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EMISSION FACTORS FOR PARTICULATE MATTER BY PHASE OF COMBUSTION FROM PRESCRIBED BURNING

BY

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ABSTRACT

Prescribed fires are used on about 155,000 acres of land each year in the Pacific Northwest states of Oregon and Washington. Particulate matter emission factors can be altered by selecting optimal burning conditions to improve combustion efficiency. This paper reports on the effects of fire behavior and fuel variables on particulate matter emissions. Data presented are from prescribed broadcast fires and from burning of tractor-piled logging slash in Oregon and Washington. Data are also presented from three test fires in California chaparral. Emissions were sampled using cable and tower systems to support sampling devices in the convection column of near full-scale prescribed fires. Measurements of emission factors were by the carbon mass balance method.

Emission factors for total particulate matter (EFPM) are higher than for particulate matter less than 2.5 um mean cutpoint diameter (EFPM2.5). EFPM2.5 values for logging slash piles are a factor of 2 less than the same material burned by a broadcast prescribed fire. Values for EFPM and EFPM2.5 from broadcast prescribed burns of hardwood logging slash are similar to those for logging slash from coniferous species.

Work continues in developing emission factor data for prescribed fires in different fuel types and burning conditions, including chaparral fuels, brush species, mixed conifer species, the effect of herbicides on emissions production, piled slash, and underburning in the long-needled pine type.

INTRODUCTION

The use of prescribed fire in Oregon and Washington is often necessary to meet forest management objectives on logging units after harvesting. Prescribed fire is also an important tool in vegetative management. In the chaparral communities of California, prescribed fire is used to maintain species diversity and the vegetative mosaic necessary for fire hazard reduction. Prescribed burning is known to be a significant source of air pollutant emissions. There is a continuing need to assess the magnitude of the problem and to reduce the adverse effects of smoke from prescribed fires.

In this paper we report new knowledge of particulate matter production and the relation with fuel and fire behavior variables. Research by the Fire and Air Resource Management project, Pacific Northwest Research Station, USDA Forest Service, has advanced the knowledge of the characteristics of emissions from prescribed burning of logging residues. Described here are the results of a field study that involved sampling of particulate and gaseous emissions from 30 test fires in California, Oregon, and Washington. A more complete profiling of the chemical characteristics of the particulate matter can be found in a companion paper (Ward 1986).

BACKGROUND

Why Emissions Research?

Emission reduction stategies are resulting in measurable improvements in regional air quality, and use of prescribed fire in forest management remains an irreplaceable tool. Sandberg and others (1985) demonstrate a reduction in particulate matter production from prescribed burning in Oregon and Washington of nearly 30 percent. This reduction was accomplished between an averaged baseline period 1976-79 and 1984, even though the number of acres treated annually increased over the same period. Figure 1 shows these trends for slash burning activity in Oregon. Emission-characterization research, when linked with companion research on fuel variables such as fuel moisture and fuel consumption, has contributed significantly to emission-reduction strategies and to the ability to document and monitor the impacts of prescribed burning on air quality.

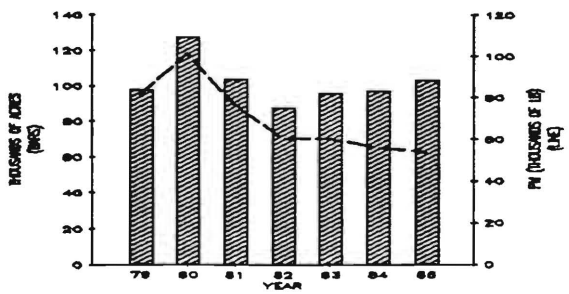


Figure 1.--Particulate production from prescribed burning in Oregon has been reduced nearly 30 percent since a 1976-79 baseline period; the number of acres treated by burning has increased slightly.

Where is Fire Used?

Nearly 155,000 acres are treated with fire annually in Oregon and Washington (Sandberg and others 1985). About 35 percent of harvested units treated by fire in Washington and Oregon are predominantly of the Douglas-fir/hemlock fuel type. Ponderosa pine fuels east of the Cascade Range are found on roughly 30 percent; the remaining 35 percent is divided between mixed conifer (20 percent) and hardwood (15 percent) types. Burning is used to accomplish management objectives in other fuel types as well, including chaparral management, range improvement, wildlife-habitat improvement, burning of fields for seed-bed preparation, and disposal of logging debris piles.

