval; Fire regime).
Fire return interval	Mean fire return interval. A mean, area-weighted time (in years) between successive fires for a respective area (i.e., the interval between two

	successive fire occurrences); the size of the area must be specified.
Fire severity	(See Burn severity.)
Fire use	The combination of wildland fire use and prescribed fire application to meet resource objectives. [6]
Fireline intensity	The rate of heat release per unit time per unit length of fire front. Numerically, it is the product of the heat yield, the quantity of fuel consumed in the fire front, and the rate of spread. [1]
Flaming combustion phase	Luminous oxidation of gases evolved from the rapid decomposition of fuel. This phase follows the pre-ignition phase and precedes the smoldering combustion phase, which has a much slower combustion rate. Water vapor, soot, and tar comprise the visible smoke. Relatively efficient combustion produces minimal soot and tar, resulting in white smoke; high moisture content also produces white smoke. (See Soot; Smoldering combustion phase). [1]
Forest floor material	Surface organic material, including duff, litter, moss, peat, down-dead woody pieces.
Forest residue	Accumulation in the forest of living or dead (mostly woody) material that is added to and rearranged by human activities such as harvest, cultural operations, and land clearing. (See Activity fuel). [1]
Fuel loading	The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel (consumable fuel) or total fuel and is usually dry weight. [1]
Fuel moisture content	The quantity of moisture in fuel expressed as a percentage of the weight; derived by weighing fuel sample both before and after thorough drying at (nominally) 212 degrees F (100 degrees C). (See Fine fuel moisture). [1]
Fuel reduction	Manipulation, including combustion, or removal of fuels to reduce the likelihood of ignition and/or to lessen potential damage and resistance to control. [1]
Fuel size class	A category used to describe the diameter of down dead woody fuels. Fuels within the same size class are assumed to have similar wetting and drying properties, and to preheat and ignite at similar rates during the combustion process. [1]

Fuel treatment	Manipulation or removal of fuels to reduce the likelihood of ignition and/or to lessen potential intensity, rate of spread, severity, damage, and resistance to control. Examples include lopping, chipping, crushing, piling and burning. [1]
Fuel type	An identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics that will cause a predictable rate of spread or resistance to control under specified weather conditions. [1]
Glowing combustion phase	Oxidation of solid fuel accompanied by incandescence. All volatiles have already been released and there is no visible smoke. This phase follows the smoldering combustion phase and continues until the temperature drops below the combustion threshold value, or until only non-combustible ash remains. (See Combustion; Flaming combustion phase; Smoldering combustion phase). [1]
Growing season burning	Prescribed burns conducted during the time of year when vegetation is actively growing, or when leaves have matured but not fallen.
Hazard reduction	Any treatment of living and dead fuels that reduces the threat of ignition and spread of fire. [1]
Haze	A sufficient concentration of atmospheric aerosols to be visible. The particles are so small that they cannot be seen individually, but are still effective in visual range restriction. (See Visual range; Extinction; Absorption coefficient; Regional haze). [2]
Heat release rate	(1) Total amount of heat produced per unit mass of fuel consumed per unit time. (2) Amount of heat released to the atmosphere from the convective-lift fire phase of a fire per unit time. [1]
Hydrocarbons	Compounds containing only hydrogen and carbon. [2]
IMPROVE	Interagency Monitoring of Protected Visual Environments. A cooperative visibility monitoring effort, using a common set of standards across the United States, between the EPA, Federal land management agencies, and state air agencies. [5]

Integrating nephelometer	An instrument that measures the amount of light scattered (scattering coefficient) and can be used to measure particulate matter concentrations from fires. [2]
Inversion	(See Atmospheric inversion) [2]
Isothermal layer	A layer of finite thickness in any medium in which the temperature remains constant.
Landscape	An area composed of interacting and inter-connected ecosystems that are repeated because of the geology, landform, soils, climate, biota, and human influences throughout the area. A landscape is composed of watersheds and smaller ecosystems.
Lead (Pb)	A criteria pollutant, elemental lead emitted by stationary and mobile sources can cause several types of developmental effects in children including anemia and neurobehavioral and metabolic disorders. Non-ferrous smelters and battery plants are the most significant contributors to atmospheric lead emissions. (See Criteria pollutants). [3]
Litter	The top layer of forest floor, composed of loose debris of dead sticks, branches, twigs, and recently fallen leaves or needles; little altered in structure by decomposition. (See Duff; Forest floor material). [1]
Mass fire	A fire resulting from many simultaneous ignitions that generates a high level of energy output. [1]
Mean fire interval	(See Fire return interval)
Micron	Micrometer (mm)—a unit of length equal to one millionth of a meter; the unit of measure for wavelength and also for the mean aerodynamic diameter of atmospheric aerosols. [2]
Mixing height	Measured from the surface upward, the height to which relatively vigorous mixing occurs in the atmosphere due to turbulence and diffusion. Also called mixing depth. [1]
Mixing layer	That portion of the atmosphere from the surface up to the mixing height. This is the layer of air within which pollutants are mixed by turbulence and diffusion. Also called mixed layer. (See Ventilation Index). [1]

