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EMISSION FACTORS FOR PARTICLES FROM PRESCRIBED FIRES BY REGION IN THE UNITED STATES.

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ABSTRACT

Emission factors and the size distribution for smoke particles from prescribed fire are described from data collected by airborne sampling, surface sampling using towers, and combustion hood systems. Emission factors for particulate matter (g/kg) range from 4 to 16 for particles less than 2.5 micrometers, from 4 to 40 for particles less than 10.0 micrometers, and from 5 to 50 for particles measured without regard to particle size. The particle size distribution suggests that 40 to 95 percent of the mass of particulate matter consists of particles less than 2.5 micrometers in diameter. Particles larger than 2.5 but smaller than 10 micrometers make up less than 10 percent of the total mass. The rate of heat release has a significant effect on the size and mass of particles produced.

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Introduction

Air resource managers need reliable emission factors and fuel consumption data to assess the magnitude of production of material from prescribed fires and wildfires. Fire managers need emission factors to predict the quantity of emission reduction that can be achieved by using various fire prescriptions (burning techniques, weather variables, and fuel parameters).

Information concerning the quantity of smoke produced from the cultural practice of prescribed burning of wildland vegetative material has been summarized in the EPA AP-42 emission factor document.[1] Techniques to inventory emissions and to reduce emissions from prescribed fires have been developed.[2,3] Improvements in receptor modeling have also been made through a better understanding of the characteristics of smoke from prescribed fires.[4,5]

This paper presents emission factors for smoke from prescribed fires and discusses the fuel and fire characteristics that affect particle size. (An **emission factor** is defined as the mass of a specific emission produced per unit mass of vegetative material consumed. In this paper, emission factors for total particulate matter (PM), for particles less than 10 μm, and for particles less than 2.5 μm are abbreviated as EF_{PM}, EF_{PM10}, and $EF_{PM2.5}$, respectively.)

Smoke from prescribed fires is a complex mixture of carbon, tars, liquids, and various gases. The open combustion source produces a wide range of sizes of particles dependent to some extent on the rate of heat release of the fire. For example, PM and PM2.5 are produced in different proportions dependent on the rate of heat release by the fire. Fire managers have an opportunity to effect change in the particle production from prescribed fires by regulating fire intensity.

Background

During the past decade, models have been developed that predict a range of particulate matter emission factors (EF_{PM}) from 2 to 100 g/kg.[6] These models show the benefits of using various techniques of burning to minimize the production of air pollutants. Other uses for the models include: (1) an update of national and regional emission inventories,[7,2] (2) a comparison of tradeoffs between smoke from wildfires and prescribed fires,[8] (3) an assessment of emissions reduction as a function of increased wood utilization,[9] and (4) an estimation of source strength for smoke dispersion calculations.[10]

More recently, data on forest fire emissions have been extrapolated to develop hypotheses regarding the potential effect of a major nuclear exchange ("nuclear winter").[11,12] Research on the nuclear winter issue has resulted in emission factors for combustion products from wildfires. In field tests for the present study, fire intensity, fuel, and weather variables are being controlled to evaluate their effect on particle production and on the content of the particles and the gases produced.[5]

Methods

Emission factors have been determined by measuring the particulate matter concentration, total volume of gases passing through a designated plane encompassing the plume, and the fuel consumed during the period of sampling. The mass of particulate matter divided by the mass of fuel consumed yields an emission factor. This method was used during the early years of field research on emissions characterization.[13,14]

Combustion laboratories have been used to control the humidity and temperature during the test while samples of forest materials are burned under a hood arrangement. Emissions are funnelled through the hood into an exhaust stack; stack sampling protocols are used to extract representative samples of the emissions.

Generally, good results are achieved when similarity of scale is observed between laboratory fires and field fires.[15] However, little has been learned to suggest that emissions production can be scaled from small, low-intensity fires to large, high-intensity fires. Most research is therefore conducted outdoors, where near full-scale conditions can be achieved for the experiments.

