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Observations of Extinction and Marginal Burning States in Free Burning Porous Fuel Beds

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Abstract—An extinction index is developed to describe the marginal burning state of free burning surface fires in porous beds of woody fuels. The index depends on the fuel surface area, fuel moisture content, endothermic heat of pyrolysis, and the heat of combustion of the pyrolyzate gases. Extinction and marginal burning state probability distribution functions are fitted to data from 470 test fires.

INTRODUCTION

Significant progress has been made in recent years toward developing wildland fire behavior and fuel management systems to meet the needs of resource managers. Fire behavior models currently in use involve empirical expressions for fire intensity supported by inadequate data in a few key areas. Consequently, studies were initiated to expand the data base and strengthen the fire models. This discussion of the marginal limits of burning gives some results of a study to reexamine the effects of several fuel characteristics (moisture, loading, depth, packing ratio, and particle size) on fire intensity and burning rate.

Current models of wildland surface fires use the concept of "extinction" as the limiting case of fire intensity and spread rate. In particular, Rothermel's (1972) original formulation for the effect of fuel moisture on burning rate includes an extinction moisture parameter, M_x, which is "the fuel moisture at which the fire ceases to spread." The requirement that the moisture function that scales burning rate also predicts extinguishment at the marginal limits of burning has not worked satisfactorily in application, primarily because there is no consistent rationale for assigning a value to "moisture of extinction."†

An alternative approach is to treat extinction independent of the moisture influence on burning rate. By this rationale a less complicated moisture function (perhaps based on physical principle) will characterize the effect of fuel moisture on the burning rate (Rothermel's reaction intensity, I_R) of fires that do not go out. An independent function, discussed here, gives the probability that a fire will burn, not burn, or burn in some defined marginal state.

†The problem is not entirely one of modeling the physical process; the concept of "extinction" is not well defined in field application. For example, an oversimplified generalization is that in the Western United States, fires sometimes burn in dry flashy fuels; the manager is concerned with the marginal condition whereby the fire is easily controlled. Alternatively, an Eastern deciduous litter fuel may burn at very high moisture content, and the management objective is to ensure the fire is dead out.

EXPERIMENTAL BACKGROUND

Moisture

The study was designed to examine the effects of fuel moisture and geometric properties of fuel beds and to avoid effects of fuel thermochemical properties by holding their variation to a minimum. Fuels were preconditioned to the desired moisture contents (measured as fraction of oven-dry weight) and were burned in ambient temperatures and relative humidities calculated to maintain the initial moisture content. Test fires were burned for each geometric bed configuration over a range of fuel moistures (in increments of 0.05) from near oven-dry up to the fiber saturation limit (approximately 0.30 for most woody fuel), or to the moisture limit for which the fire would not burn after two or more tries at reignition. Fuels at higher moisture content were assumed not to burn.

A few heavier fuel loadings were conditioned by immersion, adding free water in excess of fiber saturation in an effort to track the marginal burning state to the extreme.

Fuel Bed Geometry

Fuel bed geometry spanned the range observed in most wildland surface fires. Fuel particles were milled wood sticks or shaved excelsior 0.05 to 3.8 cm square and 0.914 m to 3.05 m long. The smallest particles (0.05 cm excelsior) approximate the fine needles, twigs, and grass fuels. The 3.8-cm square fuel sticks, which burn with flaming combustion for about 12 minutes, represent the largest fuels thought to contribute actively to surface fire propagation (Anderson, 1969).

The geometric parameters defined in Rothermel's original model are:

σ Ratio (cm^{-1}) of surface area/volume of fuel particles.

β Packing ratio, solid fuel volume/total fuel bed volume.

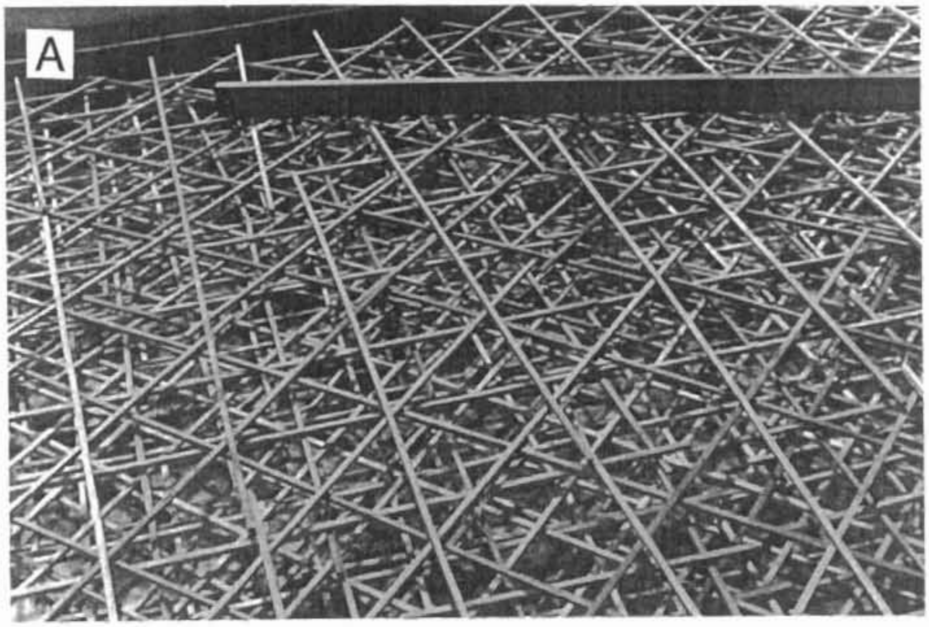
δ Fuel depth bed (cm), or fuel load per unit area/fuel bed bulk density.

