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Particulate Matter Emissions for Fires in the Palmetto-Gallberry Fuel Type

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ABSTRACT. Fire management specialists in the southeastern United States needing guides for predicting or assessing particulate matter emission factors, emission rates, and heat release rate can use the models presented in this paper for making these predictions as a function of flame length in the palmetto-gallberry fuel type. FOREST SCI. 29:761–770.

ADDITIONAL KEY WORDS. Fire management, smoke production.

PRESCRIBED FIRES are used very effectively by forest managers in the southeastern United States. The prudent fire management officer plans for the dispersion of smoke resulting from the prescribed fires. To do this, information is needed for predicting the rate of smoke production and downwind concentrations. The Southern Forestry Smoke Management Guidebook (Southern Forest Fire Laboratory Personnel 1976; hereafter referred to as the Guidebook) provides most of the needed technology for performing the smoke management activity. For the palmetto-gallberry fuel type, the Guidebook does not contain mathematical functions for adjusting emission factors for particulate matter (EF_p). EF_p is defined as the mass of particulate matter produced per unit mass of fuel consumed.

This paper presents a method for estimating EF_p, particulate matter emission rates (the rate of production of particulate matter per unit length of fireline, ER_p), and heat release rates (the rate of production of heat per unit length of fireline, I) using flame length as the independent variable. The flame length variable tends to be an integrator of the factors affecting emissions production for those fire conditions where the flaming combustion phase predominates. When the Guidebook is used, EF_p, ER_p, and I provide the inputs required to calculate downwind concentrations of particulate matter for fires burned in the palmetto-gallberry fuel type.

Flame length can be derived from the work of Hough and Albini (1978), the TI-59 fire behavior modules (Burgan 1979), or the fire behavior models as presented by Albini (1976). In addition, most experienced prescription burners can estimate flame length for a specific set of fuel and weather conditions.

Previous research has not revealed, for the continuum of fireline intensities, methods and conditions for prescribed burning which minimize particulate matter production for the palmetto-gallberry fuel type. The Guidebook contains EF_p values of 12.5 g kg^{-1} for backfires and 37.5 g kg^{-1} for head fires. But, the Guidebook makes no adjustment to the EF_p value beyond recognizing an emission production based on the different combustion processes of flaming and smoldering combustion.

This work is based on the model developed by Nelson and Ward (1980) which

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TABLE 1. Fire behavior and emission factor data from tests conducted in the palmetto-gallberry fuel type.

Fuel consumption	Rate of spread	Fire type	Fireline intensity	Emission factor
g m^{-2}	*m s*$^{-1}$		*kw m*$^{-1}$	*g kg*$^{-1}$
574	0.15	Back	12	17.8
543	6.35	Head	480	18.0
1,095	0.36	Back	55	12.5
533	0.35	Back	26	19.0
799	12.70	Head	1,413	17.6
812	15.24	Head	1,724	14.5
964	0.39	Back	52	12.4
95	2.74	Head	36	18.7
861	13.21	Head	1,589	17.9
856	11.18	Head	1,336	19.0
511	7.11	Head	502	14.6
361	7.62	Head	384	12.1
654	0.32	Back	29	18.4
1,123	0.70	Back	110	13.4
1,436	1.48	Back	296	7.8
2,217	0.88	Back	273	13.7
693	0.38	Back	36	13.8
605	0.58	Back	49	20.6
718	1.02	Back	102	17.1
1,387	1.29	Back	249	8.1

showed a declining EF_p with increasing fireline intensity, and an extension of the work reported on by Ward and others (1980). Their paper presents the first empirically derived model to include an EF_p-prediction method for fires above the 300-kw m^{-1} fireline intensity.[1] Through their model, potential differences in particulate matter production were identified for backfires and head fires up to 1,750-kw m^{-1} fireline intensity.

Emissions and Fire Behavior Data

EF_p data for head fires and backfires were collected from 20 small, 0.5-hectare (1.25-acre) plots. These data are the first field emissions data reported for head fires. Emission concentration was determined from numerous filter and gas grab samples taken from sample locations on towers located immediately downwind from the test fires. Details concerning techniques for sampling emissions and computing EF_p values have been reported elsewhere (Ward and others 1974, and Ward and others 1980).

