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BACKFIRE PARTICULATE EMISSIONS AND BYRAM'S FIRE INTENSITY

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ABSTRACT.—Particulate-matter emission factors and Byram's fire-intensity values were computed for experimental backfires in pine-litter and palmetto-gallberry fuels in the Southeast. The combined data for both fuel types were in reasonable agreement with the theoretical prediction that emission factor is inversely proportional to the cube root of Byram's fire intensity. Whether the low coefficient of determination ($r^2 = 0.56$) was due to the influence of additional variables on emission factors or to experimental error has not been determined.

Keywords: Emission factors, fire intensity, particulate matter, emission factor models.

Prescribed burning is important in management of southern forests, but it contributes to the background level of total suspended particulate matter in this region. The Southern Forestry Smoke Management Guidebook (South. For. Fire Lab. Staff 1976) has been published to aid forest managers in minimizing unfavorable impacts of smoke from prescribed fires on air quality. The Guidebook's system for computing particulate concentrations at various distances from a fire requires an emission factor (EF_p). EF_p is the ratio the mass of particulate matter produced by a fire to the mass of forest fuel consumed. Such factors have been estimated for a limited number of fire behavior and forest fuel conditions, based on field and laboratory measurements.

A major difficulty is that EF_p for a particular fuel type must be empirically determined. Appropriate data on artificially layered fuels have been reported for southern fuels by Ward and others (1974) and Ryan (1974) and for western fuels by Sandberg (1974), Darley (1977), and Fritschen and others (1970). Few measurements of EF_p exist for naturally layered fuels; some examples are in Sandberg (1974), Ward and others (1974), and Pickford and others (1978).

Research so far has not developed for practical use a relationship between EF_p and some combination of key combustion variables. If this could be done, a similar relationship might be applied successfully to other types of fuels for which little or no data are currently available. This Note reports a first step in the development of a model for predicting EF_p. It reports EF_p and fire behavior for backfires in southern fuels burned during the winters of 1974 and 1975. A correlation between EF_p and Byram's (1959) fire intensity[3] is demonstrated.

THEORETICAL CONSIDERATIONS

In the only research to date which has demonstrated a relationship between emissions and fire behavior, Sandberg (1974) has shown that EF_p for area fires in slash from western fuels is nearly inversely related to reaction intensity, I_R. The quantity I_R is the rate of heat release per unit of area in the combustion zone. Many of the effects of fuel and fire behavior on particulate-matter emissions apparently are integrated by this

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[3]The rate of heat release per unit length of fire front for a spreading fire.

variable (Sandberg and Pickford 1976). Sandberg's result can be expressed as

$$EF_p = K_1 I_R^{-1} \quad (1)$$

where K_1 is a constant. As Sandberg and Pickford (1976) have pointed out, Equation (1) leads to the simple and potentially useful prediction that particulate-matter production rate per unit area should be constant. It should be noted, however, that Equation (1) was developed from fires of constant size burned in the laboratory and has not been tested with spreading fires in the field. The burning conditions and fire types to which Equation (1) applies should be determined.

Because the field data on particulate-matter emissions and fire behavior taken during the present study did not include adequate information for obtaining I_R, Equation (1) could not be tested. However, the equation is expected to apply to the fires of this study because of similarities in the combustion process of Sandberg's area fires to backfires. Properties of the fuel layer, such as fuel particle size, arrangement, and moisture content, are believed to control the rates of burning in both fire types. In addition, combustion tends to be thorough with an insignificant smoldering phase for both types. Exploratory backfires in slash pine needles at the Southern Forest Fire Laboratory combustion facility give results which can be described by Equation (1). On the other hand, emission factors for headfires burned in the same facility do not obey the inverse relationship because of the significant contribution to emissions by the smoldering combustion phase.

Estimates of Byram's fire intensity, I, were used to establish a correlation with EF_p. As already mentioned, data for reaction intensity were not available. Furthermore, the quantity I may be a more practical variable to use in that it is easier to estimate in the field than I_R. The relationship between EF_p and I was expected to differ from the form of Equation (1) because of the formula

$$I_R D = I \quad (2)$$

where D is flame depth. Only for fires in which D is roughly constant can Equation (1) be valid when I_R is replaced by I.