Mopup	Extinguishing or removing burning material near control lines, felling snags, and trenching logs to prevent rolling after an area has burned, to reduce the chance of fire spreading beyond the control lines, or to reduce residual smoke. [1]
Mosaic	The central spatial characteristic of a landscape. The intermingling of plant communities and their successional stages, or of disturbance (especially fire), in such a manner as to give the impression of an interwoven, "patchy" design. [1]
National Ambient Air Quality Standards (NAAQS)	Maximum recommended concentrations of criteria pollutants to maintain reasonable standards of air quality. (See criteria pollutants). [3]
National Wildfire Coordinating Group (NWCG)	National interagency operational group authorized by the U.S. Secretaries of Agriculture and Interior and the National Association of State Foresters, designed to coordinate fire management programs of participating federal, state, local and private agencies to avoid wasteful duplication and provide a means of constructive cooperation.
Natural background condition	An estimate of the visibility conditions at each Federal Class I area that would exist in the absence of human-caused impairment. [5]
Nitrogen dioxide (NO_2)	The result of nitric oxide combining with oxygen in the atmosphere. A major component of photochemical smog. [1]
Nitrogen Oxide[s] (NO_x)	A class of compounds that are respiratory irritants and that react x with volatile organic compounds (VOCs) to form ozone (O_3). The primary combustion product of nitrogen is nitrogen dioxide (NO_2). However, several other nitrogen compounds are 2 usually emitted at the same time (nitric oxide [NO], nitrous oxide [NO], etc.), and these may or may not be distinguishable in available test data. [3]
Non-attainment area	An area identified by an air quality regulatory agency through ambient air monitoring (and designated by the Environmental Protection Agency), that presently exceeds federal ambient air standards. (See Attainment area). [1]
Nuisance smoke	The amount of smoke in the ambient air that interferes with a right or privilege common to members of the public, including the use or enjoyment of public or private resources.

One-hour timelag fuels	Fuels consisting of dead herbaceous plants and roundwood less than about one-fourth inch (6.4 mm) in diameter. Also included is the uppermost layer of needles or leaves on the forest floor. Fuel elements of this size usually respond to changes in moisture within one hour or less, hence the term 1-hr timelag. (See Fuel moisture content; Fine fuel moisture). [1]
One-hundred-hour timelag fuels	Dead fuels consisting of roundwood in the size range of 1 to 3 inches (2.5 to 7.6 cm) in diameter and very roughly the layer of litter extending from approximately three-fourths of an inch (1.9 cm) to 4 inches (10 cm) below the surface. Fuel elements of this size usually respond to changes in moisture within about one hundred hours or 3 to 5 days, hence the term 100-hr timelag. (See Fuel moisture content). [1]
One-thousand-hour timelag fuels	Dead fuels consisting of roundwood 38 inches in diameter and the layer of the forest floor more than about 4 inches below the surface. Fuel elements of this size usually respond to changes in moisture within about one thousand hours or 4 to 6 weeks, hence the term 1000-hr timelag. (See Fuel moisture content). [1]
Ozone (O_3)	A criteria pollutant, ozone is a colorless gas, ozone is the major component of smog. Ozone is not emitted directly into the air but is formed through complex chemical reactions between precursor emissions of volatile organic compounds (VOCs) and NO_X in the presence of sunlight. (See Criteria pollutants). [3]
Particulate matter	Any liquid or solid particle. “Total suspended particulates” as used in air quality are those particles suspended in or falling through the atmosphere. They generally range in size from 0.1 to 100 microns. [1]
Piling-and-burning	Piling slash resulting from logging or fuel management activities and subsequently burning the individual piles. [1]
PM_{10}	Particulate matter of mass median aerodynamic diameter (MMAD) less than or equal to 10 micrometers. A measure of small solid matter suspended in the atmosphere that can penetrate deeply into the lung where they can cause respiratory problems. Emissions of PM_{10} are significant from fugitive dust, power plants, commercial boilers, metallurgical industries, mineral industries, forest and residential fires, and motor vehicles. (See Criteria pollutants). [3]