The product $S=\sigma\beta\delta$ gives the total fuel surface area per unit horizontal area of fuel bed.

We note that heat transport out of the combustion zone, heat absorption by fuel particles, moisture transport into and out of fuels, production rates of volatile combustibles by pyrolysis, diffusion of air, effects of wind, and so forth, are all related to fuel surface area.

Fuel beds were 91.4 cm wide by 3.05 m long. Excelsior fuel beds were constructed by distributing a weighed fuel amount evenly over the bed area to uniform depth. The 1/16-inch and larger stick beds were constructed layer by layer to the precise geometric configurations shown in Figure 1. In each layer the fuel sticks were placed parallel with spacing calculated from the planned solid volume/total volume ratio, each layer having the same total linear measure for a given bed configuration. Layers were oriented in repetitive sequences of four equally spaced cardinal directions; the first (bottom) layer was placed lengthwise on the bed and the top layer transversely, *i.e.*, parallel to the fire front. The range of fuel loading for each size class is included in Table I.

Fires were ignited in a 20-cm section of dry fuel of the same geometric construction to which was added 10 to 15 ml of methanol (and approximately 100 g of excelsior



1(A)

1(B)

FIGURE 1 (A) Fuel bed (3 ft wide × 10 ft long) of 1/8-inch square fuel sticks; $\sigma = 12.6\ cm^{-1}$, $\beta = 0.04$, $\delta = 5.08$ cm, $M = 0.019$. (B) Fire 275 in same fuel bed.

TABLE I

Fuel bed properties

Property		Species					
		Poplar	Sugar pine	Douglas-fir	Ponderosa pine	Ponderosa pine	Conifer mix
Number of fires excluding assumed N.B.[a]		127	52	49	69	59	5
Particle thickness	(cm)	0.049	0.159	0.317	0.635	1.27	3.81
	(inches)	0.0194	1/16	1/8	1/4	1/2	1 1/2
σ, Ratio surface/vol. (cm^{-1})		81.3	25.2	12.6	6.3	3.15	1.05
W_0, Fuel load range, kg/m^2	min	0.030	0.27	0.115	0.224	0.448	17.74
	max	1.77	0.85	1.83	3.58	14.32	17.74
β, Packing ratio	min	0.00063	0.0025	0.005	0.01	0.01	0.1
	max	0.08	0.08	0.16	0.16	0.32	0.4
ρ_p, Particle density (kg/m^3)		398	352	450	442	444	388
h, Heat of combustion Total-O_2 bomb, kJ/kg		18,274	19,652	18,703	19,660	19,163	18,907
h_v, Heat of combustion Volatile-gas, kJ/kg		12,306	11,884	10,852	12,265	11,810	11,169
Q_{400}, Heat of pyrolysis, kJ/kg		711	712	781	659	721	649
S_t, Total minerals (fraction)		0.00347	0.00217	0.00109	0.00238	0.00367	0.00399
S_e, Silica free mineral		0.00322	0.00190	0.00097	0.00224	0.00322	0.00375

[a]Note: N.B. = "No Burn." See text footnote for explanation, p. 187.

for the larger sticks). Fires were allowed to run 61 cm in conditioned moist fuel in advance of the 2.44 m test section where experimental measurements were taken.

Thermochemistry

The pertinent thermochemical fuel properties are also included in Table I. For reasons of cost, each different fuel size was milled from a different lot of wood. Only the 0.63 cm and 1.26 cm sizes were from the same species. However, we first required that the ash, or total mineral content, S_t, and the silica-free ash, or "effective" mineral content, S_e, be kept to a minimum. Secondly, fuel lots were chosen for low content of resins, terpenes, tars, and waxes to minimize variability in heat of combustion, h. However, contrary to our intent, there was significant variation in the thermal parameters among the several fuels. This variation is used to infer the relationships developed below.

Concurrent work by Susott (1982a, b) addressed the thermochemistry of heat release and the endothermic heat required for pyrolysis. We have speculated that spreading wildfires are propagated primarily by the flaming combustion of gaseous fuels produced in pyrolysis with the residual glowing combustion of char contributing little to propagation. Extinction of the flames should also be governed by the gaseous fuel's characteristics. The mass ratio of gaseous products to char depends on pyrolysis chemistry and is quite variable in natural forest fuels. The heats of combustion of