In 1979, Ward et al. tested the carbon-mass balance (CMB) procedure for calculating the fuel consumed from measured emissions.[16] This accounting procedure sums the carbon of each of the major species of the combustion products (the combined total of CO_2, CO, and PM account for over 95 percent of the carbon). The carbon contained with the combustion products originates from the pyrolysis of the plant material. The plant material contains about 50 percent carbon by weight. The CMB procedure calculates the mass of fuel that burns to produce the measured emissions, and is reasonably straightforward. The CMB procedure has greatly facilitated research on emissions from open burning of forest materials. Most observations of emission factors since 1979 use the CMB method.

Emission factors are dependent on the phase of combustion--flaming or smoldering or combinations of the two. Hence, in estimating emission factors for combustion products, fairly reliable estimates can be made by (1) applying known information on the relative quantity of fuel consumed in each combustion phase (2) using this to weight the emission factors for the flaming and smoldering combustion phases, then (3) developing a composite emission factor for the fire. This technique is used in AP-42.[1]

Ward and Hardy took this method one step further by measuring the flux of carbon rising in the convection column from prescribed fires of timber harvest debris (slash). The tests were on broadcast burns--where slash on clearcut units is typically burned by firing the entire unit-- and also on fires in piled slash.[17] This approach allowed calculation of the rate of fuel consumption and provided a way to estimate the rate of heat release from the fire over the duration of the fire. The vertical velocity and concentration of the emissions were measured at 2-second intervals. Results from the calculation of rate of heat release were correlated with emissions produced.

A second part of this effort was to collect measurements of the size of particles. In some cases, good size distribution data were available for a specific set of fire and fuel conditions: for example, for the Douglas-fir/western hemlock fuel type of western Washington and western Oregon.[18] In other cases, partial size determinations have been made.[13,19]

Results

Data from several sources were summarized regarding EF_{PM}, EF_{PM10}, and $EF_{PM2.5}$ for different wildland fuel and fire conditions. Table I lists emission factors for conditions where measurements have been made; all fuel types and burning conditions have not been measured. EF_{PM10} has been inferred for many of the fuel and fire conditions from studies on particle size distribution by Radke et al.[18] and Hardy and Ward.[19]

Emission Factors by Fuel Type

Pacific Northwest Logging Slash. Prescribed fire is used on about 345,000 acres of land annually in the Pacific Northwest states of Oregon, Washington, Idaho, and Montana. Accurate emission factors exist for five different fuel types and burning methods: broadcast prescribed fires in slash from harvesting Douglas-fir/western hemlock (short-needled conifer), broadcast prescribed fires in hardwood slash, broadcast prescribed fires in ponderosa pine slash (long-needled conifer), piles of slash created with tractors (dozer-piled), and piles of slash created with cranes (crane-piled).

Emission factors from prescribed burning in Pacific Northwest fuel types have been reported as these data became available. Consequently, values have changed slightly as new data were collected and analyzed. For example, the early research for broadcast prescribed fires of Douglas-fir/western hemlock showed EF_{PM} values of 12 g/kg for the flaming phase and 27 g/kg for the smoldering phase.[14] With subsequent refinements, the emission factors have changed to 12 and 19 g/kg, as shown in Table I.[19,5] Other refinements in the emission factor data will likely result from additional research.

Pacific Southwest Chaparral. Prescribed burning is used in different fuel types in the southwestern states of Arizona, New Mexico, Nevada, and California. Dominant fuels burned in this area include sagebrush, pinion-juniper, ponderosa pine, chaparral, and grassland. Few field experiments have been performed to measure emissions from these individual fuel types. In 1986, the USDA Forest Service and cooperating agencies conducted a research burn in Lodi Canyon, in the Angeles National Forest near Los Angeles. The Pacific Northwest Research Station measured the emissions from three subplot burns of about 1 acre each; EF_{PM} and $EF_{PM2.5}$ from chaparral fuels measured 15 and 8 g/kg, respectively.

