An Approach to Predicting Slash Fire Smoke

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PRESCRIBED forest burning and wildfires release quantities of particulate matter, various hydrocarbon gases, carbon monoxide, and other materials into the atmosphere. These materials are often collectively termed "smoke"—an imprecise term usually connoting the physically obvious optical and olfactory properties of plumes from fires. Although Vogl (1974) states that "smoke is a natural and essential component of the atmosphere," smoke can, and sometimes does, interfere with the comfortable enjoyment of life and property and may cause economic loss. This, by definition, is air pollution. The U. S. Congress has authorized the promulgation of air quality standards which strictly define the maximum allowable concentrations, durations, and frequencies of atmospheric particulate matter, CO, and nitrogen and sulfur oxides. Thus, much as we enjoy convincing each other that wood smoke is harmless, foresters have no choice but to manage fuels, fire, and smoke in such a way as not to exceed these air quality standards.

The Cooperative Smoke Management Program (Cramer and Graham, 1971) in the Pacific Northwest has, of course, done just this, and has done so effectively. However, given certain improvements in data and methodology, this program and similar ones in other regions of the U. S. could provide more accurate quantitative predictions of the impact of forest burning on air quality. These improvements can reduce the potential for air pollution from forest burning. Our paper points out certain problems in current predictive methods on which most smoke management programs are based. These problems complicate research efforts to improve predictability of air quality impacts of forest burning. In addition, we offer an hypothesis, based on recent laboratory work, which may provide a more workable alternative to the present approach used in most smoke management programs.

POLLUTANT EMISSION FACTORS AND SMOKE MANAGEMENT

An effective smoke management program, such as the one in use in the Pacific Northwest, depends on predicting both the quantities of pollutants emitted during burning and the pollutant trajectory with respect to so-called "smoke-sensitive areas."

Predicting the quantity of pollutants emitted, with which we are concerned in this paper, currently requires only two pieces of information. The first is the total amount of fuel to be burned. Relatively good estimates of total fuel amount are not difficult to obtain for most slash-burning operations. Similar estimates are not readily obtainable for wildfires, since total fuel loadings are rarely known with any degree of precision in advance of fire occurrence. However, most smoke management programs are primarily concerned with controlled or prescribed burning operations. Estimated fuel amounts are usually adequate in these instances.

The second piece of information required for predicting pollutant emissions is the amount of a particular pollutant emitted per unit of material burned, usually referred to as an "emission factor." Emission factors are convenient because they relate the amount of material entering a process (such as combustion), which is easily

estimated or measured, to the amount of pollutant produced, which may be difficult or impossible to estimate directly.

Several emission factors have been proposed by various workers for each of the four major pollutants (particulate, CO, hydrocarbon gases, NOx) emitted during prescribed burning. Those most widely accepted for forest burning are listed in Table 1.

Emission factors for steady-state processes, such as fossil-fueled combustion for steam or electrical generation, can be accurately determined. These estimates are often supplemented by source monitoring that the industry itself is required to make. However, determinations of emission factors for prescribed burning of forest fuels are complicated by the highly variable, non-steady nature of combustion processes which characterize these types of burning operations.

The available data on emissions have been derived largely from burning agricultural wastes under physical and environmental conditions very much different from those typical of burning logging slash. The data in Table 1 have been applied to burning leaves, grass, barley, rice, cotton, tree prunings, and brush, as well as slash and even wildfires. This broad application is testimony to the lack of specific knowledge of emissions from open burning.

Improvements in emission factors for forest burning operations are hampered by a number of problems. We offer three broad categories which should include most of the important deterrents to further improvement.

1. *Variations in the amount of fuel actually consumed in any given burn:* These variations result partly in response to variations in

TABLE 1. Emission factors for open burning landscape and agricultural refuse[1]/

Pollutant	Pounds per ton of refuse
Particulates	17
Carbon monoxide	60
Hydrocarbons (as C)	12
Oxides of nitrogen	2

[1]/Duprey 1968.

environmental conditions (wind, slope, moisture, etc.) and partly in response to variations in the composition and physical structure of the fuel bed. Application of any emission factor to the *total* amount of available fuel will produce results varying in accuracy depending on the amount of material left unburned, which itself will vary according to conditions under which the burn is conducted.

2. *Variations in composition of the fuel bed*: Even if fuel beds are burned under identical conditions, the emissions produced depend on the composition of the fuels; e.g., relative proportions of green and cured vegetation, needles, stumps, and organic soil horizons (Cooper and Mobley, 1973; Sandberg, 1974; Fritschen et al., 1970; Philpot et al., 1972; Sandberg et al., 1975).

3. *Burning patterns and firing techniques*: Recent work at the Southern Forest Fire Laboratory (Ryan, 1974) indicates that headfires produce several times the emissions produced by backing fires in similar fuels under similar conditions.