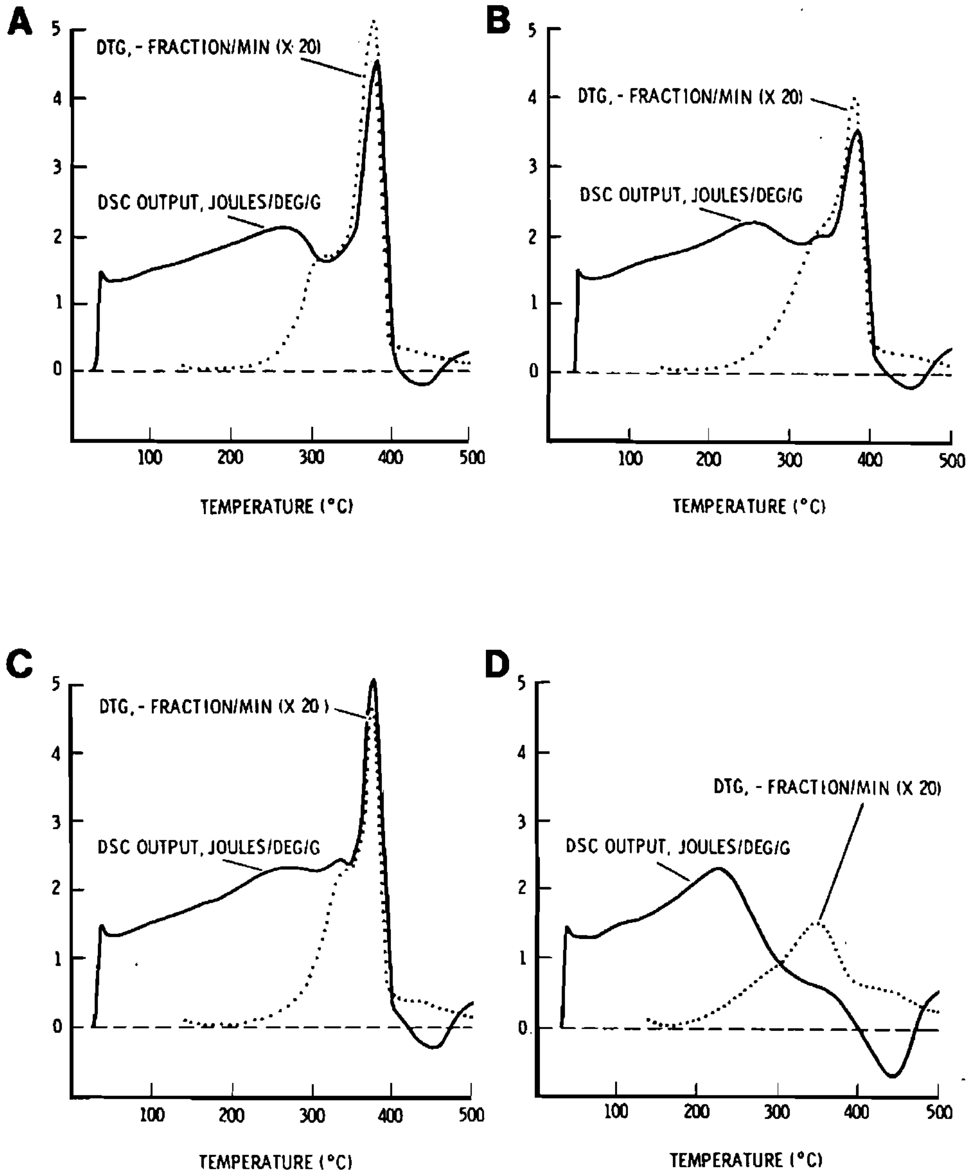


FIGURE 2 DSC and DTG curves from Susott (1982a): (A) poplar excelsior, (B) ponderosa pine heartwood, (C) Douglas-fir heartwood, and (D) Douglas-fir, cubical dry rot.

gaseous vapors, h_v, in dimensions of energy per unit mass of initial dry wood fuel (in Table I) are Susott's experimental results from oxygen depletion measurements in controlled atmospheres. Susott's "DTG" curves† (Figures 2A, B, C) show the mass loss during pyrolysis of three of our fuels. Pyrolytic gasification occurs primarily below 400°C, leaving a much less volatile carbonaceous char. Poplar excelsior produced the least char of the woody fuels in the study and had the most efficient gaseous heat production ratio, $h_v/h=0.67$. Douglas-fir wood invariably produced the greatest residual char and had the smallest ratio, $h_v/h=0.58$. For comparison, the rotten Douglas-fir shown in Figure 2D is lignin-rich and depleted in cellulosics, with $h_v/h=0.37$. This fuel produces large quantities of char and little combustible volatile. It has a marked tendency to burn by glowing combustion and does not easily support a flaming fire front. These observations support our conjecture that the gaseous heat of combustion, h_v, is the primary heat source driving spreading surface fires.

The "DSC" curves‡ of Figure 2 trace the differential net heat input required to raise a mass of woody fuel from ambient temperature through pyrolysis to 400°C. The region of uniform slope below 300°C conforms to Dunlap's (1912) often-quoted specific heat equation for wood.

Because ignition of woody fuel generally occurs in the neighborhood of 320° to 340°C, Dunlap's equation has been used to estimate the "heat of preignition," Q_{ig} (Rothermel, 1972; Frandsen, 1973):

$$Q_{ig} = \int_{\text{Amb.}}^{320^\circ\text{C}} \frac{dQ}{dT}\, dT,$$

where

$$\frac{dQ}{dT} = (0.266+0.00116T\,^\circ\text{C})\,\text{cal/(g }^\circ\text{C)}.$$

We speculate that the endothermic enthalpy for sustained fire spread should include the total heat needed to carry the fuel through pyrolysis, or at least through the gaseous production phase to support flame. For our experimental fuels, pyrolysis is complete remarkably close to 400°C. The values of Q_{400} in Table I are the integrals of Susott's DSC traces from 25°C to 400°C.

