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PARTICULATE MATTER EMISSION FACTOR MODELING FOR FIRES IN SOUTHEASTERN FUELS

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INTRODUCTION

Prescribed or planned forest burning is used in the Southeastern United States to achieve a number of forest management objectives. One of the goals is to reduce the impact of smoke from wildfires on air quality by using prescribed fires to reduce the accumulated fuel when favorable smoke dispersion can be achieved. Prescribed fires generally emit less particulate matter than wildfires and seldom emit particulate matter at rates exceeding 1 kg s^{-1}, whereas, large wildfires may emit particulate matter at rates exceeding 1,000 kg s^{-1} (Wade and Ward 1974). A major cause for the difference in emission rate is that prescribed fires are far less intense, but little is known about the relationship between a fire's intensity and its emission factor (EF_p)--the mass of particulate matter produced per unit mass of fuel consumed.

This paper reports relationships between EF_p and fire intensity for burns in the palmetto-gallberry fuel type where fireline intensities ranged up to 1,750 kw m^{-1}. A model that is presented has application in determining the optimal prescription for minimizing production of particulate matter for a given fire. New experimental methods that will help in developing models for other fuel types are also described.

In previous research, the relationship between EF_p and fireline intensity has received relatively little attention. The Southern Forestry Smoke Management Guidebook (Southern Forest Fire Laboratory Staff 1976) contains EF_p values of 12.5 for backing fires and 37.5 g kg^{-1} for heading fires in the palmetto-gallberry fuel type, but it makes no adjustment for fire intensity beyond recognizing a difference between flaming and smoldering combustion. Nelson and Ward (1980) developed a model which showed a declining EF_p with increasing fireline intensity in the palmetto-gallberry fuel type, and Sandberg (1974) developed a similar relationship for different periods during the combustion process for western logging fuels. Neither of these models, however, represented fireline intensities greater than 300 kw m^{-1} or large area fires. Since wildfire intensities are normally considerably higher, the models have limited application.

METHODS

Data for estimation of EF_p can be obtained in several ways. EF_p can be estimated with considerable precision by collecting all combustion products from burns under carefully controlled conditions in a laboratory. No matter how elaborate the laboratory is, however, there are limits on the range of conditions that can be provided. In the field, rates of combustion can be observed during a fire, and particulate matter from the fire can be sampled. EF_p can then be roughly estimated by the particulate matter flux or the carbon balance method. The laboratory and both field methods were employed in our study.

Laboratory

The combustion facility at the Southern Forest Fire Laboratory (SFFL) is equipped to sample emissions from modeled fuel beds burned under selected environmental conditions (McMahon and Tsoukalas 1978). In the combustion laboratory, 0.91-m by 1.22-m fuel beds were ignited along a line at one end of the bed, and the fire was allowed to spread without wind to the opposite end of the fuel bed. The combustion products from the fire were funneled through a 0.61-m diameter stack and 1 percent of the effluent was extracted isokinetically (within 10 percent). Particulate matter from this sample was collected on a 0.20-m by 0.25-m glass-fiber filter mat.

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Field--Particulate Matter Flux

During 1974 and 1975, several 0.5-ha areas were burned. Towers 12.2 m high were positioned along the fireline downwind from the test areas. These were used for sampling the particulate matter concentration with height within a cross section of the plume. Wind run past these towers was measured with totalizing anemometers so that the flux of particulate matter could be determined for a specified period of time. This method, which is described in detail by Ward, et al. (1974), depends on the smoke plume being fully contained below the top of the highest sampler. This condition requires a persistent, strong wind for high-intensity fires, a very tall tower, or both. Consequently, the tests were limited to fires with fireline intensities of less than 300 kw m^{-1}.