Emission factors for other fuel types in this area are poorly quantified. The Forest Service plans research for the sagebrush and pinion/juniper fuel types during 1988. In the meantime, emissions from prescribed burning of sagebrush are described by emission factors measured for the palmetto/gallberry fuel type of the Southeast..

Southeast Palmetto-gallberry and Pine Fuel Complexes. Prescribed fire is used on about 2.25 million acres of forest lands in the Southeastern United States each year. The emissions are much less on a per-acre basis than in the Pacific Northwest mainly because the fuel consumed is about 10 percent of the amount consumed (per acre) in the Pacific Northwest. EF_{PM} has been well-quantified for the palmetto/gallberry fuel type and for the long-needled fuels of the Coastal Plain area (this area constitutes about 65 percent of the total area burned). The EF_{PM} values for the long-needled and palmetto/gallberry fuel types are 35 and 16 g/kg, respectively. For the palmetto/gallberry fuel type, an emissions model was developed that correlates EF_{PM} with rate of heat release.[6] The model illustrates a minimum emission factor for line fires with flame lengths of about 1 meter.

Research in a combustion laboratory was used to measure emission factors for piled conifer slash where organic soil had been incorporated during the piling process. The organic soil consists of at least 30 percent organic material from the decomposed plant parts no longer distinguishable; the remainder is mineral soil. Modeled fuel complexes of sawgrass were burned in the combustion laboratory as well. Results from these tests comprise most of what is known about emissions from burning piled slash and grassland fuel complexes in the Southeast.[16]

Other Regions of the United States. Prescribed fire is used on fewer acres in the Northeast and Lake States than in most other regions of the country. Generally, emissions from prescribed fires in the Northeast and Lake States would reduce air quality relatively little compared to other major sources of emissions. Hence, emission factors from other regions of the United States can be adapted to the Northeast and Lake States and should be accurate enough to meet the needs of the agencies managing air quality. Emission factors from the Rocky Mountain States, however, need to be developed from additional research in fuel types such as lodgepole pine, bitterbrush, and ponderosa pine/brush combinations.

Particle Size Distribution

Hardy and Ward describe the difference between EF_{PM} and $EF_{PM2.5}$ to be correlated with the rate of energy release (Figure 1).[19] The combination of data developed by Radke et al.[18] and Hardy and Ward has contributed to the update of the AP-42 section on prescribed burning.[19]

Radke et al. used on instrumented aircraft to characterize emissions from each of six prescribed fires in 1982.[18] The number and concentration of particles were measured by fractional size ranges (Figure 2). The particles were considered to be spheres, and the volume of material by size classes were computed. These data, plotted in Figure 3, show a sharply bimodal distribution with a peak near 0.3 µm and >43 µm. The number concentration and volume of material shifted toward the larger diameters for the fires of highest intensity. In conjunction with the size distribution data, a mass monitor system was used to measure the mass of particles <2 µm so that a density could be inferred for the particles. The density was near 1 g/cm^3, which is consistent with materials of organic content.

An important concern is the difference between EF_{PM} and $EF_{PM2.5}$, and EF_{PM} and EF_{PM10} for the different fuel types. The maximum difference occurs for fires where the rate of heat release is greatest. The particle size distribution is skewed toward the larger sized particles for these situations because of the increased turbulence and entrainment of ash particles. Also, the consumption of the organic material is more complete for these fires, verified by examining the organic carbon content of the fine particles.[4] Hence, the reduction in the fine particle mode with a concurrent increase in the large diameter particle mode accentuates the effect of heat release on the difference between the EF's for these different diameter classes.

The values for EF_{PM10} reported in Table I had to be derived largely from $EF_{PM2.5}$ and EF_{PM} because few data are available for PM10. Hardy and Ward[19] only report EF_{PM} and $EF_{PM2.5}$. Radke et al.[18] have provided the only data set to date that includes both $EF_{PM2.5}$ and EF_{PM10} as well as EF_{PM}. In those data, 17 percent of the particle mass larger than PM2.5 wa also smaller than PM10. In constructing Table I, that percentage was assumed constant for all fuel types and combustion phases.