Fuel consumption, fire behavior, and prevailing weather variables were measured for each test. The fuel consumption was determined by taking from three to five 0.25-milacre (1.012-m^2) samples before and after each test fire. The samples were ovendried, and the difference in weight was used to represent the fuel consumed for each test. The rate of spread of the fire was determined by measuring the distance traveled by the flame front during the time of emission sampling. Rate of fire spread multiplied by fuel consumption and heat of combustion yields

[1] In this paper, fireline intensity is expressed in SI units. To convert to English units, multiply kilowatts per meter by 0.289 Btu s^{-1} ft^{-1}.

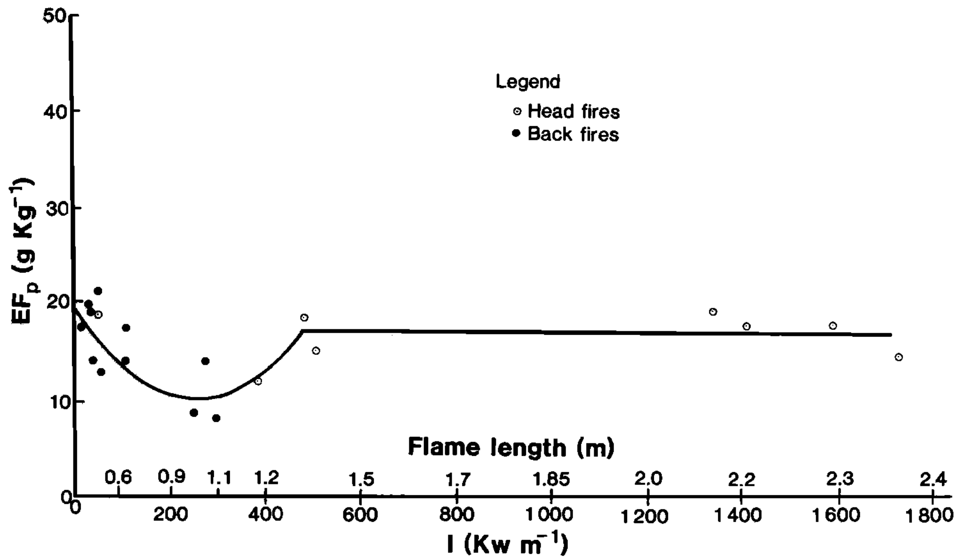

FIGURE 1. Relationship between particulate matter emission factors (EF_p) and fireline intensity (I) for the palmetto-gallberry fuel type.

the fireline intensity. Flame length was estimated by an observer. Wind run was measured, with a Biram anemometer, at 1.2 m (4 feet) above ground in the stand and was then converted to average windspeed by dividing by the sample time (usually 20 minutes).

DEVELOPMENT OF THE EMISSION RATE MODEL

Fuel consumption, spread rates, fireline intensities, and emission factors for test fires in the palmetto-gallberry fuel type in Georgia and Florida are summarized in Table 1. From these data, a best-fit model was developed with EF_p as a function of fireline intensity (Ward and others 1980). 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. The data base is limited in the zone from 500 to 1,400 kw m^{-1}. A parabolic model seems to best fit the data below 500 kw m^{-1} with

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

which has an adjusted R^2 of 0.48, $n = 15$, and standard deviation from regression of 2.8. The physical model presented by equation (1) was first derived from EF_p data generated from laboratory burning experiments which provided a data base for assessing the shape of equation (1) (Ward and others 1980). For fireline intensities from 470 to 1,750 kw m^{-1}, it is sufficient to use a constant EF_p of 17 g kg^{-1}. The least-squares regression equation which best fits the data has a slope coefficient of 0.000243 with a y-intercept of 16.7 g kg^{-1} and a standard deviation from regression of 2.1 g kg^{-1}. Because of the small slope coefficient, the results for these tests are plotted in Figure 1 using the constant EF_p of 17 g kg^{-1} for fires of greater than 470 kw m^{-1} fireline intensity.

To make the results useful to prescription burners, it is necessary to express particulate matter emission rate (ER_p) in terms of some readily predictable parameter. As has been shown previously by Byram (1959) and others, flame length can be correlated with fireline intensity. The relationship developed by Byram