Field--Carbon Balance

The carbon balance method was used to estimate EF_p for fires with intensities ranging from 12 to over 1,500 kw m^{-1}. In this method, samples of gases and particulate matter must be taken at different points in the smoke plume. Basically, the carbon balance method for computing EF_{pn} values requires that the major fraction of carbonaceous gases and particulate matter be accounted for in a unit volume of air. It also requires that the elemental percent carbon be known for the fuel consumed by the fire. Thus, in making the calculation, the carbon contained in the unit volume of gases is converted into the equivalent mass of fuel which was consumed in producing that amount of carbonaceous combustion products. The equation for computing EF_{pn} for sample height, n, is described in Appendix A. To sample the particulate matter concentration, we spaced 47-mm filter holders at 1.5 m intervals from 1.5 to 18.3 m along the side of a collapsible tower raised vertically in the smoke plume. Adjacent to the array of filter holders a second line of samplers was positioned for sampling gases and for monitoring windspeed. The CO_2 concentration was determined from the integrated bag samples using a Horiba[1/] nondispersive infrared gas analyzer. CO concentration was determined with an ECOLYZER analyzer. The concentration of total hydrocarbons was determined with a Mine Safety Appliances Co. analyzer equipped with a flame ionization detector. All particulate matter filter samples were weighed on a CAHN 4100 electrobalance.

1/ Mention of trade names throughout this paper does not constitute endorsement by the U.S. Department of Agriculture.

Fuels

Our purpose was to develop an EF_p model for the palmetto-gallberry fuel complex (Hough and Albini 1978). This fuel type is widely spread across the lower Coastal Plain of the Southern United States. Palmetto and gallberry are two of the most common plants occurring in forest understories in this region. In this fuel type, live and dead fuels accumulate rapidly. Wildfire in a 5-year accumulation of fuel can seriously damage or kill the southern pine overstory trees, even though they are fire resistant. Hazard reduction burning, therefore, is widely practiced in this region.

The EF_p data presented in this paper are from several locations across southern Georgia and northern Florida. Much of the data were taken from plots burned on the Osceola National Forest near Lake City, Florida. These 0.8-ha plots were ideal because of the diversity in accumulations of fuels; the plots are burned at 1-, 2-, and 4-year intervals. These burning rotations have been maintained for over 20 years. Sackett (1975) discussed details of the burning interval plots and the fuel associations. Fuel consumption was determined from a series of before and after fuel samples taken from 1/4 milacre plots (approximately 1 m^2). For determining fuel moisture content, samples of the different fuel strata were taken, placed in polyethylene jars, and ovendried at 85°C. Fuel consumption was also determined from a combination of the particulate matter flux and carbon balance techniques as described in Appendix A.

Weather

Windspeed, wind direction, and wind persistence influence fuel consumption, fire behavior, and especially the smoke plume trajectory. We monitored all of these through the use of three different wind sensing systems. Windspeed and direction were continuously monitored 1.4 m and 6.1 m above the forest floor with two R. M. Young propeller-vane units. During each test, wind run near the samplers downwind from the fire was recorded with totalizing anemometers. Wind run was measured 1.5, 3, and 6.1 m above the forest floor. In addition, for the 1980 tests, windspeed was measured at the gas-grab sampler locations on the 18.3 m tower using a heated thermistor system developed by Ryan, et al.

(1979). Wind run data were collected at mid-flame height using a separate Biram totalizing anemometer.

Temperature and humidity were recorded on a hygrothermograph. Spot observations of temperature and humidity were acquired with a sling psychrometer.

Fire Behavior

Rate of spread, flame height, flame depth, and flame residence time were observed periodically during each burn. Time required for the fire to move a fixed distance was used in determining the rate of spread. Flame height and depth were measured by observing marked reference stakes. Flame residence time was determined by timing the passage of the flame front past a fixed thin rod. Flame depth was also calculated by multiplying the rate of spread by the measured flame residence time. Fireline intensity, I, is defined as the heat release rate per unit length of fireline, whereas reaction intensity, I_R, is the heat release rate per unit area. I_R was calculated by dividing I by the flame depth.

RESULTS

When FF_p values were determined by both the particulate matter flux and the carbon balance method for the same fire, values for the carbon balance method averaged about 20 percent less than those for the particulate matter flux method (Table 1). This difference may be caused by some systematic error, such as overestimating windspeed, underestimating fuel consumption, or assigning a low value for the carbon content of the fuel. Work with emission factors for open burning is relatively imprecise, and a 20 percent error is not normally considered extreme. Ward, et al. (1979) estimated EF_p values by three reasonably independent techniques and reported similar discrepancies. Sample calculations of EF_p by the two methods employed in the present study are shown in Table 2.