$PM_{2.5}$	Particulate matter of mass median aerodynamic diameter (MMAD) less than or equal to 2.5 micrometers A measure of fine particles of particulate matter that come from fuel combustion, agricultural burning, woodstoves, etc. Often called respirable particles, as they are more efficient at penetrating lungs and causing damage. (See Criteria pollutants). [3]
Point sources	Large, stationary, identifiable sources of emissions that release pollutants into the atmosphere. Sources are often defined by state or local air regulatory agencies as point sources when they annually emit more than a specified amount of a given pollutant, and how state and local agencies define point sources can vary. [3]
Precursor emissions	Emissions from point or regional sources that transform into pollutants with varied chemical properties. [2]
Prescribed fire	Any fire ignited by management actions to meet specific objectives. A written, approved prescribed fire plan must exist, and NEPA requirements must be met, prior to ignition. This term replaces management ignited prescribed fire. [6]
Prescribed natural fire	Obsolete term. (See Wildland fire use) [6]
Prescription	A written statement defining the objectives to be attained as well as the conditions of temperature, humidity, wind direction and speed, fuel moisture, and soil moisture, under which a fire will be allowed to burn. A prescription is generally expressed as acceptable ranges of the prescription elements, and the limit of the geographic area to be covered. [1]
Prevention of Significant Deterioration (PSD)	A program identified by the Clean Air Act to prevent air quality and visibility degradation and to remedy existing visibility problems. Areas of the country are grouped into 3 classes that are allowed certain degrees of pollution depending on their uses. National Parks and Wilderness Areas meeting certain criteria are “Class I” or “clean area” in that they have the smallest allowable increment of degradation. [1]
Reasonably Available Control Measures (RACM)	Control measures developed by EPA that apply to residential wood combustion, fugitive dust, and prescribed and silvicultural burning in and around “moderate” PM10 nonattainment areas. RACM is designed to bring an area back into attainment and uses a smoke management program that relies on weather forecasts for burn/no-burn days.

	(See Best Available Control Measures [BACM]). [1]
Regional Haze	Visibility impairment caused by the cumulative air pollutant emissions from numerous sources over a wide geographic area. (See Haze).
Relative humidity (RH)	The ratio of the amount of moisture in the air, to the maximum amount of moisture that air would contain if it were saturated. [1]
Residual combustion phase	(See Smoldering combustion phase)
Residual smoke	Smoke produced by smoldering material. The flux of smoke originating well after the active flaming combustion period with little or no vertical buoyancy, and, therefore, most susceptible to subsidence inversions and down-valley flows. (See Nuisance smoke). [1]
“Right-to-burn” Law	A state law that provides liability protection for prescribed burners, providing they meet specified training and planning criteria. The degree of liability protection varies by state.
Saturated adiabatic lapse rate (SALR)	Adiabatic cooling in an atmosphere that is saturated with moisture. Usually about -3.0 degrees Fahrenheit per 1,000 feet (~-5.5 degrees centigrade per kilometer). (See Adiabatic lapse rate; Dry adiabatic lapse rate).
Scattering (light)	An interaction of a light wave with an object that causes the light to be redirected in its path. In elastic scattering, no energy is lost to the object. [2]
Secondary aerosols	Aerosol formed by the interaction of two or more gas molecules and/or primary aerosols. [2]
Slash	(see Activity fuel) [1]
Smoke concentration	The amount of combustion products (in micrograms per cubic meter) found in a specified volume of air. [1]
Smoke intrusion	Smoke from prescribed fire entering a designated area at unacceptable levels. [1]