Particulate Matter Research

Numerous research efforts have described the formation, production, and characteristics of particulate matter from prescribed burning. Pollutant emissions are typically described in terms of emission factors; that is, the mass of emission produced per mass of fuel consumed.

Particulate matter (PM) is defined to be material of ash, tar, and carbon suspended in the air--regardless of particle size. The fine particle fraction (PM2.5) is particulate matter with particle diameter of less than 2.5 micrometers (um).

Emission factors have been derived from small-scale laboratory tests, combustion hood experiments, airborne sampling, and from ground-based sampling of nearly full-scale slash burns. In the first field sampling of emissions Ward (1983) described an emission-rate model for backing and heading fires in the Palmetto-Gallberry fuel type where the emission factor for PM was a function of fire intensity. That research led to a sampling system design for measuring emissions from West Coast prescribed fires, where PM emission factors of 12 and 27 g/kg were reported for flaming and smoldering combustion, respectively (Ward and others 1982). Detailed airborne measurements of emissions from prescribed fires in 1982 are reported by Radke and others (1985); results include emission factors for particulate matter in several size classes. They report emission factors of 12.2 ±3.6 g/kg for PM and 4.1 ±1.5 g/kg for particles <2 um diameter. These values are in general agreement with more recent ground-based emissions-characterization research by Ward and Hardy (1984) in the Douglas-fir/hemlock fuel type.

The emission factor data (Ward and Hardy 1984) was coupled with fuel consumption algorithms (Sandberg and Ottmar 1983, Ottmar and others 1985) to produce an inventory of emissions by region within Oregon and Washington (Sandberg and others 1985). The results showed a decrease in the total emissions produced from burning for forest management during the period 1979-84. Fuel type-specific emission factor data from the present research will be used in the emissions inventory system to calculate total emissions production from individual burning projects.

THE PRESENT RESEARCH

Objective

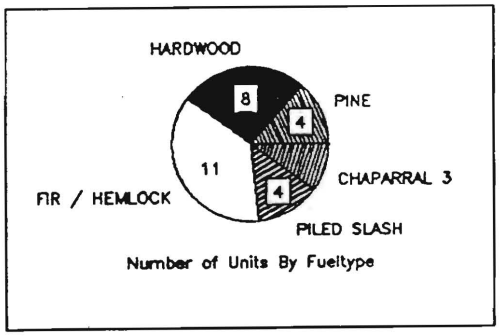
The objective of the present research was to relate production of particulate matter from prescribed burning to fuel and fire variables. Particulate matter emission factors describe the masses of PM and PM2.5 produced per mass of fuel consumed for each of five fuel types and two combustion phases. Three major variables were evaluated:

1. Fuel type/arrangement (the predominant species, if broadcast burned; arrangement refers to tractor-piled slash of mixed species). Figure 2 illustrates the distribution of fuel types studied.

2. Fuel characteristics (fuel loading and relative abundance of live vegetation).

3. Fire behavior (phase of combustion).

Figure 2.--Emissions characterization has been completed on 30 tests in five fuel types.



Calculating Emission Factors

The design of this research required measuring the concentrations of particulate matter by two size classes (PM and PM2.5), and of the carbon-bearing species of gases produced from the combustion of the forest fuels--carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and non-methane hydrocarbons (NMHC). When the concentrations of the particulate matter and of these carbonaceous gases are measured, the carbon contained in a unit volume of air can be derived and then converted to the equivalent mass of fuel consumed to produce the combustion products. This chemical accounting method, known as carbon-mass balance, provides all the information necessary to determine emission factors (EF) for each measured combustion product--in this case, PM and PM2.5. The validity of this application of the carbon-mass balance method requires that (1) the carbon in the fuel be released in a one-to-one ratio to the total amount of carbon contained in forest fuels; (2) the carbon content of forest fuels be known (approximately 50 percent by weight); and, (3) the emissions be well-mixed in the sampling environment.

It follows, then, that the mass of fuel consumed (Wv) to produce the combustion products contained in a unit volume of gas can be calculated using the following equation:

$$Wv = (\Sigma\ Cn)/R;$$

where,

Wv= fuel consumed, mg/m3;
Cn= carbon fraction of the emission, mg/m3;
n = CO_2, CO, NMHC, CH_4, PM; and
R = carbon fraction of fuel (0.497).