OBSERVATIONS AND RESULTS

We observed early in the study that both linear spread rate and mass loss rate followed a regular pattern, varying inversely with fuel particle size and moisture content. The trend was monotone and regular up to some fuel moisture content above which the fires became erratic or went out. This critical moisture content varied widely and was inconsistent with burning rate observations. We observed a qualitative

†DTG is an acronym for Differential Thermogravimetric Analysis by which the weight loss of a heated sample is determined as a function of its temperature.

‡DSC stands for Differential Scanning Calorimetry, which is a standard technique for measuring the specific heat capacity of a material as a function of temperature.

instability in the marginal fires. While no definitive measurements were made, there was a marked tendency for fire intensity and spread rate to oscillate between growth and decay near marginal fuel moisture limits. Thus, early in the study we constructed an arbitrary "Marginal Burning Index" (MBI) that defines the state of flaming combustion and indicates each fire's proximity to extinction. Self-sustaining fires were given MBI values equal to the fraction of bed width with flame base attached to the combustion zone as measured from photographs. A vigorous fire with solid flame front had MBI = 1.0; fires that went out had MBI = 0.

One might expect that, with larger surface areas, $S = \sigma\beta\delta$, fires would be more likely to burn with higher fuel moisture, M. Indeed, as the experimental burning progressed, we found a rule of thumb—that fires rarely burn if

$$M > 0.25 \ln(2\sigma\beta\delta).$$

At the dry limit ($M = 0$) fires seldom burn if $S \leq 0.5$; similarly, at $M = 0.25$ this rule of thumb predicts extinction if $S \leq 1.36$.

A plot of surface area, S, vs. fuel moisture, M, is shown in Figure 3 for the complete data set. For display, all marginal fires with MBI greater than zero and less than one are identified by "X."

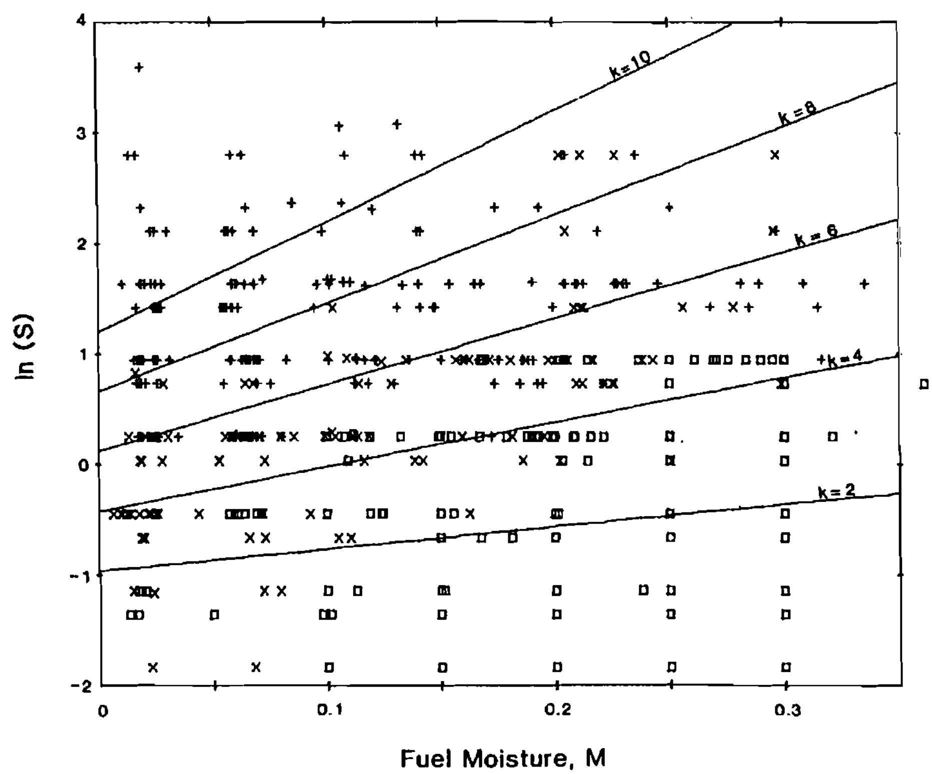


FIGURE 3 Partition of fire states by fuel moisture, M, and logarithm of surface area, $\ln(S)$: + indicates marginal burning index, MBI = 1; × indicates fires with $0 < \text{MBI} < 1$; and □ indicates MBI = 0.

Based on the above empirical observations, an equation of the form

$$k = \frac{\ln(aS)}{b+M}$$

was used to order a partitioning of the fires into groups with approximately equal values of MBI. A histogram, plotted as points in Figure 4, was constructed by ordering and grouping the fires in 20 equal successive increments of k and calculating the average fraction of fireline aflame, $P_f(k)$, in each increment. An arbitrary "S"-shaped function was fitted:

$$P(k) = 1/\{1+\exp[-\pi(k-\bar{k})/(3^{1/2}s)]\},$$

where $\bar{k}$ and s are parameters of the logistic distribution (Johnson and Kotz, 1970). The constants a and b that led to the best fit were found, giving

$$k = \frac{\ln(4.48S)}{0.27+M} \tag{1}$$

and a chi-square test-of-fit statistic for $P(k)$, $\chi^2 = 11.22$ with 19 degrees of freedom ($\bar{k}=4.6$ and $s=1.3$). The chi-squared distribution predicts a value greater than 11.65 with 90 percent probability. This best-fit $P(k)$ has a mean absolute error of 0.037.