Table 1.--Emission factors for particulate matter (EF_p), fuel consumption, and fire behavior for each of the test fires conducted during 1980 for the palmetto-gallberry fuel type. EF_p data were generated using the carbon balance and particulate matter flux techniques.

Test number	ROS	Fuel consump.	Fireline intensity	Comb. effic.[1]	Reaction intensity I_R	EF_p[2] part. flux	EF_p carbon balance
	($cm\ s^{-1}$)	($g\ m^{-2}$)	($kw\ m^{-1}$)	(%)	($kw\ m^{-2}$)	($g\ kg^{-1}$)	($g\ kg^{-1}$)
1	0.15	574	12	87	1000	27.1	17.8
2	6.35	543	480	82			18.0
3	0.36	1095	55	89	1735	15.6	12.5
4	0.35	533	26	89	1040	25.7	19.0
5	4.57	201					
6	12.70	799	1413	90	1544		17.6
7	15.24	812	1724	91	1134		14.5
8	0.39	964	52	89	2080	13.2	12.4
9	2.74	95	36	86	271		18.7
10	13.21	861	1589	86	1204		17.9
11	13.72	897					
12	11.18	856	1336	86			19.0
13	7.11	511	502	91	1731		14.6
14	7.62	361	384	90	711		12.1
15	0.32	654	29	88	1160	24.8	18.4

1/ Combustion efficiency equals actual CO_2 concentration divided by the CO_2 production that would exist if all carbon were completely oxidized.

2/ Based on before- and after-burn fuel sampling.

Table 2.--Sample of calculations of particulate matter emission factors (EF_p) by the particulate matter flux and carbon balance methods. Data are for test no. 4 in the palmetto-gallberry fuel type for a backfire (test duration 20 minutes).

Sample height (m)	Part. matter con. ($mg\ m^{-3}$)	Window area (m^2)	Wind run (m)	Wind vol. (m^3)	Part. matter flux ($g\ m^{-1}$)	CO_2	CO	THC	Part.	Total	Carbon flux ($g\ m^{-1}$)	EF_{pn} 1/ ($g\ kg^{-1}$)
						($mg\ m^{-3}$)						
18.3	0.83	1.52	1493.4	2270	1.88	9.8	0.8	0.3	0.8	11.7	26.6	35.3
16.8	0.67	1.52	1493.4	2270	1.52	19.6	1.5	0.6	0.6	22.3	50.6	14.9
15.2	1.11	1.52	1493.4	2270	2.52	22.1	1.6	0.7	1.1	25.5	57.9	21.6
13.7	0.59	1.52	1493.4	2270	1.34	24.5	1.7	0.9	0.6	27.7	62.9	10.6
12.2	0.42	1.52	1493.4	2270	0.95	27.0	2.0	0.7	0.4	30.1	68.3	6.9
10.7	1.15	1.52	1493.4	2270	2.61	29.4	2.2	0.6	1.1	33.3	75.6	17.2
9.1	1.67	1.52	1493.4	2270	3.79	34.3	2.4	0.6	1.6	38.9	88.3	21.3
7.6	2.39	1.52	1493.4	2270	5.42	39.2	2.7	0.6	2.3	44.8	101.7	26.5
6.1	2.98	1.52	1493.4	2270	6.76	61.2	4.2	0.9	2.8	69.1	156.9	21.4
4.6	3.74	1.52	1476.6	2244	8.39	83.3	5.6	1.2	3.6	93.7	210.3	19.8
3.0	5.07	1.52	1459.9	2219	11.25	105.4	7.4	1.6	4.8	119.2	264.5	21.1
1.5	4.51	1.00	1444.5	1444	6.51	127.4	9.1	2.1	4.3	142.9	206.4	15.7
1.0	4.51	1.25	722.2	903	4.07	120.0	8.8	2.4	4.3	135.5	122.4	16.5
Total					57.01 $g\ m^{-1}$						1492.4 $g\ m^{-1}$	

Calculated fuel consumed during test = 1492.4 g carbon $\frac{(1\ g\ fuel)}{(.497\ g\ carbon)}m^{-1}$
(from Equation 5, Appendix A)

= 3002.9 g fuel m^{-1} fireline for sample period.