An emission factor is calculated for a single point within a series by dividing the mass concentration of the emission (PM or PM2.5) by the total mass of the fuel consumed to produce the emission at that measurement point, as follows:

$$efn = en/Wv;$$

where,

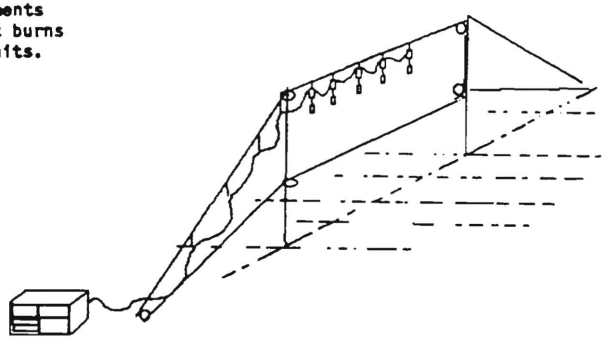
efn= emission factor at a sample point for emission n, g/kg;
en = concentration of the emission n, g/m3; and
Wv = fuel consumed, kg/m3.

Sampling Methodology

We used a unique sampling system that measured emissions from nearly full-scale, operational prescribed fires without disturbing the fuel complex. The same sampling technique was used on all 30 units shown in figure 2. The only deviation was the way the sample instruments were suspended above the various fuel types, as will be described.

Five sample packages were suspended above the burn site on a steel tower and cable apparatus. For the broadcast burns in clearcut logging units—which included the fuel types with Douglas-fir/hemlock, hardwood, and ponderosa pine—the sample packages were suspended from a movable cable system strung between two steel towers (figure 3a). To position the sample packages at the appropriate height and position within the smoke plume over the fire the horizontal suspension cable could be lowered or raised (as high as 80 feet), and could also be moved forward or backward.

Figure 3a.--A steel tower and movable cable system supports sample instruments over broadcast burns in clearcut units.



For sampling emissions from tractor-piled slash, the packages were suspended from a 30 foot long, horizontal boom attached to a carriage that was systematically traversed through the smoke plume between the two steel towers (figure 3b). The three chaparral units were on terrain that was too adverse for the movable cable systems. Instead, the packages were suspended above the fires on a crane-like tower (figure 3c).

Figure 3b.--The higher intensity plumes from tractor-piled slash were sampled by traversing the instruments with a boom suspended on movable cables.

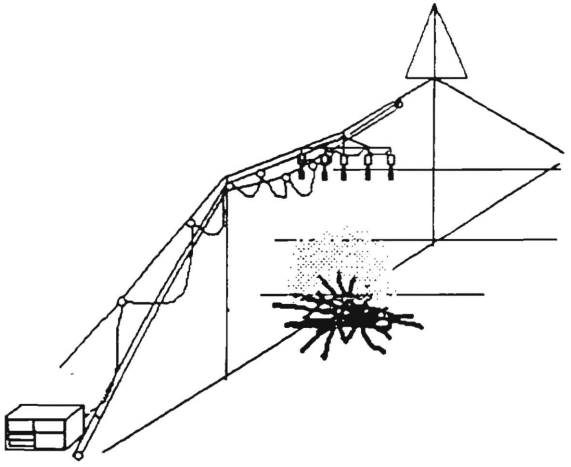
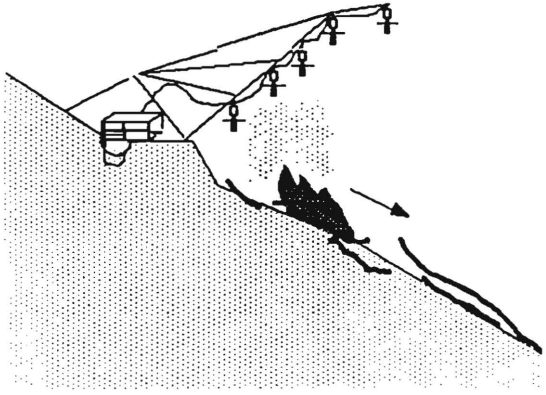


Figure 3c.--The chaparral tests required a crane-like tower system for positioning the instruments in the emission plume.



Each sample package was connected to a vacuum hose and electrical umbilical, and grab samples of PM, PM2.5, and gases were collected concurrently with real time measurements of temperature, vertical velocity, CO, and CO2. PM samples were collected at 5-7 lpm on 47-mm glass fiber filters. The PM2.5 size-segregated samples were collected using cyclone-fitted 37-mm filter cassettes, sampled at 2 lpm. For discrete sampling of each combustion phase (flaming and smoldering), the sample packages were periodically removed from the sample environment to exchange filters.