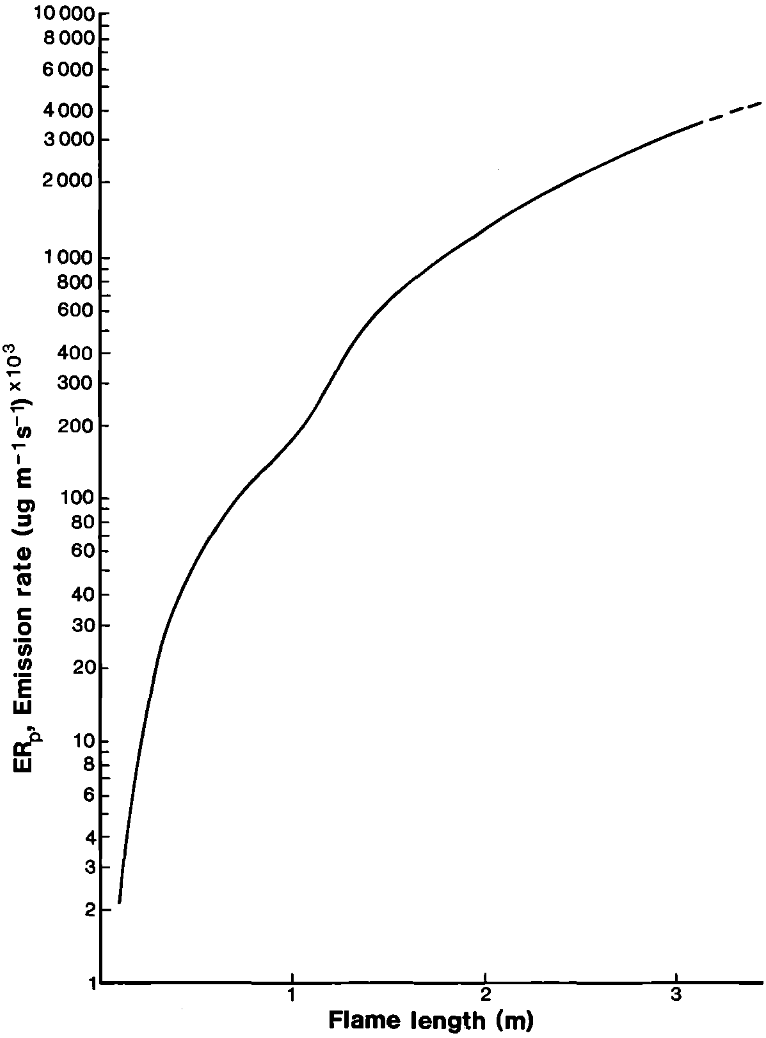

FIGURE 2. Particulate matter emission rate as a function of flame length for backfires and head fires in the palmetto-gallberry fuel type.

expresses flame length, h, in meters as a function of fireline intensity, I, in kw m^{-1}, as

$$h = 0.0775\ I^{0.46}. \tag{2}$$

Fireline intensity is generally defined as the heat release rate per unit length of fire perimeter (Byram 1959) and can be calculated from the equation

$$I = Hwr = HW \tag{3}$$

where

I = fireline intensity, kw m^{-1} or kj s^{-1} m^{-1}
H = heat yield, assumed to be 15.1 kj g^{-1}
w = available fuel, g m^{-2}
r = rate of spread, m s^{-1}
W = wr = rate of fuel consumption, g m^{-1} s^{-1}.

TABLE 2. Typical conditions and evaluated variables used in the Southern Forestry Smoke Management Guidebook (Southern Forest Fire Laboratory Personnel 1976) for predicting downwind concentration of particulate matter.[a]

Condition or variable	Typical case number (from Guidebook)	
	5	6
Fire type	Backing	Heading
Pasquill stability class	C	C
Mixing height (m)	1,500	1,500
Heat release rate, *HRR*		
(Megacal/sec)	37.632	137.984
(kw m^{-1})	197	721
Flame length (m)	0.9	1.6
Length of fireline (m)	800	800
Transport windspeed (m s^{-1})	8	8
Emission rate, ER_p		
$\mu g\ m^{-1}\ s^{-1}$ (Guidebook)	168,000	616,000
$\mu g\ m^{-1}\ s^{-1}$ (Fig. 2)	138,000	812,000

[a] Please refer to the Guidebook for correction factors if your environmental fuel variable input values are significantly different from the examples given here.