Because Eq. (1) partitions the data well, the following rationalization is proposed. The latent heat of fuel moisture is additive to the pyrolysis enthalpy, Q; that is, $(Q+Q_wM)$ is the total endothermic heat input to the fuel. From $Q=Q_{400}$ in Table I and Q_w below, note that $0.25 < Q/Q_w < 0.31$ for our experimental fuels. Next,

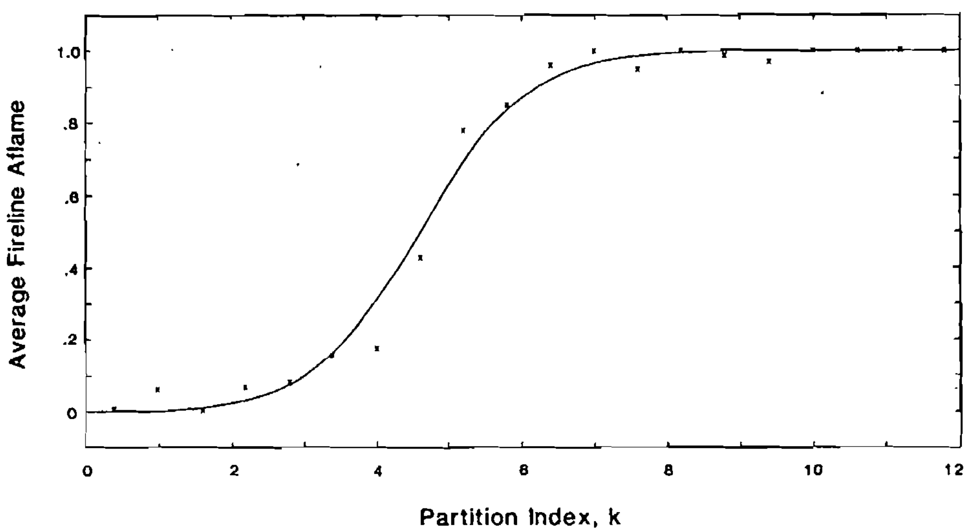


FIGURE 4 Distribution of fire states by index, k.

recall that fuel surface area is associated with energy transport; that is, "heat flux" in dimensions of energy per unit area. And that the driving flux should be proportional to the heat of combustion (for our fuels $4.2 < h_v/Q_w < 4.8$). Thus, we observe that k, Eq. (1), may represent a ratio of energy terms where:

1) $\ln(h_v/Q_w \cdot S)$ measures the fraction of heat released from the flaming zone that is collected by the fuel surface area, S.

2) (Q/Q_w+M) measures the energy required for sustained burning.

3) The energy terms are scaled by the desiccation heat

$$Q_w = 4.186(100-T_a+540)\ \mathrm{J/g},$$

which varies minutely from 2550 J/g with ambient temperature ($21\,°\mathrm{C} < T_a < 35\,°\mathrm{C}$).

Contrary to our initial intentions, Q and h_v vary among the experimental fuels. Thus, Eq. (1) can be reformulated and tested for use as an extinction index,

$$n_x = \frac{\ln(hv/Q_w \cdot S)}{(Q/Q_w+M)}. \tag{2}$$

Large values of n_x imply greater likelihood of good burning when the fuel moisture or the heat of pyrolysis is small and when the heat of combustion or the fractional surface area is large. This formulation also incorporates the effects of minerals, inorganics, and other fuel chemistry differences through the respective heat parameters. The extinction index, n_x, was calculated for each of 470 fires, including 109 "assumed No Burns."†

The index, n_x, and the experimental data are replotted in Figure 5. Not shown are some two dozen fires that fell outside of the designed experiment, with $0.5 < M < 1.2$. Of these, six burned with marginal fire fronts and n_x between 3 and 5, 13 went out with smaller n_x, and the rest burned well with generally higher n_x.

The data were ordered and grouped in equal successive increments of n_x, and three nonexclusive histograms of fire state probabilities as functions of n_x were generated:

1) The average fraction, $P_f(n_x)$, of fire line aflame (Figure 6).

2) The probability $P_0(n_x)$, that a fire does not go out; that is, that it has $\mathrm{MBI} > 0$, (Figure 7).

3) $P_s(n_x)$, the probability that a fire burns steadily with a solid flame front; that is, that it has $\mathrm{MBI} = 1$ (Figure 7).

The histogram of average fraction of fireline aflame is plotted as points in Figure 6 along with the logistic function with $\bar{n} = 4.6$ and $s = 1.3$. The chi-squared test-of-fit statistic for these data is $\chi^2 = 3.3$ with 19 degrees of freedom; the chi-squared distribution predicts a value greater than 6.8 with 99.5 percent probability. The good fit is further supported by a mean absolute error less than 0.034.

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†Of 361 experimental fires, 66 went out. When a particular configuration of loading and fuel moisture did not burn after two trials, the study matrix of loading and moisture was truncated, assuming fires would also go out with higher fuel moisture at that particular loading and with lighter loadings at that fuel moisture. This economic procedure deleted 109 fires from the light loading/wet fuel moisture side of the experimental matrix. All "No Burns," including these 109, were assigned an $\mathrm{MBI} = 0$.