Variables

Three variables were evaluated for their effects on EFPM and EFPM2.5. A description of each of these variables and a discussion of how each was evaluated follows:

Fuel type and arrangement.—Fuel type refers to the predominant species of residue (slash) to be treated. A series of study units was selected in each of three broadcast fuel types—Douglas-fir/hemlock, hardwood, and ponderosa pine. Chaparral units were in southern California. Fuel arrangement refers to broadcast versus tractor-piled debris. All piles were composed of mixed species. We will hereafter refer to the five respective fuel types and arrangements as follows: fir/hemlock, hardwood, pine, chaparral, and piled slash.

Fuel characteristics.—These are described by loading (mass of fuel, measured by size class), fuel moisture, and the abundance of live herbaceous vegetation. In previous work, units were selected for both fuel loading and fuel moisture to achieve a wide range of combustion environments (Ward and Hardy 1986). The rate of heat release was a dominant variable when emission factors were correlated to the combustion environment; both fuel loading and fuel moisture affect the rate of heat release. Units for this study were selected to achieve a range of fuel loadings and a range of fuel moistures that were similar to previous work. The analysis of the affect of these variables on emission factors is not complete, but the role that fuel characteristics may play in subsequent analyses is important to understand. Fuel loadings were measured, by size class, using the planar intersect technique (Brown 1974). The mass of live herbaceous vegetation was measured on several units to obtain a baseline scale. The remaining units were estimated against the baseline units from supplemental stereo photographs taken of all the units. All units were then given a relative rating; the unit with the greatest mass of live vegetation was rated as 1.00.

Combustion phase.— The data were stratified by phase of combustion: flaming phase, the active stage of combustion where radiation and convection dominate; and smoldering phase, where glowing combustion takes place and conduction dominates. Discrete grab samples and subsequent carbon-mass balance calculations were obtained over time for each combustion phase.

Weighting of Emission Factors

Because the sample packages extended in a line across the test fire, the concentrations of measured emissions were higher at some sample points than at others for the same test and combustion phase. We assumed that the sample points with the highest concentrations of emissions also represented regions of the burn area with the highest rate of fuel consumption. Therefore, to calculate an average emission factor a weighting procedure was used whereby the emission factor measured at a given sample point was weighted by the total carbon measured at that sample point. The products for the five sample points were summed and then divided by the total carbon sampled from all five sample points, according to the following equation:

$$EFn = \left(\sum_{i=1}^{j} efni\ Ci \right) \Big/ \sum_{i=1}^{j} Ci \ ;$$

where,

EFn = weighted emission factor for emission n;
efni= emission factor for n at package i;
n = PM or PM2.5;
Ci= mass of carbon measured at package i; and
j = number of packages (in this case, 5).

This procedure was used to calculate emission factors for each combustion phase for each test. The weighted emission factors for each combustion phase were then averaged (as simple means) for all units within each fuel type.

EMISSION FACTOR RESULTS

Combustion Phase Duration

The average duration for the flaming phase sample in the pine, hardwood, and fir/hemlock tests was 15 ±3 minutes. Flaming phase duration for each of the four piled slash tests was considerably longer—from 20 minutes to as long as 53 minutes. In the chaparral tests the smoke plume was predominantly from flaming combustion lasting the entire test—as long as 60 minutes.

The duration of the smoldering combustion process ranged from 1 hour to as long as 4-1/2 hours. Typically, two to four sets of grab sample filters and bags were required to sample for the extended smoldering period.

All emission factors were tabulated by combustion phase and are presented in Tables I and II.

Table I.—Summary of emission factors for the five fuel types, expressed in grams of particulate per kilogram of fuel consumed for each combustion phase. The coefficient of variation (CV) is given as percent.