Smoke management	The policies and practices implemented by air and natural resource managers directed at minimizing the amount of smoke entering populated areas or impacting sensitive sites, avoiding significant deterioration of air quality and violations of National Ambient Air Quality Standards, and mitigating human-caused visibility impacts in Class I areas.
Smoke management program (SMP)	A standard framework of requirements and procedures for managing smoke from prescribed fires, typically developed by States or Tribes with cooperation from stakeholders.
Smoldering combustion phase	Combined processes of dehydration, pyrolysis, solid oxidation, and scattered flaming combustion and glowing combustion, which occur after the flaming combustion phase of a fire; often characterized by large amounts of smoke consisting mainly of tars. Emissions are at twice that of the flaming combustion phase. (See Combustion; Flaming combustion phase, Glowing combustion phase). [1]
Soot	Carbon dust formed by incomplete combustion. [4]
Stable atmosphere	A condition of the atmosphere in which vertical motion in the atmosphere is suppressed. Stability suppresses vertical motion and limits smoke dispersion. In a stable atmosphere the temperature of a rising parcel of air becomes cooler than its surroundings, causing it to sink back to the surface. Also called stable air. (See Atmospheric stability; Unstable atmosphere).
Standard atmosphere	A horizontal and time-averaged vertical structure of the atmosphere where standard atmospheric pressure at sea level is 1,013 mb, at 5,000 feet (~1,500 m) it is 850 mb, at 10,000 feet (~3,000 m) it is 700 mb, and the standard atmospheric pressure at 20,000 feet (~6,000 m) is 500 mb. Actual pressure is nearly always within about 30% of standard pressure. (See Atmospheric pressure).
State Implementation Plan (SIP)	Plans devised by states to carry out their responsibilities under the Clean Air Act. SIPs must be approved by the U.S. Environmental Protection Agency and include public review. Same as Tribal Implementation Plan (TIP). [5]
Subsidence inversion	An inversion caused by settling or sinking air from higher elevations. (See Atmospheric inversion; Temperature inversion).

Sulfur dioxide (SO_2)	A gas (SO_2) consisting of one sulfur and two oxygen atoms. Of interest because sulfur dioxide converts to an aerosol that is a very efficient at scattering light. Also, it can convert into acid droplets consisting primarily of sulfuric acid. (See Criteria pollutants). [2]
Sulfur oxides (SO)	A class of colorless, pungent gases that are respiratory irritants and precursors to acid rain. Sulfur oxides are emitted from various combustion or incineration sources, particularly from coal combustion. [3]
Temperature inversion	In meteorology, a departure from the normal decrease of temperature with increasing altitude such that the temperature is higher at a given height in the inversion layer than would be expected from the temperature below the layer. This warmer layer leads to increased stability and limited vertical mixing of air. [2]
Ten-hour timelag fuels	Dead fuels consisting of roundwood 1/4 to l-inch (0.6 to 2.5 cm) in diameter and, very roughly, the layer of litter extending from immediately below the surface to 3/4 inch (1.9 cm) below the surface. Fuel elements of this size usually respond to changes in moisture within about ten hours or less than a day, hence the term 10-hr timelag. (See Fuel moisture content). [1]
Total fuel	All plant material both living and dead that can burn in a worst-case situation. [1]
Tribal Implementation Plan (TIP)	Plans devised by tribal governments to carry out their responsibilities under the Clean Air Act. TIPs must be approved by the U.S. Environmental Protection Agency and include public review. Same as State Implementation Plan (SIP). [5]
Understory burn	A fire that consumes surface fuels but not overstory trees (in the case of forests or woodlands) and shrubs (in the case of shrublands).
Unstable atmosphere	A condition of the atmosphere in which vertical motion in the atmosphere is favored. Smoke dispersion is enhanced in an unstable atmosphere. Thunderstorms and active fire conditions are common in unstable atmospheric conditions. In an unstable atmosphere the temperature of a rising parcel of air remains warmer than its surroundings, allowing it to continue to rise. Also called unstable air. (See Atmospheric stability; Stable atmosphere).

Ventilation index	An index that describes the potential for smoke or other pollutants to ventilate away from its source. Also called clearing index. It is the product of mixing height and the mean wind within the mixed layer (trajectory wind).
Visual range	Maximum distance at which a given object can just be seen by an observer with normal vision. [1]
Volatile Organic Compounds (VOC)	Any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate that participates in atmospheric photochemical reactions. [3]
Wet-bulb temperature	Originally, the temperature measured with a mercury thermometer whose bulb is wrapped in a moist cloth. Commonly it is a measure of the atmospheric temperature after it has cooled by evaporating moisture. (See Dry-bulb temperature; Dew point).
Wildland Fire	Any non-structure fire, other than prescribed fire, that occurs in the wildland. This term encompasses fires previously called both wildfires and prescribed natural fires. [6]
Wildfire	An unwanted wildland fire. This term was only included [in the new Federal policy] to give continuing credence to the historic fire prevention products. This is NOT a separate type of fire under the new terminology. [6]
Wildland Fire Managed for Resource Objectives	(See Wildland Fire Use) [6]
Wildland Fire Use	The management of naturally ignited wildland fires to accomplish specific pre-stated resource management objectives in predefined geographic areas outlined in Fire Management Plans. Wildland fire use is not to be confused with “fire use,” which is a broader term encompassing more than just wildland fires. [6]
Wildland Urban Interface (WUI)	The line, area, or zone, where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuel.

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