Measured fuel consumption = 2239.0 g fuel m^{-1} fireline for sample period.

EF_p by part. flux (meas. fuel cons.) $= \frac{57.01\ g\ part.\ matter}{2.239\ kg\ fuel} = 25.70\ g\ kg^{-1}$

EF_p by part. flux (calc. fuel cons.) $= \frac{57.01\ g\ part.\ matter}{3.003\ kg\ fuel} = 18.98\ g\ kg^{-1}$

EF_p by weighted carbon flux using equation 4, Appendix A.

$$EF_p = \frac{16.5\ (122.4) + 15.7\ (206.4) + \ldots + 35.3\ (26.6)}{(122.4) + (206.4) + \ldots + (26.6)} = 18.96\ g\ kg^{-1}$$

1/ EF_{pn} values calculated using equation 3, Appendix A.

More than half of the test fires observed in 1974 and 1975 were in pine litter rather than palmetto-gallberry fuels. Table 3 shows EF_p values for each test burn during those years as estimated by the particulate matter flux method. Table 4 shows EF_p values for sawgrass fuels burned in the combustion laboratory.

Results of all of these tests are shown in figure 1, in which EF_p values are plotted against fireline intensity (I). A relationship between EF_p and fireline intensity appears to exist.

For the palmetto-gallberry fuels, EF_p decreases as I increases where I is less than 250 kw m^{-1}. When I exceeds 250 kw m^{-1}, EF_p increases and seemingly reaches a plateau. Unfortunately, the data base is somewhat limited in the zone from 500 to 1,400 kw m^{-1}. However, a parabolic model seems to best fit the data below 500 kw m^{-1} with

$$EF_p = 19.5 - 0.0737\ I + 0.000145\ I^2 \quad (1)$$

where the standard error of the estimate term is ± 2.8 g kg^{-1}. The shape of the EF_p versus I function from 500 to 1,750 kw m^{-1} is assumed to be linear because there are no data supporting a curvilinear response. For the fireline intensity range from 500 to 1,750 kw m^{-1}, the equation which best fits the data is

$$EF_p = 16.7 + 0.000243\ I \quad (2)$$

where the standard error of the estimate term is ± 2.1 g kg^{-1}.

The inverse relationship between EF_p and I when I is less than 250 kw m^{-1} has important implications. A log-log regression between EF_p and I for all the data where I is less than 250 kw m^{-1} results in $EF_p \alpha I^{-0.41}$. On the other hand, if EF_p is plotted against I on logarithmic paper for only the tests in palmetto-gallberry fuels, the result is $EF_p \alpha I^{-0.23}$. These results will be discussed in greater detail in the next section.

Table 3.--Emission factors for particulate matter (EF_p) estimated by the particulate matter flux method for slash pine needle litter (SPNL) fuels and palmetto-gallberry (PG) fuels burned during 1974 and 1975 field experiments.

Fuel type	Fuel consump. ($kg\ m^{-2}$)	Rate of spread ($cm\ s^{-1}$)	Fireline intensity ($kw\ m^{-1}$)	EF_p ($g\ kg^{-1}$)
SPNL	0.762	0.20	21.1	23.9
SPNL	0.830	0.20	23.5	21.5
SPNL	0.674	0.21	19.6	23.1
SPNL	1.299	0.30	55.3	25.7
SPNL	1.211	0.32	54.0	24.6
SPNL	1.167	0.31	50.5	25.8
SPNL	0.381	0.37	19.4	25.6
SPNL	0.708	0.76	74.7	12.3
SPNL	0.254	0.54	19.1	24.1
SPNL	0.293	0.63	25.7	13.6
PG	1.123	0.70	109.8	13.4
PG	1.436	1.48	296.0	7.8
PG	2.217	0.88	273.4	13.7
PG	0.693	0.38	36.3	13.8
PG	0.605	0.58	48.9	20.6
PG	0.718	1.02	101.7	17.1
PG	1.387	1.29	248.6	8.1

Table 4.--Particulate matter emission factors for the burning of sawgrass fuels in the SFFL combustion laboratory on fuel baskets (1.22 m by 0.91 m).