FUEL TYPE	COMBUSTION PHASE	PM EFPM		CV	PM2.5 EFPM2.5		CV
Douglas-fir/ hemlock	Flame	12.3	±6.6	55	7.4	±5.0	70
	Smolder	17.9	±6.0	34	13.0	±2.4	19
Hardwood	Flame	13.5	±8.5	65	7.3	±4.4	63
	Smolder	26.7	±18.3	71	15.9	±9.3	60
Ponderosa-pine	Flame	9.2	±0.8	9	5.9	±1.3	24
	Smolder	24.9	±8.7	38	16.0	±7.0	47
Tractor-piled slash	Flame	6.9	±4.1	64	4.6	±2.5	58
	Smolder	15.1	±6.1	43	6.5	±1.8	30
Chaparral	Fire	14.9	±6.0	43	7.2	±1.0	15

Table II.—The difference between EFPM and EFPM2.5 is expressed by reporting EFPM2.5 values as percentage of EFPM.

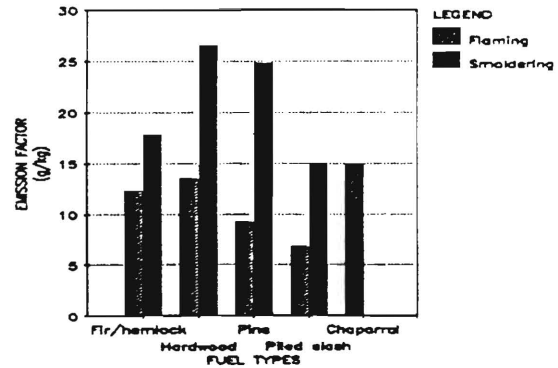
FUEL TYPE	COMBUSTION PHASE	EFPM2.5 % OF PM
Douglas-fir/ hemlock	Flame	56
	Smolder	81
Hardwood	Flame	59
	Smolder	62
Ponderosa pine	Flame	64
	Smolder	63
Tractor-piled slash	Flame	71
	Smolder	49
Chaparral	Fire	55

PM Emission Factors

Emission factors for PM during the flaming phase ranged from 6.8 g/kg for piled slash to 13.5 g/kg for the hardwood tests. Although the EFPM differences between individual fuel types (and arrangements) were not found to be significant at the 95% level of confidence, data from additional observations may contribute to the significance of the differences, particularly for comparisons to the pine fuel type, where only three observations were made.

The relative differences are presented here and are illustrated in figure 4a. Smoldering phase EFPM ranged from 15.1 g/kg for piled slash to 26.6 g/kg for the hardwood units. Note that the lowest and highest values for both phases were from piled slash and hardwoods, respectively. For broadcast burns, the flaming phase EFPM was lower in ponderosa pine logging slash east of the Cascade Range than in the other broadcast-burned fuel types—25 percent lower than in fir/hemlock and 32 percent lower than in hardwoods. The overall EFPM for the chaparral tests (14.9 g/kg) compares well with flaming EFPM for fir/hemlock and hardwoods.

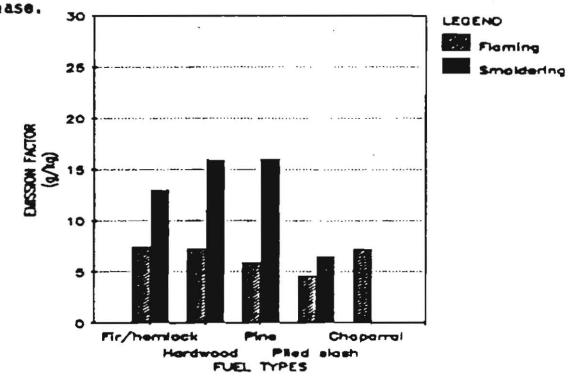
Figure 4a.—Emission factors for PM can be compared by fuel type for each combustion phase.



Variability in EFPM2.5

Fuel arrangement.—The mean emission factors for both PM and PM2.5 were significantly different (at the 95 percent level of confidence) between the pooled broadcast-burned units (fir/hemlock, hardwood, pine) and piled slash burns. PM2.5 emission factors for both phases were lowest in the tests on tractor-piled slash, with the flaming EFPM2.5 of 4.6 g/kg and a smoldering EFPM2.5 of 6.5 g/kg (these relations are shown in figure 4b).

Figure 4b.—Emission factors for PM2.5 can be compared by fuel type for each combustion phase.



Fuel type.—A non-significant difference (less than 2 percent) in flaming phase EFPM2.5 was found between the fir/hemlock (7.4 g/kg) and hardwood (7.3 g/kg) fuel types. In the ponderosa pine tests, EFPM2.5 for the flaming phase was 5.9 g/kg, lower then both Douglas-fir/hemlock and hardwood by 20 and 18 percent, respectively. The smoldering phase EFPM2.5 for the pine fuel type was similar to the other two broadcast-burn fuel types (less than 1 percent higher than the hardwood values). For the chaparral type, the overall average EFPM2.5 (7.2 g/kg) is within 3 percent of the flaming EFPM2.5 for fir/hemlock and hardwood types.