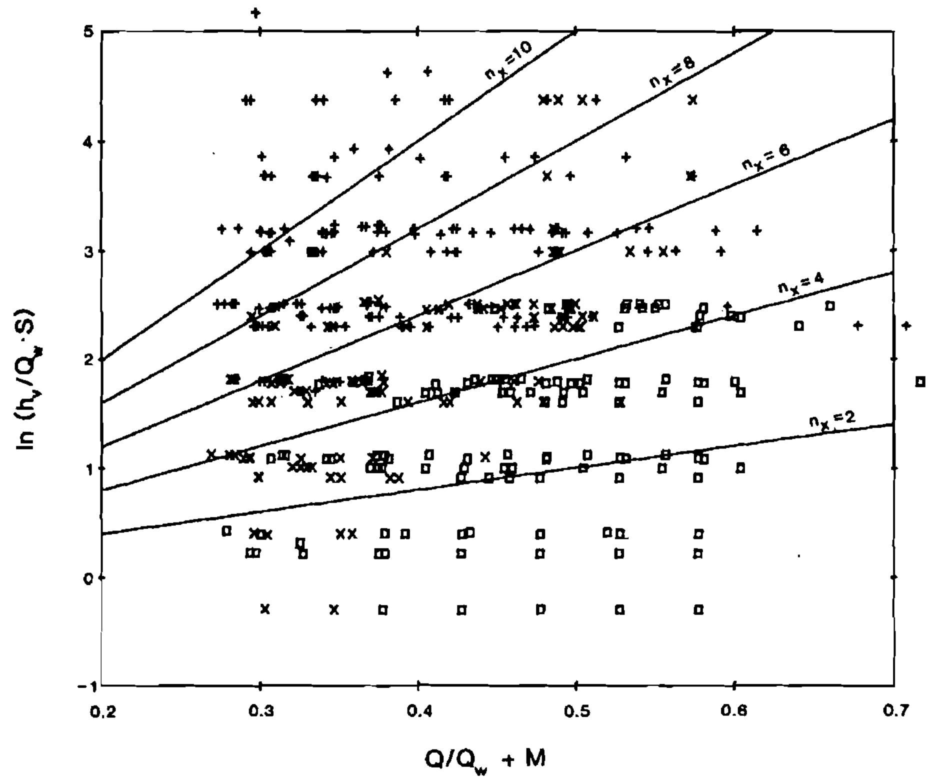

FIGURE 5 Partition of fire states by the extinction index, n_x: + indicates marginal burning index, MBI = 1; × fires with 0<MBI<1; and □ indicates MBI = 0.

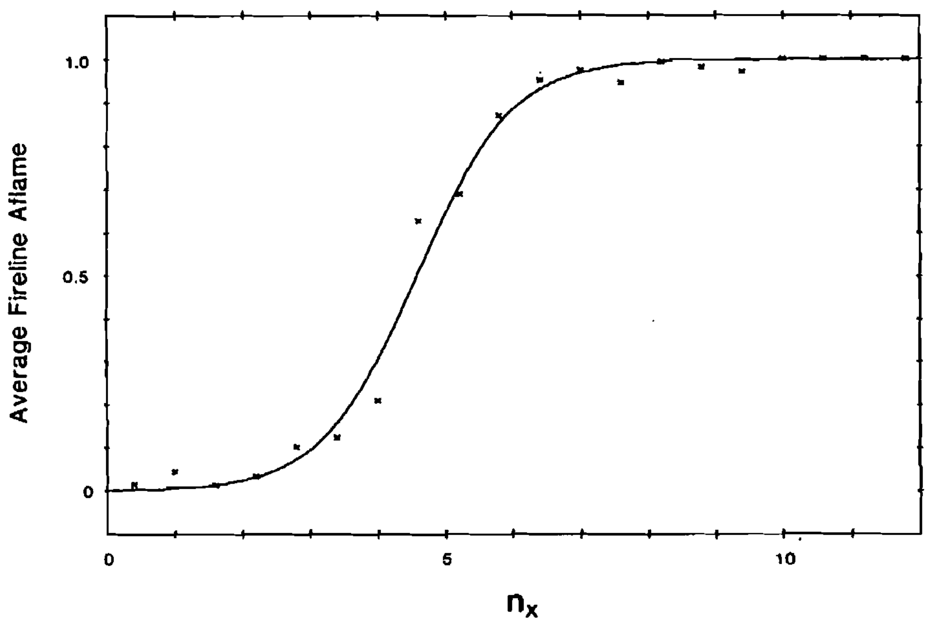

FIGURE 6 Distribution of marginal burning states.