Fire no.	ROS ($cm\ s^{-1}$)	Fuel consump. ($g\ s^{-1}$)	Fireline[1/] intensity ($kw\ m^{-1}$)	EF_p ($g\ kg^{-1}$)
SG-15	0.64	11.12	169.8	9.6
SG-16	0.16	0.94	14.4	34.1
SG-17	0.68	13.49	205.9	6.5
SG-18	0.39	1.72	26.3	14.7
SG-19	0.64	6.86	104.7	6.3
SG-20	0.73	5.87	89.6	7.8
SG-21	0.55	3.21	49.0	12.1
SG-23	0.56	8.22	125.5	10.3

1/ $I = \frac{(\text{Fuel consump.})\ 13.95\ kj\ g^{-1}}{\text{Fuel bed width}}$

DISCUSSION

Consumption of fuels by forest fires is a complex and dynamic process in which changes in the association of fuel elements and fuel strata affect fuel involvement and fire intensity. Fuel strata involvement by the fire and fuel dynamics for the palmetto-gallberry fuel type have been treated in depth by Hough and Albini (1978). It was expected that particulate matter production for fires burning in this fuel type would vary with changes in combustion efficiency and as different combustion processes became active.

Smoldering combustion is a major contributor to particulate matter production. For example, the rate of particulate matter production increases dramatically as flaming combustion subsides. Fires of very low fireline intensities (<15 kw m^{-1}), those for which the flaming combustion process is barely sustained, would likewise be expected to produce large amounts of particulate matter, as has been previously noted by Nelson and Ward (1980). On the other hand, for fireline intensities in excess of 300 kw m^{-1}, the flaming combustion and residual smoke production processes have never been studied. Hence, the effects on the rate of particulate matter production are unknown. The main purpose of this research has been to examine EF_p values for a range of fireline intensities from 300 to over 1,500 kw m^{-1}. Fireline intensities from 100 to 500 kw m^{-1} are common in prescribed strip head fires.

Particulate Matter Formation Process

As the flame dimensions and fire intensity increase, the flame characteristics and the chemical processes occurring in the flame zone change. The pyrolyzed fuel no longer necessarily passes through an active oxidation zone. At times, pockets of unburned, partially oxidized gaseous fuels escape the combustion zone or undergo delayed ignition. The flame turbulence level increases with increasing fire intensity, and pyrolyzed fuel and oxygen may mix poorly. Due to the increased depth and height of the flame zone, heading fires create a reducing environment in which continued pyrolysis and synthesis of hydrocarbon gases and fragmented particles can occur in a reduced-oxygen environment. If the temperature in the interior of the flame zone is appropriate, rapid particle formation and accretion of carbonaceous organic particles will take place. Consumption of these particles requires prolonged exposure at high temperatures in an abundant oxygen concentration zone.