Other observations of particle size distributions in prescribed fire smoke have been reported. For example, Sandberg and Martin[20] found 18 percent of the particulate matter to be larger than 1 µm for laboratory experiments using modeled fuel arrays. Ward et al.[13] found less than 1 percent of the mass of aerosol to be greater than 11 µm and from 4.6 to 8.6 percent of the mass to be above 1.0 µm. These experiments were for commonly burned fuels in the Southeast including slash pine needles and palmetto-gallberry fuel types.

Emission Factors Averaged by Region

Average emission factors have utility for general air quality management. Generally speaking, air resource managers should work closely with the forest managers of a given area to develope an emissions inventory that most accurately represents the impact of prescribed burning on air quality in that region. Usually fuel types and emission factors are different by regional areas because of climate, soil, and topographical differences. Hence, localized emissions inventories need to be developed.[2]

The emission factors in Table II are adapted from Table I to the dominant fuel types of each of the major regions of the United States. The fire environments are shown by five generally recognized regions of the United States. The dominant fuel burned was developed from a compilation of information from experts in the U.S. Department of the Interior, Bureau of Land Management and the USDA Forest Service. Other fuel types are likely burned, but those listed are thought to represent the mix of fuels in each specific region. The percent fuel consumption does not represent a localized area; hence, there is need to acquire local fuel inventory data.

Summary

This paper provides technical documentation for emission factors to be published in AP-42[1] for smoke from prescribed burning of wildland vegetation. Emission factors for PM and PM2.5 are reviewed from published and unpublished sources. Emission factors for PM10 are derived from pertinent observations of particle size distributions.

The adequacy of coverage of emission factors is uneven among fuel types. Research has provided adequate emission factors for several fuel types in the Pacific Northwest and, to a lesser extent, for the Southwest and Southeast. Emission factors for most range and brush types, most fires in brush or litter under forest canopies, hardwood forests other than in the Pacific Northwest Coast Range, and logging slash other than in the Northwest, are lacking. Emission factors for wildfires and prescribed natural fires are also unavailable.

These emission factors, and AP-42, can be used to compile generalized emission inventories for large geographic areas. The tables of emission factors for fuel types in several U.S. regions are intended as a quide, and may be improved by compiling a better statistical profile of the fire activity in specific areas.

Acknowledgments

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TABLE I. Emission factors for each fire/fuel configuration by phase of combustion.

Fire/fuel configuration	Phase of combustion[b]	Emission factor (g/kg)[a] Particulate matter PM2.5	PM10	TOTAL	Fuel mix (%)
PACIFIC NORTHWEST BROADCAST LOGGING SLASH					
Hardwood	F	6	7	13	33
	S	13	14	20	67
	Fire	11	12	18	
Short-needled Conifer	F	7	8	12	33
	S	14	15	19	67
	Fire	12	13	17	
Long-needled Conifer	F	6	6	9	33
	S	16	17	25	67
	Fire	13	14	20	
PILED LOGGING SLASH					
Dozer-piled Conifer					
No mineral soil	F	4	4	5	90
	S	6	7	14	10
	Fire	4	4	6	
10-30% Mineral soil	S			25	
25% Organic soil	S			35	
Crane-piled Conifer (No twigs or needles).					
SOUTHWEST					
Chaparral		8	9	15	
SOUTHEAST LINE FIRES					
Long-needled Conifer	S/Heading		40	50	
	F/Backing		20	20	
Palmetto/Gallberry	Heading		15	17	
	Backing		15	15	
Grasslands			10	10	
Sawgrass			10	10	

[a] The source(s) for these data are discussed in the text.

[b] F=flaming, S=smoldering, Fire=fire-weighted average of F and S.

TABLE II. Calculation of average emission factors by region for the fuel and fire configurations.