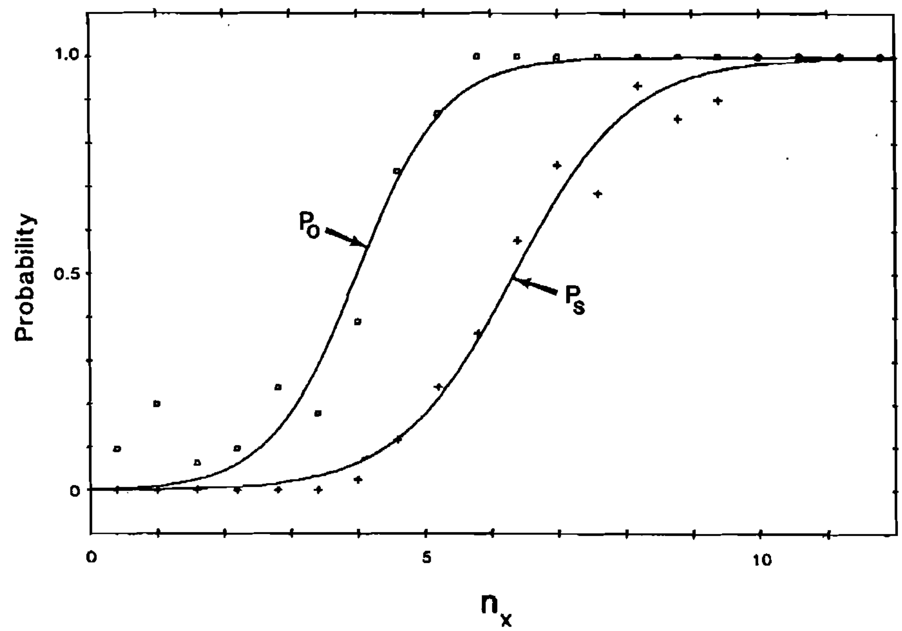

FIGURE 7 Probability distributions of fires in two marginal burning states; P_0—the fires that did not go out; P_s—"steady state" fires with 100 percent contiguous flame front.

Note that the variances for data in Figures 4, 6, and 7 are not uniformly distributed. The biases in the variance distributions have roots in the physical process. With the lighter fuel loadings near extinction (small n_x), the effects of nonuniformities in the fuel bed are more pronounced. At least six of the lightly loaded fuel beds may have burned that would not have been predicted to burn because a few sticks in the bed probably had anomalously high heat content (pitch and resins) or, perhaps, low fuel moisture content. These are the marginal fires shown in the lower left corner in Figures 3 and 5. Such anomalies in individual fuel particles are not critical with heavier loaded fuel beds. We must also acknowledge two observational biases: we tended to assign fractional MBI values to vigorously burning fires whenever the least break occurred in the fire front, and to assign integer multiples of 0.1 to values of MBI.

The analysis using k, Eq. (1), permits descriptions almost as good as those using n_x. The differences are statistically small, given the relatively small variation in the energy parameters h_v and Q for the several fuels. However, a detailed examination of the residuals indicates that the errors from the fit are more uniformly distributed using n_x of Eq. (2). Using k, Eq. (1), without the energy terms, produces consistent under- or over-prediction of fire state, depending on fuel type. This is particularly noticeable with poplar excelsior and the 0.63 cm ponderosa pine (small Q, large h_v) and Douglas-fir (largest Q, smallest h_v) fuels.

Figure 7 plots two fire state distributions—P_0, the fraction of fires that did not go out ($\bar{n}=4.0$, $s=1.2$), and P_s, the fraction of fires with 100 percent contiguous flame front ($\bar{n}=6.35$, $s=1.6$). Here the experimental points are counts of dichotomous events within small increments of n_x, hence the data show more scatter. The goodness of fit test for P_0 gives $\chi^2=7.9$, to be compared to a probability of 97.5 percent that χ^2 is greater than 8.9 for the 19 degrees of freedom. The mean absolute error is less than 0.06. By far the largest errors for the "sustained burning" probability, P_0, are contributed by those few lightly loaded fuel beds mentioned above. The fit for P_s has $\chi^2=4.6$ and a mean absolute error of 0.032. The P_s distribution is not affected by the marginal fires at small n_x but does reflect the bias noted above to assign marginal status (MBI < 1.0) to vigorous fires that exhibited momentary breaks in their flame fronts.

Considerable thought was given to removing the identifiable systematic errors, but we concluded that doing so would not change the results significantly, and that a study of nonuniformities in the respective heat values of natural wildland fuels is appropriate.

The indices s and 0 on the independent variables to follow are associated with the respective P_s and P_0 curves (Figure 7).

We observe that at $P=0.5$ the ratio $n_0/n_s=0.63$ and that $0.58<(n_0/n_s)<0.68$ for $0.1<P<0.9$; that is, for practical purposes and within the observational errors, one might use

$$n_0/n_s \cong 2/3 \quad \text{at any } P. \tag{3}$$

The effects of heat load, Q, and fuel moisture, M, are inferred by letting $h_0S_0=h_sS_s$. Then in the marginal burning region we have by Eqs. (2) and (3)

$$\frac{n_0}{n_s}=\frac{(Q/Q_w+M)_s}{(Q/Q_w+M)_0}\cong 2/3. \tag{4}$$

For constant $Q_0=Q_s\cong 0.3\ Q_w$ for most of our woody fuels,

$$M_0-M_s \cong 0.1+M_0/3.$$

This implies that the width of the marginal zone is equivalent to a fuel moisture difference equal to 10 percent of the oven-dry fuel weight plus a third of the extinction moisture content.

For constant moisture, $M_0=M_s$, from Eq. (4)

$$\frac{Q_0-Q_s}{Q_0}=\frac{1}{3}+\frac{MQ_w}{3Q_0}\cong\frac{1}{3}+M.$$

Thus, in fire situations where $M\leq 0.10$, it follows that 30 to 40 percent increase of Q would change the fire state from the extinction limit to a vigorously burning fire at equal probability levels.

The effects of variation of fuel surface area, S, and heat of combustion, h_v, are estimated by noting that

$$n_s-n_0 = 2.35\pm 0.48 \quad \text{for} \quad 0.1<P<0.9. \tag{5}$$

For constant typical values $Q/Q_w=0.3$ and $M=0.05$ we have from Eqs. (2) and (5)

$$n_s - n_0 = \frac{1}{0.35}\left[\ln\left(\frac{h_v}{Q_w}\cdot S\right)_s - \ln\left(\frac{h_v}{Q_w}\cdot S\right)_0\right] \cong 2.35,$$

or

$$(h_v S)_s \cong 2.3(h_v S)_0.$$

Thus, the difference between fires at the extinction limit, P_0, and vigorous burning, P_s, is equivalent to roughly doubling of the heat of combustion or the fuel surface area.