The rate of fuel consumption per unit length of fireline during the flaming combustion period can be shown to be a function of flame length:

$$W = 17.2h^{2.174}. \quad (4)$$

Now, to obtain the particulate matter emission rate, ER_p, in mg m^{-1} s^{-1} for a fire, the fuel consumption per unit length of fireline, W, must be multiplied by an appropriate emission factor, EF_p, for the fire conditions. The equation

$$ER_p = W \cdot EF_p \quad (5)$$

is the relationship used. EF_p values were shown to be a function of fireline intensity by equation (1) and Figure 1. The results of equation (1) can be used in equation (5) to form the following equations by substituting appropriately for W and EF_p where

$$I < 470 \text{ kw m}^{-1} \text{ and } I = (12.903h)^{2.174}$$

$$ER_p = (17.2\ h^{2.174})(19.5 - 0.0737\ I + 0.000145\ I^2) \quad (6)$$

$$I > 470 \text{ kw m}^{-1}$$

$$ER_p = (17.2h^{2.174})(17.0). \quad (7)$$

Equations (6) and (7) express ER_p as a function of flame length for line fires burning in the palmetto-gallberry fuel type. The results are plotted in Figure 2. It should be noted that equations (6) and (7) were developed from tests in palmetto-gallberry fuels of less than 7-year roughs. No verification tests have been performed, and it is likely that results from these models may be in error where smoldering combustion dominates and persists for longer than 30 minutes. Nevertheless, general application of these models is considered valid.

Discussion of Model

From a particulate matter production standpoint, the least amount is produced per unit mass of fuel consumed when the flame lengths are between 0.7 and 1.2 meters (2.5 and 4.0 feet). This is reflected in Figure 1 by the saddle region and

TABLE 3. Particulate matter concentrations at various distances downwind for typical backfires and head fires in the palmetto-gallberry fuel type based on the emission rate (ER) values in Table 2. Data are adapted from Table VI-M-4 in the Southern Forestry Smoke Management Guidebook (Southern Forest Fire Laboratory Personnel 1976).

Distance downwind (km)	Particulate matter concentration	
	Backfire	Head fire
	$\mu g\ m^{-3}$	
0.1	901	3,302
.2	479	1,756
.4	265	933
.8	135	496
1.0	110	402
2.0	57	206
5.0	25	59
10.0	10	25
20.0	3	10
40.0	1	6
50.0	1	5
100.0	1	3

in Figure 2 where the slope decreases over the range of ER_p between 100,000 and 500,000 $\mu g\ m^{-1}s^{-1}$. It is to be noted, however, that the most efficient fires produce only 50 percent of the particulate matter of the very intense fires. Fires of higher fireline intensity with longer flame lengths release heat at a much higher rate. Therefore, the convection column created and the smoke produced may rise to greater heights and the surface smoke concentration may be reduced even though the rate of smoke production and the total smoke produced may be greater.

On the other hand, when burning in young pine plantations, the potential for damage to the stand may prevent using head fires or backfires of optimal combustion efficiency (0.7- to 1.2-meter flame lengths). The introduction of prescribed fire into young pine plantations can often be done most effectively at nighttime during a period with persistent winds and stable atmospheric conditions. Care must be exercised to direct the smoke away from smoke-sensitive areas because the fire is purposely being burned at a lower fireline intensity condition which produces little plume buoyancy and higher EF_p.

Generally speaking, flaming combustion produces less particulate matter per kilogram of forest fuel than that produced by smoldering processes. Smoldering combustion in the palmetto-gallberry fuel type is not thought to contribute in a major way to the total emissions produced. This seems to be true for areas burned one or more times during each 4-year interval. Sample periods of no more than 10 minutes in length were required to collect samples of the smoke from 90 percent of the visible residual combustion. This would indicate that most of the fuel is consumed by the flaming combustion process, and that the smoke sampled was due to that process. Regardless, most of the smoke from the combustion of residual fuels is included in the samples from which the EF_p values were calculated.

Fireline intensity is primarily a function of rate of spread and fuel consumption with the range in fuel heat value being a secondary effect. Therefore, if fuel consumption remains constant, fireline intensity will change only if the rate of spread changes. Hence, EF_p is most heavily influenced by changes in the param-