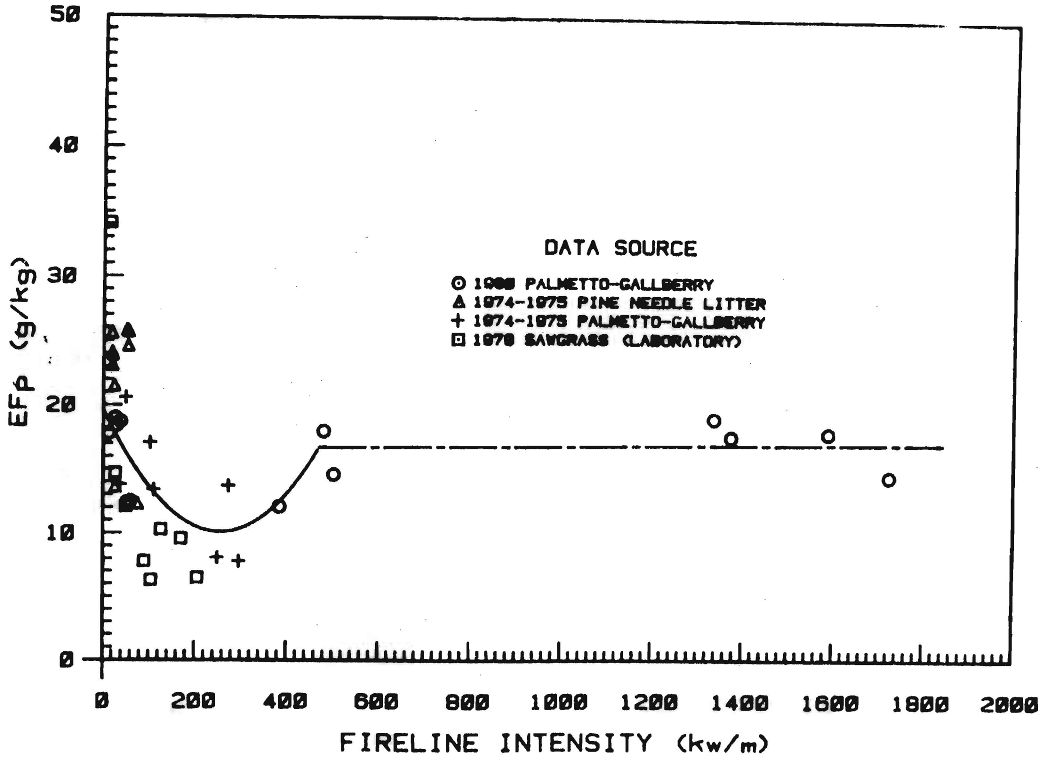

Figure 1. Relationship between particulate matter emission factors (EF_p) and fireline intensity for the palmetto-gallberry fuel type. Data for the other fuel types shown were not used in fitting the curve to the palmetto-gallberry data. Table 1 carbon balance EF_p data are plotted.

Oxidation of these particles depends partly on the degree of premixing of pyrolyzed fuel and oxygen which takes place in the zone of active solid fuel pyrolysis. Greater premixing should result in lower expected particulate matter production. Fuel arrangement can greatly influence air entrainment, as can turbulence.

The processes described have not been well quantified, and it is impossible to explain the exact mechanisms contributing to particle formation and oxidation at this time. More data are needed regarding flame temperature, gas concentrations, and particulate matter size and mass distribution for horizontal and vertical cross sections of the flame zone.

Effect of Fireline Intensity on EF_p

EF_p was found to be proportional to $I^{-0.41}$ for the combined data where I is less than 250 kw m^{-1}. However, when only the palmetto-gallberry data are considered where I is less than 250 kw m^{-1}, it was found that $EF_p \alpha I^{-0.23}$. It may be concluded that the dependence of EF_p on I is sensitive to variation in bulk density of the fuel layer for the low-intensity fires. In general, pine litter fuels exhibit higher EF_p values than do the palmetto-gallberry fuels. The palmetto-gallberry fuels, in turn, yield higher EF_p values than the sawgrass fuels. Future research may identify a family of curves which clarifies the effect of bulk density on EF_p. If this effect is ignored, it can be noted that the $I^{-0.41}$ dependence, based on all fuel types, is not far different from the $EF_p \alpha I^{-0.33}$ proposed for backing fires by Nelson and Ward (1980).

Equations 1 and 2, as illustrated in figure 1, incorporate the palmetto-gallberry data from Table 1 with the 1980 data for the same fuel type. It is readily seen, a minimum EF_p is obtained at a fireline intensity near 250 kw m^{-1}. It is, therefore, proposed that fires with intensities in the neighborhood of 250 kw m^{-1} will tend to minimize particulate matter production.

The shape of the curve from 470 to over 1,500 kw m^{-1} may be questioned because of missing data. However, the available data suggest that EF_p does not vary appreciably over this range of higher fireline intensities.

