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

[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

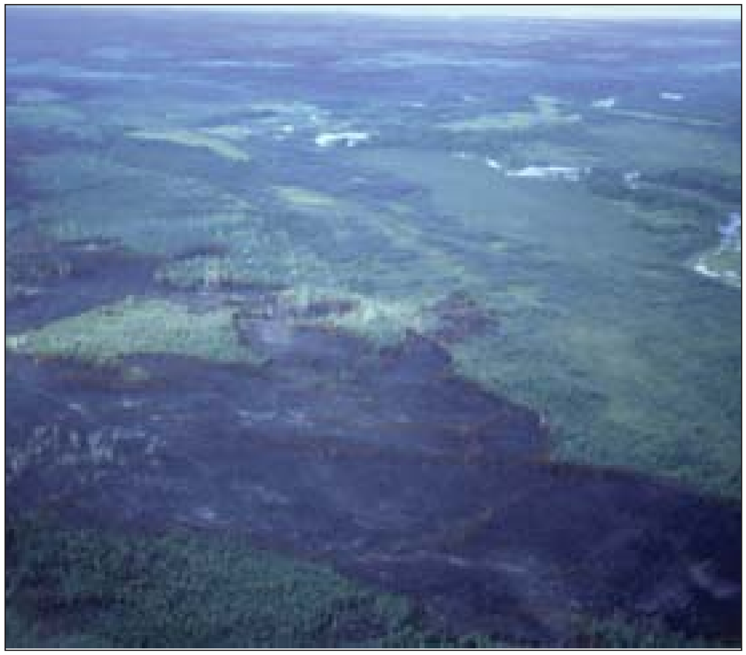

Figure 8.1. Mosaic burning creates patches of burned and unburned areas resulting in reduced emissions.

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.

- **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.

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.

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.

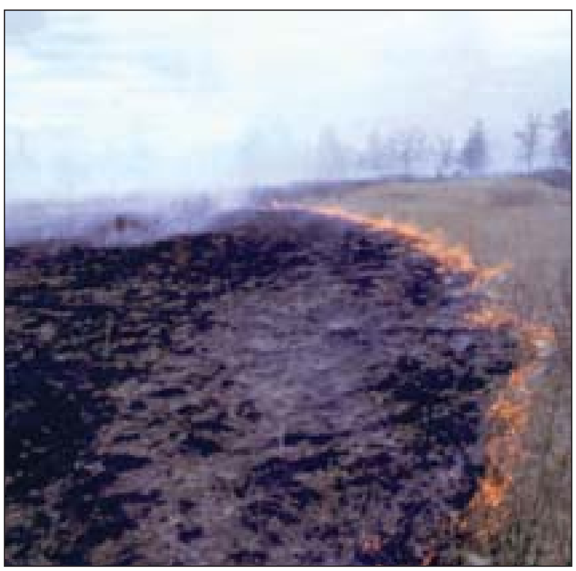

Figure 8.5. Backing fires in uniform, noncomplex fuelbeds consume fuels more efficiently than during a head fire resulting in fewer emissions.

- **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 8.6. 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.

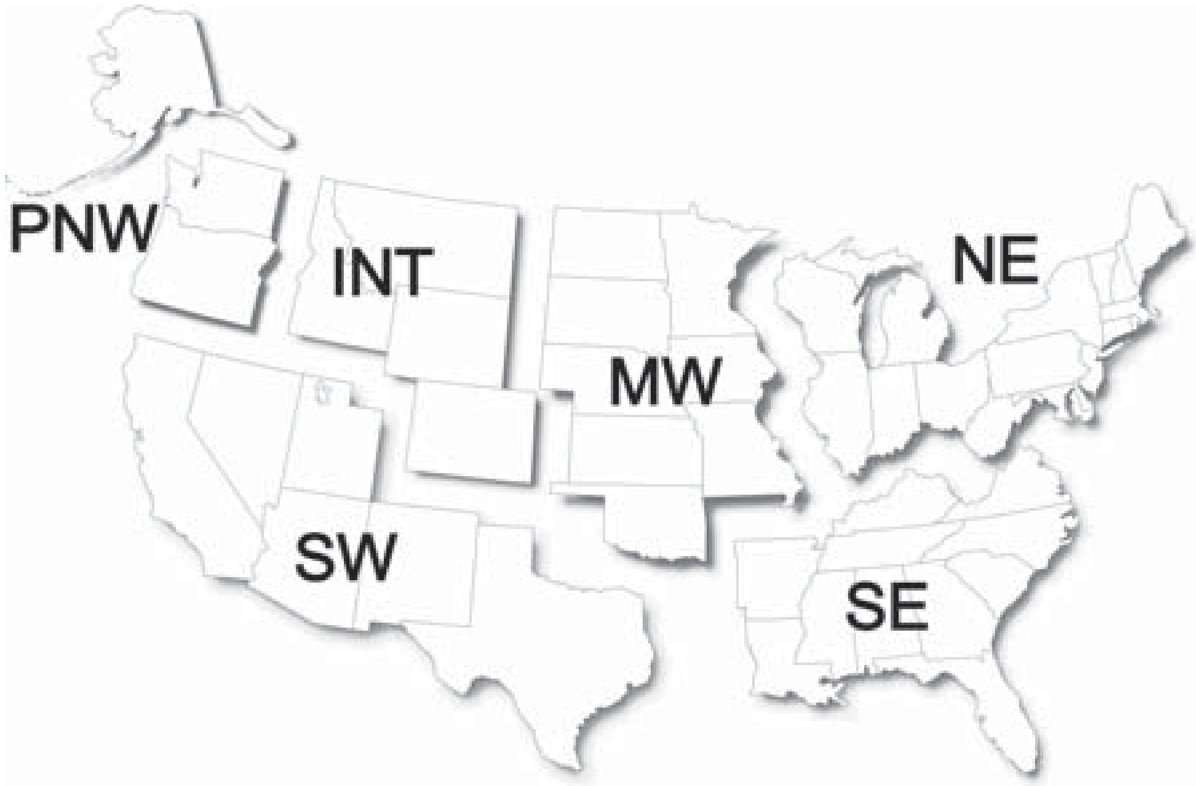

Figure 8.9. Prescribed burning regions including Pacific Northwest including Alaska (PNW), Intermountain (INT), Midwest (MW), Southwest (SW), Southeast including Hawaii (SE), and Northeast (NE).

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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