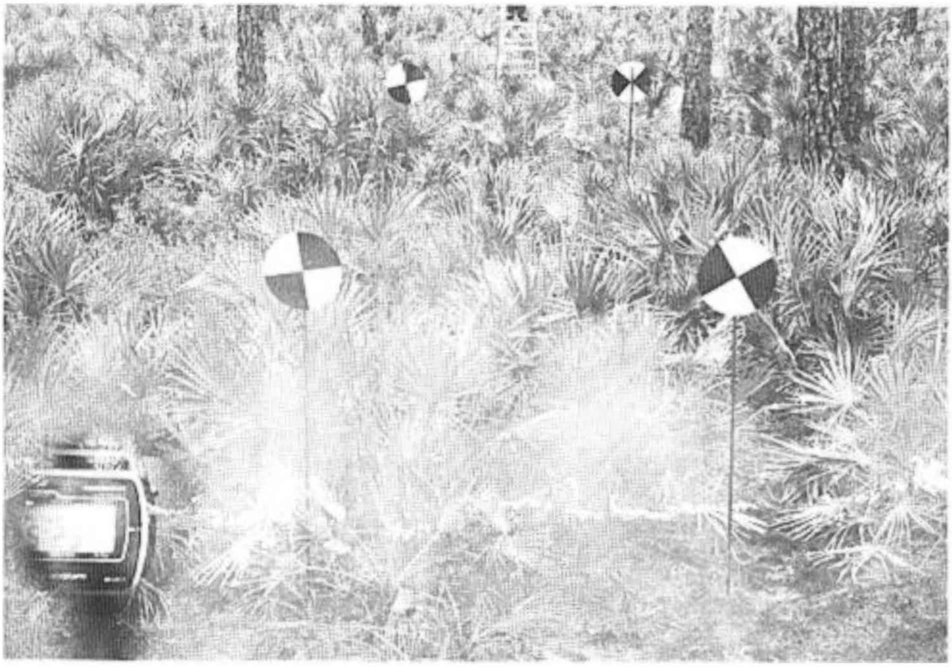

FIGURE 3. Backfire in the palmetto-gallberry fuel type with an average flame length of 0.1 m and a predicted source strength of 2,200 $\mu g\ m^{-1}\ s^{-1}$.

eters which have a direct effect on fireline intensity—rate of spread, fuel consumption, and method of burning.

In Table 1 and Figure 1, there is a small zone of overlap in test results for backfires and head fires. The combustion process differences between backfires and head fires have not been considered in this analysis. Head fires of low fireline intensity and backfires of equal intensity are thought to produce EF_p values of comparable magnitude. The data from this study are not in conflict with the concept of a single curve for predicting EF_p values for both head fires and backfires.

The Guidebook used a factor-of-3 difference in EF_p values for backfires vs. head fires for the palmetto-gallberry fuel type. This work would indicate a factor-of-2 increase in EF_p for the higher fireline intensity head fires over the fires burning in the 200- to 300-kw m^{-1} range. The result is not totally unexpected considering the low bulk density of the palmetto-gallberry fuel complex and the minimal amount of smoldering combustion.

APPLICATION OF EMISSION RATE MODEL

The fire manager can regulate fire intensity by applying any of a number of management techniques. For example, it is possible to adjust the burning schedule to include more frequent burning of an area to minimize the amount of fuel consumed by any one fire, or weather conditions can be selected which slow a fire's spread and minimize the fuel consumed. On the other hand, to achieve optimal combustion efficiency, it may be necessary to burn under drier conditions or at less frequent intervals. All of these variations can be used to advantage by the fire manager in an effort to minimize the adverse effects of the fire and to accomplish the desired benefits from the prescription.

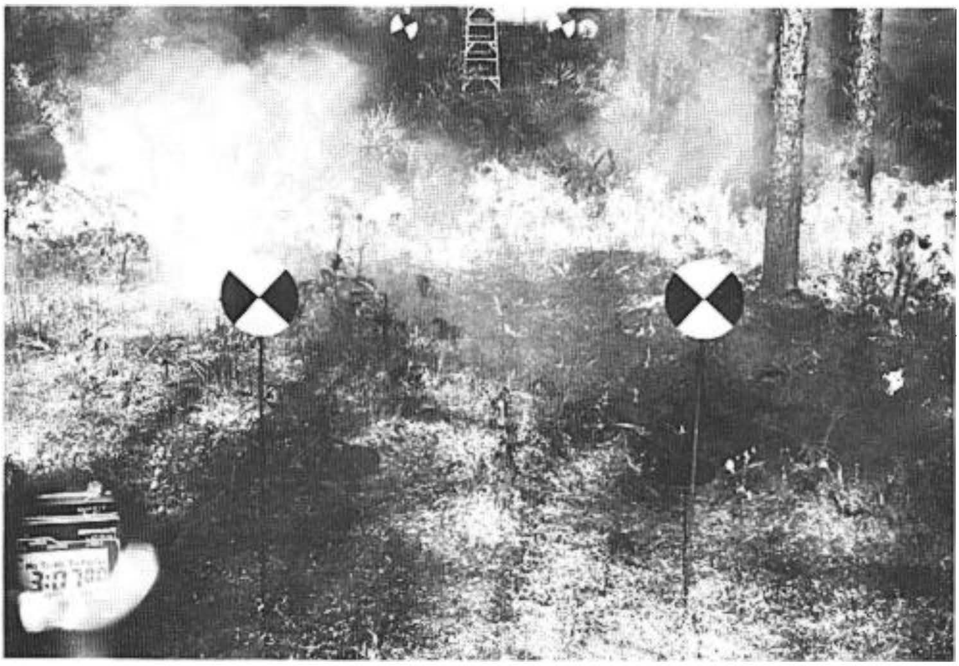

FIGURE 4. Head fire in the palmetto gallberry fuel type with an average flame length of 0.6 m and a predicted source strength of 82,000 $\mu g\ m^{-1}\ s^{-1}$.