Effect of Reaction Intensity on EF_p

Though fireline intensity apparently can be used to predict particulate matter emission factors, it may be possible to relate these same emission factors to a different fire behavior variable defined in the Methods Section as reaction intensity, I_R. This concept is based on experiments by Sandberg (1974), who burned area fires in the laboratory using 1-meter-square beds of western logging debris. Particulate matter emissions from various fuel components (needles, wood, etc.) were sampled over short periods (20 or more seconds) relative to the total fire duration. Mass loss from the bed was measured during these same periods so that values of EF_p and I_R could be computed. It was found that EF_p was nearly inversely proportional to I_R for all fuel components, despite the fact that other variables such as fuel moisture, particle surface-to-volume ratio, bed porosity, and fuel loading, were varied independently.

It is of interest to compare the results of Sandberg's work with information from this study. In Table 1 are suitable data for 11 of the 15 fires burned in 1980 on the Osceola National Forest. A log-log plot of the data is shown in figure 2 in which 9 of the 11 data points fall in a reasonably straight line with a slope of -.50 with little apparent dependence on fire type. The remaining two points define a line of nearly the same slope. Whether these points are displaced because of an extremely weak dependence of EF_p on I_R or because of experimental error cannot be resolved until more data become available. However, if $EF_p \propto I_R^{-1/2}$ for palmetto-gallberry fuels, then the unit area particulate matter emission rate must vary as $I_R^{1/2}$. On the other hand, if EF_p is constant, then the unit area emission rate must vary directly with I_R. Neither of these relationships between EF_p and I_R would agree with the work of Sandberg and Pickford (1976) which showed that an inverse relationship between EF_p and I_R observed by Sandberg (1974) leads to a constant unit area particulate matter emission rate. It is noted, however, that the I_R values of Sandberg's work were determined for area fires during short time intervals within the burning process, whereas I_R values in the present work must be regarded as values obtained by averaging over the entire flaming zone of a line fire. Further resolution of how EF_p for line fires depends on I_R must await collection of additional data.

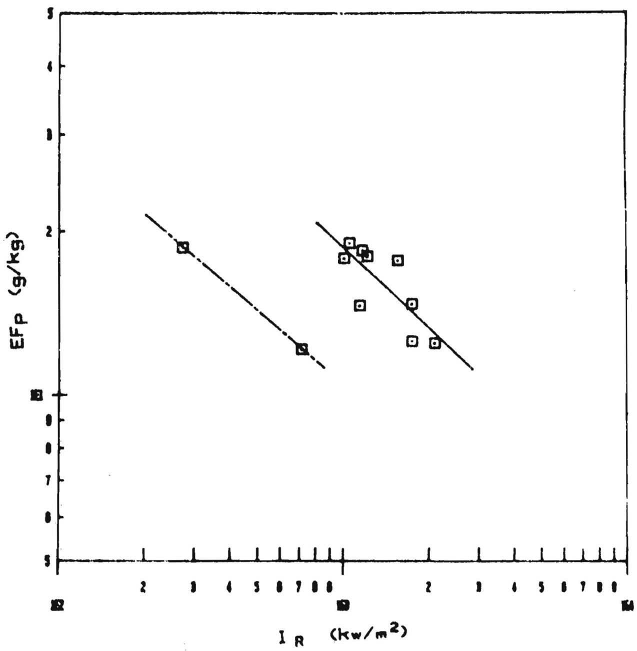

Figure 2. Relationship between particulate matter emission factor (EF_p) and reaction intensity (See Table 1 for carbon balance EF_p and I_R data).

Fire Management Implications

The functional relationship defined in Figure 1 and the supporting data indicate EF_p values for heading fires and backing fires of equal fireline intensity, I, to be nearly equal. In addition, by carefully selecting the burning conditions through the use of the guide by Hough and Albini (1978) for predicting fire behavior in palmetto-gallberry fuel complexes, the fire manager can prescribe conditions which minimize the production of particulate matter. Fire behavior models in the TI-59 hand-held calculator (Burgan 1979) or the nomograms developed by Albini (1976) can also be utilized in selecting the optimal burning conditions for achieving a fireline intensity between 200 and 300 kw m^{-1}.