In the absence of severe chemical treatment (fire retardants, for example), variations by a factor of two in heats of combustion, h_v or h, are not often observed in natural forest fuels. However, the heat of pyrolysis, Q, fuel moisture, M, and fuel surface area, S, of natural wildland fuels will regularly vary in excess of those noted above.

The practical use of this formulation is demonstrated by application to two stylized fuel models currently used in wildland fire management. The fuel parameters given in the caption for Figure 8 represent the fine fuel loading, W_0, and geometric configuration typical of cured short grasses, model NFFL No. 1 (cheatgrass, Idaho fescue, and others), and timber litter, model NFFL No. 9 (conifer needles, packed hardwood leaves). The heat values, h_v and Q, are from personal communications with Susott. So, with the fuel parameters given, the extinction index, n_x, depends only on fuel moisture content. The marginal burning probabilities for the two fuel

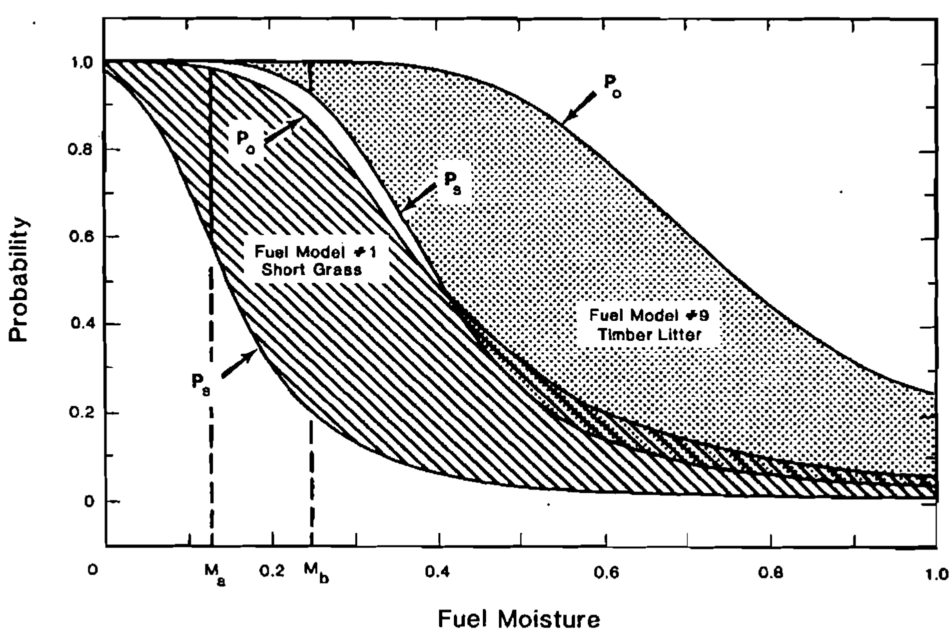

FIGURE 8 Comparisons of marginal burning zones for two stylized fuel models: NFFL No. 1—h_v=8000 J/g, Q=700 J/g, W_0=0.166 kg/m^2, σ=155 cm^{-1}, δ=0.30 m, ρ_p=400 kg/m^3; NFFL No. 9—h_v=9560 J/g, Q=550 J/g, W_0=0.654 kg/m^2, σ=82 cm^{-1}, δ=0.06 m, ρ_p=400 kg/m^3.

models are plotted against fuel moisture in Figure 8. Because n_x varies inversely with fuel moisture, M, the curve giving the probability of steady burning, P_s, lies below the extinction curve, P_0, for each fuel moisture as one would expect.

The fuel moisture, $M_a = 0.12$, shown in Figure 8 represents the generally accepted extinction moisture used in western grass fields and is based on fire behavior expectations of fire managers. This value of extinction moisture for fuel model No. 1, interpreted analytically from Figure 8, provides about 98 percent probability that fires will not go out and between 50 and 60 percent probability that grass fires will have a contiguous fire front. This interpretation of "extinction" means that fires are at the edge between good and marginal burning. The value $M_b = 0.25$ used in the West for timber litter provides even higher probability of good burning, though still close to the marginal state. We must note that, with similar fuels in different situations, fire managers have found it necessary to use extinction moistures larger than 0.4 to provide "acceptable" fire behavior predictions in timber litter.

SUMMARY

The fire extinction phenomenon is shown to be quantifiable, and a methodology is demonstrated here to describe it. Evidence suggests that extinction is primarily an energy balance phenomenon and is not related directly to the combustion power density or burning rate. Thus, the moisture function scaling burning rate in the surface fire spread models should not necessarily predict extinguishment. A definitive exploration requires examination of an extended range of the heat of combustion, h_v, and of pyrolysis, Q. Both values may vary significantly in natural forest fuels.

A foundation is provided to resolve the ambiguous concepts of extinction among wildfire and resource managers. Not only can extinguishment be predicted, but probability distributions are provided by which estimates can be made of the risk that the fire might depart from the predicted behavior. Fire planning and prescriptions can be made more rigorous and the potential range of useful fire intensities broadened by use of these options.

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