The work of Hough and Albini (1978) can be used for predicting fuel consumption, fireline intensity, and flame length. Their model has been used for the lower intensity fires—for the normal prescribed burning range of fire intensities. The model requires inputs of stand density, years since the last fire, percent cover of understory vegetation, dead fine-fuel moisture content, and windspeed at mid-flame height. This method was used in the Guidebook.

The ER_p and heat release rate (HRR)[2] estimates reported here can be employed through the Guidebook for estimating downwind concentrations of particulate matter. In the Guidebook, case examples are used which represent typical prescribed fires. For example, cases 5 and 6 in the Guidebook are for a backfire and a head fire in the palmetto-gallberry fuel type. The heat release rate, flame length, and other pertinent data are presented in Table 2. If the reader is comparing the data from Table VI-M-1 (page 123) of the Guidebook with the tabular information in Table 2, it is noted that EF_p and ER_p values calculated in this paper are lower for the backfire and higher for the head fire. The combustion efficiency correction built into the EF_p model in Figure 1 likely resulted in these differences and is the key to providing the improved accuracy.

Table 3 lists the predicted downwind particulate matter concentration that would result from fires burned under the conditions presented in Table 2. It should be noted that fire with a flame length of 0.9 meter is burning near the level of optimal combustion efficiency as defined by Figure 1. Also, as the fireline intensity decreases, ER_p is reduced, but not at the same rate as EF_p. Hence, the source

[2] Heat release rate (HRR) values with units similar to the Guidebook can be obtained by multiplying the fireline intensity values by 239 cal/s per kw times the length of fire line in meters.

FIGURE 5. Head fire in the palmetto-gallberry fuel type with an average flame length of 1.20 m and a predicted source strength of 330,000 $\mu g\ m^{-1}\ s^{-1}$.

strength would change proportional to ER_p but would not be proportional to the rate of fuel consumption. This would produce particulate matter concentrations at downwind locations similar to those listed in Table 3 for the backfire.

For the head fire situation, EF_p is constant, so that ER_p is proportional to rate of fuel consumption and the source strength for the fire. The surface concentrations would be expected to increase significantly with increases in flame length and ER_p. Hence, a necessity exists for making adjustments to the downwind concentrations as specified in the Guidebook. Table 3 concentrations can be converted into miles of visual range equivalencies by dividing 730 μg miles/m^3 by the tabular concentration values. Thus, the visual range in smoke of 3,300 $\mu g\ m^{-3}$ is calculated to be about 0.2 miles or 350 m.

Based on his experience in prescribed burning in a given fuel type under various weather conditions, the fire behavior specialist can predict the approximate range in flame lengths to expect. The estimated flame lengths can be compared with the case examples presented in Table 2, and estimates of downwind concentration derived from Table 3. For example, the three photographs in Figures 3–5 are samples of research backfires and head fires. The mean flame lengths for the fires shown are estimated to be 0.1, 0.6, and 1.2 m, with corresponding estimated source strengths of 2,200, 8,200, and 330,000 $\mu g\ m^{-1}s^{-1}$, respectively. If all factors listed in Table 2 were similar to those for the examples in Figures 3–5 except flame length, EF_p, and HRR, it would be safe to say the only fire with which the land manager needs to concern himself is the one shown in Figure 5—and for this fire, only out to a distance of about 1 km. These guides can be used in determining the need for prescription changes resulting from expected particulate matter concentrations downwind from the source.

Conclusions

A model has been developed for predicting particulate matter emission rates as a function of fireline intensity and flame length for prescribed fires in the palmetto-gallberry fuel type. The emission rate model has application through the use of other fire behavior prediction models which can be used for predicting flame length, or based on the experience of the fire management specialist. These emission rate values and environmental conditions can be compared with the case examples given in the Southern Forestry Smoke Management Guidebook (Southern Forest Fire Laboratory Personnel 1976) for assessing downwind smoke concentrations.

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