Although backing fires are usually thought to be more efficient from a combustion standpoint than heading fires, it is worth noting that very low-intensity backing fires burning in the palmetto-gallberry fuel type may have a high EF_p value. Also, these fires achieve minimal convective lift of smoke plumes; therefore, very low intensity fires (below about 25 kw m^{-1}) should be avoided unless they are necessary to prevent damage to very young trees.

Fires with fireline intensities of from about 400 to over 1,500 kw m^{-1} may have nearly constant EF_p values of approximately 17 g kg^{-1}. This EF_p is less than 2 times greater than the minimum EF_p attained for fires of 250 kw m^{-1} fireline intensity. Thus, where overstory conditions will permit higher intensity fires and where maximum plume lift is desired for smoke dispersion, higher intensity fires may be employed. It must be recognized, however, that such fires will produce additional emissions, and that higher source strengths associated with higher intensity fires tend to increase the particulate matter concentration in the smoke plume.

CONCLUSIONS

1. Two independent methods were used to estimate emission factors for particulate matter (EF_p) on prescribed fires in the palmetto-gallberry fuel type. These methods are comparable; the discrepancy between estimates averaged 20 percent.

2. The carbon balance method for determining EF_p values has proven to be practical for estimating EF_p of fires with fireline intensities, I, up to 1750 kw m^{-1}.

3. Equations for predicting the appropriate EF_p in g kg^{-1} are expressed as a function of I in units of kw m^{-1}. Fireline intensity can be estimated from work reported by Hough and Albini (1978). The equations are:

a. where $I < 470$ kw m^{-1}
use $EF_p = 19.5 - 0.0737\ I + 0.000145\ I^2$

b. where $I > 470$ kw m^{-1}
use $EF_p = 16.7 + 0.000243\ I$.

4. It follows from the equations above that particulate matter production can be minimized for prescribed fires in the palmetto-gallberry fuel type by keeping fireline intensities between 200 and 300 kw m^{-1}.

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APPENDIX A

Carbon Balance Technique

In the carbon balance method, concentrations of major carbon-containing combustion products must be measured simultaneously at different levels above the forest floor, as is illustrated in Table 2. The carbon content of the forest fuel must be known. In this study, we assumed a carbon content of 49.7 percent as given by Brown and Davis (1974). Chin and DeGroot (1977) reported a range between 47 and 55 percent. The equation below is used for computing the EF_p at level n as follows:

$$EF_{pn} = \frac{P\ K}{C_{CO} + C_{CO_2} + C_{THC} + C_p} \qquad (3)$$

where,

- P is the particulate matter concentration, mg m^{-3}
- C_{CO} is the carbon fraction of the carbon monoxide concentration, mg m^{-3}
- C_{CO_2} is the carbon fraction of the carbon dioxide concentration, mg m^{-3}
- C_{THC} is the carbon fraction of the hydrocarbon concentration, mg m^{-3}
- C_p is the carbon fraction of the particulate matter concentration, mg m^{-3}
- K is the carbon fraction of the fuel elemental analysis, 0.497.

Essentially, equation (3) converts the carbon per unit volume back into fuel and divides the particulate matter concentration by the fuel concentration to yield an EF_p at height n.

In Table 2, the EF_{pn} values are weighted according to the flux of carbon through a sample window[2/] n according to the following:

$$EF_p = \frac{\sum_{n=1}^{13} EF_{pn} C_n}{\sum_{n=1}^{13} C_n} \qquad (4)$$

where,

- EF_{pn} is the calculated EF_p value for window n, g kg^{-1}, and
- C_n is the total mass flux of carbon through window n, g.

It immediately follows that if the total flux of carbon can be determined, then the fuel consumption during the sample interval can be calculated according to the following:

$$F = \frac{\sum_{n=1}^{13} C_n}{K} \qquad (5)$$

where F is the fuel consumed and the other variables are as previously defined. Equation 5 is only valid when the plume is fully contained below the top sampler as was defined for the particulate matter flux method.

2/ A sample window is defined as a vertical plane 1 m wide, normal to the plume trajectory extending from ground level to the midpoint between sample locations 1 and 2, and subsequently midpoint to midpoint between adjacent sample heights. The window areas are given in Table 2.