Workers using the emission factors in Table 1 apparently consider these figures as representive of "average" fuel bed and environmental conditions over the entire range of possibilities in the U. S. The simplicity of this approach in making estimates of total emissions and the minimal amount of necessary input data make this approach to forecasting total emissions extremely attractive. However, where excessive smoke concentrations from forest burning operations pose serious threats to human activities, the use of "average" emission factors may lead to unacceptably poor predictions. In these instances, emission factors may be arbitrarily increased to include a safety factor. This approach, adopted by Pharo (1973) for smoke management in the Southeast, is analogous to a "worst case" prediction and can over-constrain prescribed burning in many cases. Nevertheless, emission estimates derived from the use of emission factors are, and probably will remain, useful for such applications as emission source inventories and certain low-resolution modeling efforts.

EMISSION RATES AS AN ALTERNATIVE TO EMISSION FACTORS

Emission factors can be derived by integrating the rate of pol-

lutant production over time. For steady state processes, the resulting emission factors amount to integrating a simple constant. For non-steady state processes, such as prescribed burning, this integration involves several complex relationships between the fuel, its environment, and time.

Recent laboratory work with small (3 ft^2, 30 lb) fuel beds (Sandberg, 1974; Sandberg et al., 1975) indicates that combustion of forest fuels takes place in three distinct phases: (1) a short duration, high intensity phase where needles dominate fire behavior; (2) flaming from fuel beds after needles are consumed, or in beds containing no needles; (3) a final smoldering phase where no flames are visible. Emission factors developed for each of these three phases (Fig. 1) showed a strong correlation to fire intensity (BTU ft^{-2} min^{-1}) (Sandberg, 1974). For example, particulate emissions during the second flaming phase (EF_R) were estimated by the regression:

$$EF_R = 2163\, I_R^{-.98} \qquad (1)$$

where I_R is fire intensity in BTU ft^{-2} min^{-2}, with an r^2 of 0.83 and standard error of 0.167 lb ton^{-1}. By comparison, emission factors for the entire burning period ranged from 3 to 73 lb ton^{-1} for individual fires making up this series of experiments.

Figure 1 indicates a strong dependence of pollutant emission on burning phase. Similar indications have been observed by others. Fritschen et al. (1970) measured 4.0 to 4.6 lb ton^{-1} of particulates for western hemlock and Douglas-fir branches, respectively. Philpot et al. (1972) measured an average of 6.2 lb ton^{-1} of particulates from Douglas-fir slash fuel without needles. The presence of needles in laboratory fuel beds has resulted in much higher emissions. Sandberg et al. (1975) measured an average of 12 lb ton^{-1} from ponderosa pine fuel beds containing 33 percent needles. Sandberg (1974) measured 14 and 24 lb ton^{-1} particulates from ponderosa pine fuel beds containing 4 percent and Douglas-fir fuel beds containing 13 percent needles, respectively.

Ryan (1974) measured emissions from level pine needle fuel beds ranging from 30 to 85 lb ton^{-1}, depending on fuel moisture content and compactness. Apparently, emissions can be quantitatively re-

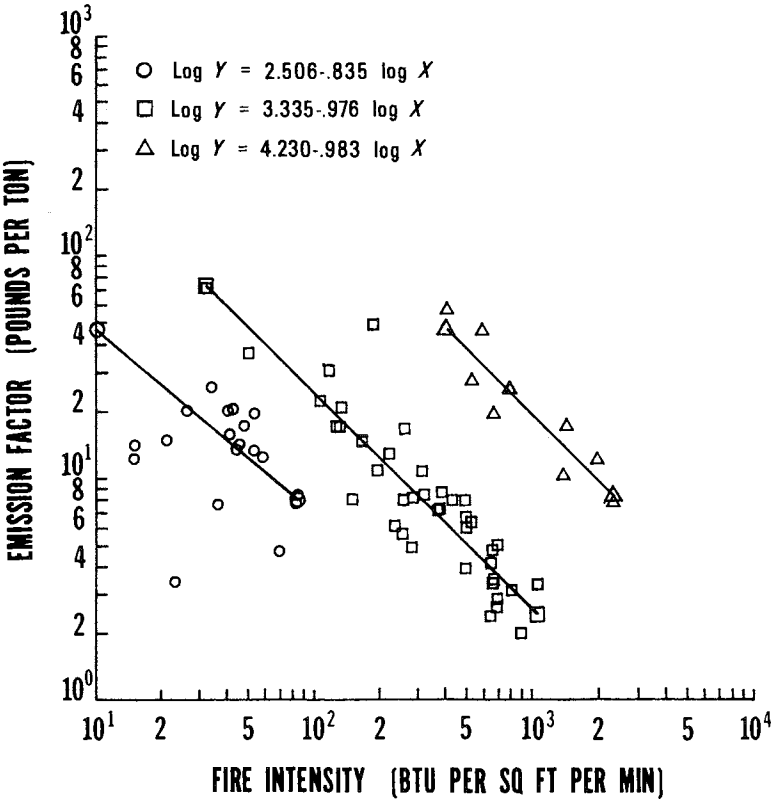

Fig. 1. Emission factors vs. fire intensity.

lated to fire intensity, if the sequence of fuel involvement (or burning phase) is considered.