Byram (1966) and Corlett (1967) have developed scaling laws for modeling the convective features of free-burning area fires. Both investigators have identified a number, written here as π, which is an expression of reaction intensity in dimensionless form. The number is written as

$$\pi = I_R(gD)^{-1/2} (\rho_a c_p T_a)^{-1} = K_2 I_R D^{-1/2} \quad (3)$$

where I_R is reaction intensity, K_2 is constant, g is acceleration due to gravity, $\rho_a c_p T_a$ is the constant volumetric heat content of the ambient air, and D is a length that characterizes the combustion zone. In this equation, D is taken as flame depth. A key question related to expressing EF_p in terms of Byram's fire intensity through Equation (1) concerns how D is related to I_R. For a series of fires, the question becomes one of how π changes from fire to fire. When the values of π for a series of backfires are roughly constant, a relationship between EF_p and fire intensity may be determined. If Sandberg's result in Equation (1) is valid and π is constant, combining Equations (1), (2), and (3) leads to

$$EF_p = K_3 I^{-1/3} \quad (4)$$

where K_3 is a constant. Thus, Equation (4) provides a prediction model for EF_p based on the results of Sandberg and a dimensionless variable identified in previous fire modeling work. This provisional interpretation suggests that the effects on emission factor of fuel variables such as moisture content, available fuel loading, and surface-to-volume ratio are accounted for by the variable I.

METHODS

Equation (4) was tested with measurements of fuel moisture, fuel consumption, fire spread, and particulate-matter production from 17 backfires in southern fuels. Fuel moistures were obtained by ovendrying representative samples of the fuel strata. Fuel consumption was estimated by the gravimetric techniques reported by McNab and others (1978). Prior to burning, the litter and/or vegetation up to 1 inch in diameter was removed from 1/4-milacre plots arranged systematically in the area to be burned. The burned area was then resampled in the same manner to determine the amount of fuel remaining. The weight differences for the plots before and after burning provided an estimate of fuel consumption. Spread rates were determined by noting the times when fires passed reference stakes spaced along several lines perpendicular to the direction of spread expected for the burn. Byram's fire intensity, I (in kW m^{-1} or kJ m^{-1} s^{-1}), was computed from

$$I = HWR$$

where

W is unit area fuel consumption (kg m^{-2})

R is rate of spread (m s^{-1})

H is heat yield (kJ kg^{-1})

and H is assigned the constant value of 13,954 kJ kg^{-1} (6,000 Btu lb^{-1}).

Particulate-matter emissions were computed from the flux through a stationary plane normal to the direction of plume drift (Ward and others 1974). Typically, three 12-m masts were positioned 8 m apart along a fireline parallel to the fire front. As the fire backed away from the masts, smoke transported past the masts was sampled with 47-mm glass fiber filters positioned at intervals as specified in table 1. During the sample period, particulate matter from a measured volume of air was collected for subsequent weighing in the laboratory. Thus, a concentration could be computed for each filter location. Airflow through the filters was regulated using precalibrated flow-limiting orifices. The wind run during the sample period was determined with totalizing anemometers at three heights. It was assumed that the vertical component of the wind was negligibly small. The flux of smoke was calculated from the wind run and filter weight measurements.

Table 1 illustrates the computation of EF_p. The mass of particulate material flowing through a window of unit width at each sample height is the product of the mean concentration of particulate matter and the volume flow of air during the sample time. To obtain EF_p, the sum of the particulate-matter masses is divided by the fuel consumed per unit length of fireline during the sample period.

The efficacy of the experimental procedure was greatest when variability in burning conditions was small. Changes in windspeed and/or emission rate during sampling caused errors in EF_p because some particulate matter passed over the tops of the masts. If it was judged from visual observations that less than 20 percent of the smoke escaped the masts, the experiment was considered successful from the standpoint of data collection. Later, an inspection was made of the reduced data to evaluate the decrease in measured particulate concentration with height. If the top filter locations produced low particulate-matter concentration values as compared to the middle and bottom filter locations, the experiment was considered useful for further work. Attempts were made to correct EF_p using plots of particulate matter flux (g m^{-1} s^{-1}) versus filter height. However, no meaningful method of correction could be devised with the information available.

Table 1.—An example of the method for computing particulate-matter emission factors. Data are for a palmetto-gallberry fuel burned at Patterson, Georgia. Fuel consumption per unit length of fireline during the 20-minute sample time was 23.56 kg m^{-1}.

Filter height (meters)	Mast number			Mean concentration	Window[1] area	Wind run	Volume of air	Particulate mass per meter of fireline
	1	2	3					
	.... *mg m^{-3}*		....	*mg m^{-3}*	*m^2*	*m*	*m^3*	*g m^{-1}*
0.91	34.6	21.4	23.7	26.6	1.36	1,981	2,694	71.7
1.83	30.5	23.6	21.8	25.3	.91	1,996	1,816	45.9
2.74	24.8	20.6	20.0	21.8	1.22	1,966	2,398	52.3
4.27	15.3	16.1	17.3	16.2	1.52	1,905	2,896	46.9
5.79	9.9	10.9	13.5	11.4	1.52	1,838	2,794	31.9
7.32	7.0	7.3	10.3	8.2	1.52	1,829	2,780	22.8
8.84	6.2	5.6	8.2	6.7	1.52	1,829	2,780	18.6
10.36	3.7	5.8	7.3	5.6	1.52	1,829	2,780	15.6
11.89	3.6	4.0	7.7	5.1	1.52	1,829	2,780	14.2
								319.9

$$EF_p = \frac{319.9 \text{ g m}^{-1}}{23.56 \text{ kg m}^{-1}} = 13.6 \text{ g kg}^{-1} = 27.2 \text{ lb/ton}$$

[1]A window 1 m wide parallel to the fireline is used.