Combustion Phase

EFPM.—The relative difference between flaming and smoldering emission factors ranged from ponderosa pine, where the EFPM was 63 percent higher for the smoldering phase versus the flaming phase, to 31 percent in fir/hemlock. The respective difference in hardwoods was 49 percent; in tractor-piled slash the difference was 55 percent. None of the differences between PM emission factors for flaming and smoldering was significant at the 95 percent level of confidence.

EFPM2.5.—Differences between emission factors for PM2.5 were relatively similar to those for PM. For tractor-piled slash, however, smoldering EFPM2.5 was only 29 percent higher than the flaming phase EFPM2.5. All the differences between flaming and smoldering emission factors for PM2.5 were found to be significant at the 95 percent level of confidence (except in the ponderosa pine tests, where no significant difference was found).

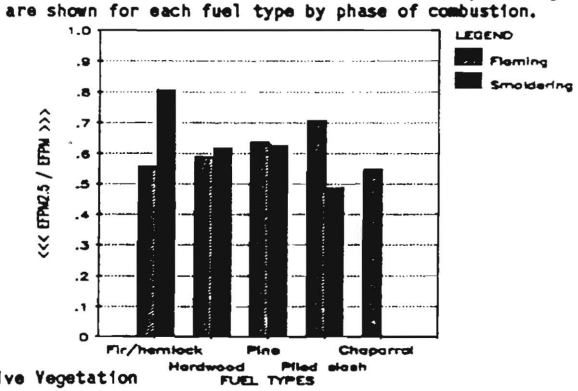
Comparison of EFPM and EFPM2.5

Because PM2.5 is clearly a fraction of the PM, emission factors for PM2.5 were consistently less than those for PM. The difference is expressed by reporting EFPM2.5 values as a percentage of EFPM, as shown in Table II. Referring to figure 5 is helpful when the relative differences for each fuel type, by phase, are compared.

Combustion phase.—The differences were higher for flaming-phase emission factors than for the smoldering phase values (except in the tests on tractor-piled slash). For example, flaming-phase EFPM2.5 for fir/hemlock was only 56 percent of EFPM, but the smoldering EFPM2.5 was much closer (81 percent) to EFPM. The contrast between flaming and smoldering differences was much less distinct in the other fuels.

Fuel type and arrangement.—Difference values for the flaming phase in Douglas-fir/hemlock (56 percent) and hardwood (59 percent) are similar to the overall fire value for chaparral (55 percent). In the ponderosa pine type, very little contrast is seen between phases. In tractor-piled slash, the relation is inverse to the other fuel types.

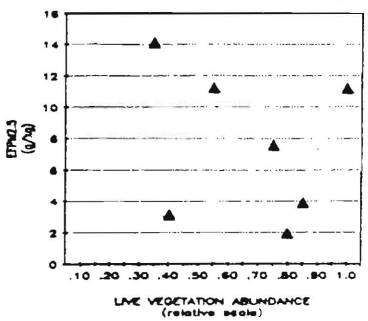
Figure 5.—EFPM2.5 values here are calculated as percentage of EFPM and are shown for each fuel type by phase of combustion.



Effects of Live Vegetation

Emission factors for flaming phase PM2.5 are plotted in figure 6 for seven tests in the hardwood fuel type. The dependent variable, live vegetation, is a relative rating; the unit with the greatest abundance of live vegetation (EAA) was rated as 1.00. The preburn mass of live vegetation on EAA was 1264.4 kg/ha. These data offer inconclusive results on the effects of live vegetation on flaming EFPM2.5 in the hardwood fuel type.

Figure 6.—Emission factors for flaming phase EFPM2.5 are plotted against the relative abundance of live vegetation for seven hardwood units.

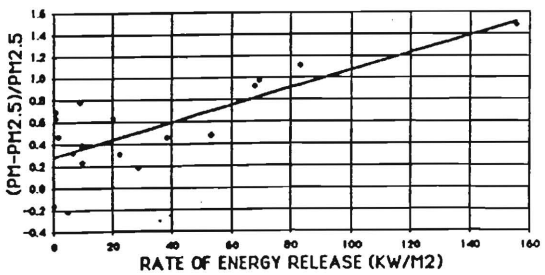


DISCUSSION

After the analyses of real time data are completed, values will be available for the rate of fuel consumption and for the rate of heat release. These data are critical to a complete analysis of the relations between emission factors and fire behavior.