We suggest that emission rates can be used as a relatively simple and considerably more accurate alternative to overall emission factors, as follows. The emission rate, Q, is related to the emission factor during a given burning phase by the fuel consumption rate $\overset{\circ}{\omega}$ (lb min^{-1} ft^{-2}) in the equation:

$$Q = \frac{EF \overset{\circ}{\omega} a}{2000} \qquad (2)$$

where a is the fuel bed area involved in that burning phase (ft^2). Fuel consumption rate is related to fire intensity, I (BTU min^{-1} ft^{-2}) by

$$I = \frac{\delta}{a} h \qquad (3)$$

where h is the heat of combustion of the fuels involved (BTU lb^{-1}), here assumed to be 8000 BTU's lb^{-1}. Substituting (3) into (2),

$$Q = \frac{EF\, I\, a}{1.6 \times 10^7}$$

or

$$Q = \frac{EF\, I\, A}{367.3} \qquad (4)$$

where A is the area involved in the given burning phase in acres. Combining (1) and (4) to describe the emissions rate for the second flaming period during test fires (Sandberg 1974),

$$Q = \frac{I\, A}{367.3} \quad \frac{2163}{I^{.98}} \cong 5.8A \qquad (5)$$

Equation 5 does not include explicitly any consideration of fuel loading, porosity, moisture content, or species composition. These variables are accounted for by their influence on fire intensity, I. More importantly, because emission rates were inversely related to fire intensity, the second flaming phase of combustion in these fuel beds produced about 6 lb min^{-1} $acre^{-1}$ of particulate matter, regardless of fire intensity. Emission rates for needle-dominated flaming and for smoldering were 46 and 1 lb min^{-1} $acre^{-1}$, respectively. If these relationships can be verified by further work, they can provide an accurate and relatively simple means of estimating pollutant production from prescribed burning.

Following this argument further, total pollutant production, E, is

$$E = Q_N\ T_N + Q_R\ (T_R - T_N) + Q_S\ T_S \qquad (6)$$

where the subscripts N, R, and S refer to needle-dominated flaming, non-needle flaming, and smoldering, respectively, and T is the duration of the phase in minutes. The duration, T, of each phase must be known. Additional work may produce relationships between duration and a few environmental or fuel bed variables affecting burning behavior. This problem is closely related to fire behavior modeling studies at the Northern Forest Fire Laboratory. Rothermel (1972) has published a mathematical model for predicting fire spread in wild land fuels, given fuel, wind, and slope measurements.

The model defines a "reaction zone" which is essentially the same as our flaming phase of fire behavior. Rothermel equated reaction time or duration, T, to reaction zone depth or distance from fire front to the point of last visible flaming, D (ft), and forward rate of spread, R (ft min^{-1})

$$T = \frac{D}{R} \tag{7}$$

In turn, he equated reaction time to reaction velocity, r(min^{-1}), and completeness of combustion which he terms "reaction efficiency," N_a (percent):

$$T = \frac{Na}{r} \tag{8}$$

In equations (7) and (8), the rate of spread and reaction velocity are predictable by the model, but depth of reaction zone and reaction efficiency are not. Moreover, the model does not consider the smoldering phase at all, nor does it separate flaming into the two phases we propose as necessary. Nevertheless, the groundwork represented by this model provides a solid base on which estimations for duration of each burning phase can be developed.

In summary, we present the hypothesis that the particulate mass emission rate (and probably emission rates of other pollutants as well) is roughly constant regardless of fire intensity or fuel bed condition and depends only on the burning phase (e.g., flaming, smoldering) and fuels dominating burning in that phase (e.g., needles, branchwood, herbaceous vegetation). We propose that emission rates, when developed, will prove more useful than present emission fac-

tors for making smoke management decisions in specific instances, for fuel management plans, local dispersion estimates, or estimating emissions from large fires.

Additional research is needed. The hypothesis is not conclusively proven by the available data and requires additional testing. Emission rates for other fuels such as herbaceous vegetation, peat, and rotten wood are required to complete the model. A method for reliably estimating the duration of each burning phase is also required.

We expect that research needed to accomplish these tasks will be considerably less complicated or voluminous than the research required to extend emission factors to cover the extreme ranges in fuel beds and environmental conditions encountered in prescribed burning.

The Federal Government and local air resource management authorities are responding to environmental concerns by more and more rigorous definition of acceptable concentrations of atmospheric pollutants. Dispersion models that predict air quality downwind of a pollution source are becoming more sophisticated and quantified. We can expect that we will be required to make better estimates of pollutant production from prescribed burning and wildfires, and to make management decisions from a better intelligence base. The challenge falls on fire research to provide and verify a workable approach to this end.

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