RESULTS

Particulate-matter emission factor and fire-behavior data, by fuel type and location, are shown in table 2. In general, high EF_p values are associated with low fire intensities and with the pine-litter fuel type. Though the fires burned were from two different fuel types, it was assumed that, from the standpoint of particulate-matter production, all effects introduced by fuel type could be accounted for by fire intensity and fuel moisture variables as listed in table 2. To the authors' knowledge, no evidence exists in the literature for assuming otherwise. Thus, the combined data were analyzed by multiple regression with moisture content and fire intensity as independent variables. Regression models were developed for all variables as measured and for the same variables after performing logarithmic transformations. Separate analyses using upper-layer and composite-layer moisture contents indicated that emission factors were not appreciably more sensitive to the upper-layer moisture content than to the composite-layer moisture content, even though only the upper layers of fuel were consumed by many of the fires. The regression work further showed that even the upper-fuel-layer moisture content did not significantly influence EF_p at the 95 percent level. Perhaps these results should not be surprising in view of the rather restricted range in moisture content. The emission factors are predicted by

$$\ln EF_p = 4.108 - 0.313 \ln I$$

which can also be written as

$$EF_p = 60.8\, I^{-0.313} \tag{5}$$

where EF_p is in g kg^{-1} and I is in kW m^{-1}. The experimental data and Equation (5) are shown in figure 1. Equation (5) is similar in form to Equation (4) and slope values are nearly equal. The relatively small coefficient of determination ($r^2 = 0.56$) associated with the data suggests that variables other than fire intensity affected the emission factors, or that substantial measurement errors exist. Equation (5) may or may not represent data from two different populations—separate regressions (including moisture content), by fuel type, were not significant at the 95 percent level. Even though the data are regarded as weak from a statistical point of view, we believe that Equation (5) has merit when the factors such as small sample size and large experimental error usually associated with field measurements

Table 2.—Particulate-matter emission factors and fire-behavior data for backfires in southern fuels

Location	Fuel type	Moisture content		Fuel consumption	Rate of spread	Fire intensity[1]	Emission factor
		Upper	Composite				
		Percent		*kg m^{-2}*	*cm s^{-1}*	*kW m^{-1}*	*g kg^{-1}*
Cochran, Ga.	Pine litter	23	84	0.762	0.20	21.1	23.9
Cochran, Ga.	Pine litter	23	84	.830	.20	23.5	21.5
Cochran, Ga.	Pine litter	23	84	.674	.21	19.6	23.1
Cochran, Ga.	Pine litter	20	60	1.299	.30	55.3	25.7
Cochran, Ga.	Pine litter	20	60	1.211	.32	54.0	24.6
Cochran, Ga.	Pine litter	20	43	1.167	.31	50.5	25.8
Macon, Ga.	Pine litter	30	31	.381	.37	19.4	25.6
New Bern, N.C.	Pine litter	24	47	.708	.76	74.7	12.3
Leesville, La.	Pine litter	25	64	.254	.54	19.1	24.1
Kirbyville, Tex.	Pine litter	15	46	.293	.63	25.7	13.6
Patterson, Ga.	Palmetto-gallberry	17	35	1.123	.70	109.8	13.4
Patterson, Ga.	Palmetto-gallberry	22	38	1.436	1.48	296.0	7.8
Patterson, Ga.	Palmetto-gallberry	28	50	2.217	.88	273.4	13.7
Homerville, Ga.	Palmetto-gallberry	15	29	.693	.38	36.3	13.8
Lake City, Fla.	Palmetto-gallberry	10	44	.605	.58	48.9	20.6
Lake City, Fla.	Palmetto-gallberry	10	36	.718	1.02	101.7	17.1
Waycross, Ga.	Palmetto-gallberry	18	46	1.387	1.29	248.6	8.1

[1]Heat yield, H, is taken as 13,954 kJ kg^{-1} (6,000 Btu lb^{-1}).