Region and Fuel type	Percent of Region	Emission factors (g/kg) PM2.5	PM10	PM
Pacific Northwest				
Logging Slash				
Piled slash	42%	4	5	6
DF-WH	24%	12	13	17
Mixed conifer	19%	12	13	17
Ponderosa pine	6%	13	13	20
Hdwd	4%	11	12	18
Under-burning ponderosa	5%	30	30	35
Average EF for region	100%	9.5	10.3	13.5
Pacific Southwest				
Chaparral	20%	8	9	15
Sagebrush	35%		9	15
Understory Ponderosa	15%		30	35
Pinion/juniper	20%		13	17
Grassland	10%		10	10
Average EF for region	100%		13.0	17.8
Southeast				
Palmetto-gallberry	35%		15	16
Conifer(long-need	30%		30	35
Grassland	10%		10	10
Logging slash	20%		13	20
Other	5%		17	17
Average EF for region	100%		18.8	21.9
Rocky Mtn.				
Conifer(long-need	20%		30	35
Grassland	20%		10	10
Logging slash	50%		4	6
Other	10%		17	17
Average EF for region	100%		11.7	13.7
N. Central and Eastern				
Conifer (long-need	10%		30	35
Grassland	30%		10	10
Logging slash	50%		13	17
Other	10%		17	17
Average EF for region	100%		14.2	16.7

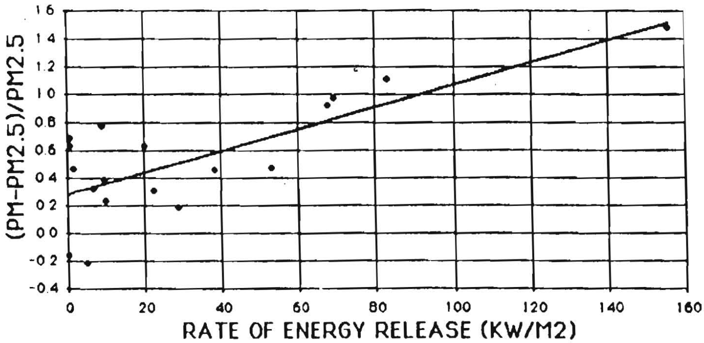

Figure 1. The percentage of difference between EF_{PM} and $EF_{PM2.5}$ has been shown in previous research to increase proportionally to the rate of energy release.

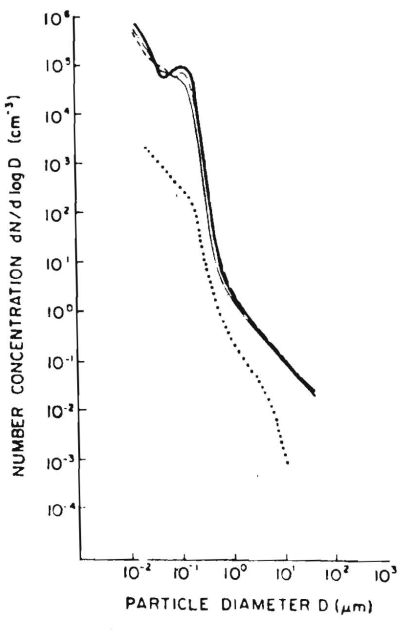

Figure 2. Number concentrations versus size of particles measured near the center of the plume and 3.3 km downwind of a burn at three points in time (heavy solid line, dashed line, and solid line). The ambient particle size distribution is also shown (dotted line).

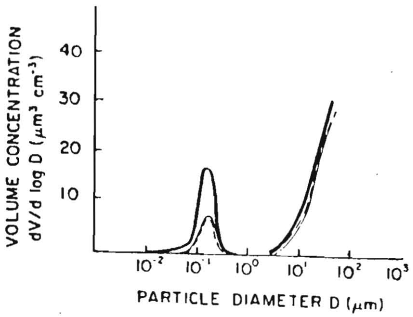

Figure 3. Volume concentrations versus size of particles measured near the center of the plume and 3.3 km downwind of a burn at three points in time (heavy solid line, dashed line, and solid line).