The analysis of differences between EFPM and EFPM2.5 cannot be completed without real time data. We have, however, previously reported difference values from 12 tests in the Douglas-fir/hemlock fuel type (Ward and Hardy 1984). In that report, we demonstrated a significant, positive relation between the percentage of difference ((EFPM-EFPM2.5)/EFPM2.5) and fireline intensity (the rate of energy release). This relation, plotted in figure 7 for the 12 tests, is partially explained by the entrainment of larger sized particles in the highly buoyant plume of the flaming phase.

Figure 7.—The percentage of difference between EFPM and EFPM2.5 has been shown in previous research to increase proportionally to the rate of energy release.



Further analysis of real time data (including temperature and vertical flux measurements) will provide insight to the differences between EFPM and EFPM2.5. Ponderosa pine, for instance, exhibits difference values that are nearly the same for both phases. The presence or lack of duff material and the degree of consumption of duff in each phase may contribute to the similarity between phases. Combustion processes in piled slash are much different than in broadcast burns. The arrangement and mixing of fuels in tractor-piled slash encourages much more evenly sustained and complete combustion, with a much less-defined transition from flaming to the later smoldering combustion. During smoldering combustion, tractor-piled slash tends to collapse into the core of the fuel bed, entraining ash and giant particles through mechanical disturbances.

Research underway is designed to measure the difference in emissions production for tractor-piled slash versus landing piles built with loaders or cranes versus broadcast burns. Clearly, the fuel composition of piles is significantly different than the composition of clearcut units. Emissions from the burning of logging residues piled by crane on landings are expected to differ from either broadcast burns or tractor-piled slash burning.

Data presented here on the effects of live vegetation on EFPM2.5 (figure 6) do not support the authors' previous observations that EFPM values increase as live fuel increases (Ward and Hardy 1984). The previous observations included data specific to Douglas-fir/hemlock tests in 1982 and 1983. Data from the present study are specifically from hardwood units, and the scatter of data is fairly evenly distributed for both the dependent (flaming EFPM2.5) and independent (live vegetation) variables. The interaction of live vegetation and fire intensity for hardwood units may have obscured the expected similarity to results observed for Douglas-fir/hemlock units.

Although the number of observations in the Douglas-fir/hemlock and hardwood fuel types has been adequate to demonstrate no significant differences in emission factors between the two fuel types, we believe that real differences can be demonstrated between these fuel types and the ponderosa pine fuel type east of the Cascade Range. Data reported here for EFPM and EFPM2.5 from ponderosa pine units included only three tests. The statistical significance of differences between pine and other types cannot be determined without further data. Research has not been done in several other kinds of burning including underburns, field burning, range-improvement burns, and broadcast burning of uncured slash.

Emission factors for the gaseous emissions, combustion efficiency, and fire intensity can be calculated and will be presented in a subsequent report after the real time measurements have been fully evaluated. The additional information is expected to resolve some of the variances observed for particulate matter production as functions of the variables discussed in this paper.

CONCLUSIONS

We showed that emission factors for particulate matter are affected by the two distinct combustion phases. EFPM values for flaming combustion in Douglas-fir/hemlock, hardwood, ponderosa pine, tractor-piled slash, and chaparral were 12.3 g/kg, 13.5 g/kg, 9.2 g/kg, 6.8 g/kg, and 14.9 g/kg, respectively. EFPM2.5 values were consistently lower than EFPM values, although this difference was smaller for the smoldering phase than for the flaming phase.

No significant difference can be described for either PM or PM2.5 emission factors between Douglas-fir/hemlock and hardwood fuel types. For the flaming phase, emission factors from ponderosa pine tests are considerably lower than respective values in either Douglas-fir/hemlock or hardwoods. As expected, the lowest emission factors for either phase for both PM and PM2.5 were measured in tractor-piled slash burns--flaming EFPM and EFPM2.5 were 6.8 g/kg and 4.6 k/kg, respectively. Emission factors were measured for chaparral burns of 15.0 g/kg and 7.2 g/kg for PM and PM2.5, respectively. These values are similar to those measured for the flaming phase of other fuel types.

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