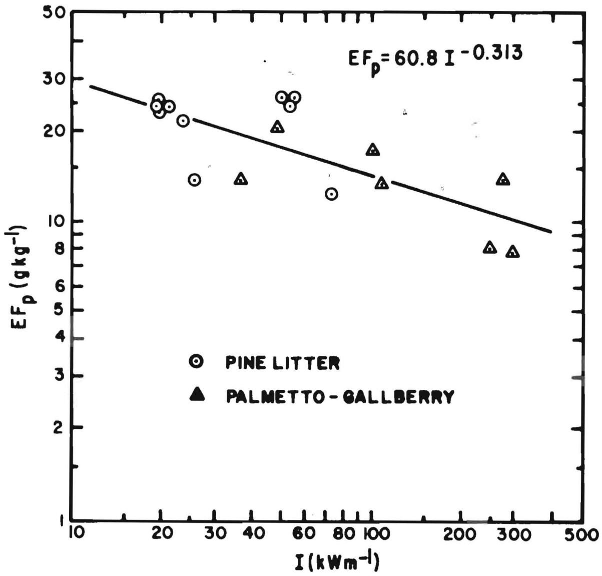

Figure 1.—Particulate-matter emission factors for backfires in southern fuels as a function of Byram's fire intensity.

are considered.

Variables other than moisture content and fire intensity were not examined for possible correlation with EF_p. Because the data of table 2 can be used to develop a plot of EF_p versus rate of spread, R, with $r^2 = 0.68$, R must be considered a potential predictor of EF_p. We emphasize the importance of Equation (5) here because of its development from theoretical considerations.

DISCUSSION

Overall, we consider the relationship expressed by Equation (5) and illustrated in figure 1 to be acceptable and important. The dependence of EF_p on I appears from the figure to be stronger for palmetto-gallberry than for pine-litter fuel. The ranges in both I and EF_p for burns in the litter were relatively small. In laboratory burns, however, we have obtained evidence that EF_p is dependent on I for pine-litter fuel.[4] A clear explanation for the absence of a relationship in this study cannot be given. The litter data are included in figure 1 because they are in line with the palmetto-gallberry data and they do contribute positively to r^2 (about 10 percent). All that can be said is that there is little evidence of large differences in particulate emissions due to differences in fuel type.

The theoretical result expressed by Equation (4) is strongly dependent on whether the dimensionless number π remains approximately constant from fire to fire. For the present experiments, the argument can be made that it does.

Equation (3) can be written as

$$\pi = K_2 I_R D^{-1/2} = K_2 I D^{-3/2}$$

through substitution of Equation (2). Table 2 shows that the average I for the pine-litter fires ($36.3\ kW\ m^{-1}$) is considerably smaller than that for the palmetto-gallberry fires ($159.2\ kW\ m^{-1}$). Though measurements were not made, D for palmetto-gallberry exceeded that for litter. Because both I and D are larger for palmetto than for litter, π tends to remain the same for the two fuel types. Values of D in palmetto-gallberry burns would have to be two to three times larger than in pine litter to keep π roughly constant. This result agrees with visual estimates of D for fires in the two fuels.

If Equation (4) is valid, it is easy to show that the particulate-matter emission rate per unit length of fireline (sometimes referred to as source strength) should vary as $I^{2/3}$. This result provides an alternative to the use of emission factors in expressing the relationship between particulate-matter emissions and fire intensity.

Our results show that Byram's fire intensity is at least partially related to, and possibly is a predictor of, backfire emission factors for particulate matter. We do not know whether this variable alone is an adequate predictor. Moisture contents of the upper- and composite-fuel layers had no significant effect on emission factor within the ranges encountered. However, since the range was limited, it seems premature to conclude that moisture content affects particulate-matter emissions only through Byram's fire intensity.

The model presented in this paper represents an effort to predict particulate-matter emissions for differing fuel types with a single equation. Even though the work is encouraging, the equation developed applies to only a limited number of fuel complexes. Work in progress is expected to better define the relationship between EF_p and fire intensity and the fuels in which it can be used.

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Though English units are still commonly used in forestry in the United States, the primary system of units in this Note is the metric system. Conversion factors from metric to English units are:

From metric	*To English*	*Multiply by*
centimeter second^{-1}	foot minute^{-1}	1.9685
gram kilogram^{-1}	pound ton^{-1}	2.0000
kilogram meter^{-1}	pound foot^{-1}	.6721
kilogram meter^{-2}	pound foot^{-2}	.2049
kilogram meter^{-2}	ton acre^{-1}	4.4609
kilogram meter^{-3}	pound foot^{-3}	.0624
kilowatt meter^{-1}	Btu min^{-1} foot^{-1}	17.3383
kilowatt meter^{-2}	Btu min^{-1} foot^{-2}	5.2873
megajoule kilogram^{-1}	Btu pound^{-1}	429.9226
meter	foot	.3048
meter^2	foot^2	.0929
meter^2	1/4-milacre	.9884
meter^3	foot^3	.0283

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