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THE RELATIVE IMPORTANCE OF FUELS AND WEATHER ON FIRE BEHAVIOR IN SUBALPINE FORESTS[1]

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Abstract. Surface fire intensity (kilowatts per metre) and crown fire initiation were predicted using Rothermel's 1972 and Van Wagner's 1977 fire models with fuel data from 47 upland subalpine conifer stands varying in age from 22–258 yr and 35 yr of daily weather data (fuel moisture and wind speeds). Rothermel's intensity model was divided into a fuel component variable and weather component variable, which were then used to examine the relative roles of fuel and weather on surface fire intensity (kilowatts per metre). Similar variables were defined in the crown fire initiation model of Van Wagner. Both surface fire intensity and crown fire initiation were strongly related to the weather components and weakly related to the fuel components, due to much greater variability in weather than fuel, and stronger relationship to the fire behavior mechanisms for weather than for fuel. Fire intensity was correlated to annual area burned; large area burned years had higher fire intensity predictions than smaller area burned years. The reason for this difference was attributed directly to the weather variable frequency distribution, which was shifted towards more extreme values in years in which large areas burned. During extreme weather conditions, the relative importance of fuels diminishes since all stands achieve the threshold required to permit crown fire development. This is important since most of the area burned in subalpine forests has historically occurred during very extreme weather (i.e., drought coupled to high winds). The fire behavior relationships predicted in the models support the concept that forest fire behavior is determined primarily by weather variation among years rather than fuel variation associated with stand age.

Key words: Abies lasiocarpa; *crown fire initiation; fire behavior; fire ecology; fire weather; fuel accumulation;* Picea engelmannii; Pinus contorta *var.* latifolia; Populus tremuloides; *Rothermel's fire behavior model; surface fire intensity; Van Wagner's crown fire model.*

INTRODUCTION

Forest fire ecologists have found it difficult to determine the relative importance of fuels or weather on fire behavior (e.g., intensity and crown fire occurrence). On the one hand fuel accumulation (Heinselman 1973, Romme and Knight 1981, Lotan et al. 1985), fuel chemistry (Mutch 1970), crown/understory fuel structure (Despain and Sellers 1977), and community development or aging (Habeck and Mutch 1973, Agee and Huff 1987, Clark 1988, Despain 1990) are often thought to be central in determining fire behavior. On the other hand, weather variability is also thought to be central in determining fire behavior (e.g., Schroeder et al. 1964, Anderson 1968, Finklin 1973, Newark 1975, Alexander et al. 1983, Harrington et al. 1983, Street 1985, Flannigan and Harrington 1986, Stocks and Flannigan 1987, Harrington and Flannigan 1987, Fryer and Johnson 1988, Swetnam and Betancourt 1990, Johnson and Larsen 1991, Johnson and Wowchuk 1993, Swetnam 1993).

The purpose here is to assess the relative roles played by weather (fuel moisture content and wind speed) and fuel (fuel loads, fuel depth, mass density, heat of combustion and surface-area-to-volume ratio) in forest fire behavior. Fuel data collected from 47 subalpine forest stands and weather data from the southern Canadian Rocky Mountains were used to model fire intensity with Rothermel's (1972) surface fire intensity model and crown fire initiation with Van Wagner's (1977) crown fire initiation model. Both models were reorganized by collecting all weather and fuel components into single fuel and weather variables that allowed the determination of the relative contribution of fuel load/crown structure variation and weather variation on surface intensity and crown fire initiation. These variables also allowed quantitative examination of weather-caused variation in fire behavior among years and fuel-caused variation in fire behavior among stands of varying composition and ages.

Fire behavior modelling objectively determines the role of fuels in fire behavior based on the mechanisms of fire behavior. This approach differs from simply accepting the intuitive assumption that increased fuel loads always lead to increased fire behavior potential (e.g., Heinselman 1973). Furthermore, the inclusion of a full range of weather conditions in the fire behavior modelling differs from past approaches in which all fires were modelled under identical weather conditions (Agee and Huff 1987, Keane et al. 1990).

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Our objective is to answer the following three questions:

1) What are the relative roles of fuel and weather in each of surface fire intensity and crown fire initiation?

2) How strongly does fire behavior variation relate to weather variation, when the effects of fuels are excluded from the predictions?

3) How does the potential for high intensity or crown fires relate to fuel variation among stand ages when the effects of weather are excluded from the predictions?

Surface fire intensity model

Rothermel's (1972) model predicts rate of spread (metres per second) and intensity (kilowatts per metre) for surface forest fires. This model is the basis of the National Fire Danger Rating System of the U.S. Forest Service (Bradshaw et al. 1984). Fire spread is idealized as a series of particle ignitions at a rate determined by the interaction of fuels, weather, and slope. Rate of spread (R, metres per second) is determined by dividing the forward heat flux (kilowatts per square metre) by the fuel heat sink (kilojoules per cubic metre):

$$R = \frac{\text{Flux}}{\text{Sink}} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{\text{ig}}}, \tag{1}$$

where

I_R = reaction intensity (kW/m^2)
ξ = propagating flux ratio (dimensionless)
ϕ_w = wind coefficient (dimensionless)
ϕ_s = slope coefficient (dimensionless)
ρ_b = fuel bulk density (kg/m^3)
ϵ = effective heating number (dimensionless)
Q_{ig} = heat of pre-ignition (kJ/kg)

Reaction intensity is the total rate of heat release *per unit area (kilowatts per square metre)*:

$$I_R = \eta_m \eta_s \Gamma h W_n \tag{2}$$

η_m = moisture damping function (dimensionless; The moisture of extinction used in calculating η_m was 0.3.)
η_s = mineral damping function (dimensionless)
Γ = optimum combustion rate (s^{-1})
h = heat of combustion (kJ/kg)
W_n = net fuel load (kg/m^2).

Intensity (I in kilowatts per metre) is the product of rate of spread, reaction intensity, and flame residence time (Albini 1976):

$$I = I_R R t_r, \tag{3}$$

where

I_R = reaction intensity (kW/m^2)
R = rate of spread (m/s)
t_r = flame residence time (s).

Substitution and rearrangement results in the following intensity equation:

$$I = \frac{(\eta_m \eta_s \Gamma h W_n)^2 \xi (1 + \phi_w + \phi_s) t_r}{\rho_b \epsilon Q_{\text{ig}}}. \tag{4}$$

There are two general groups of components: fuel components (variables derived from fuel load, surface-to-volume ratio, fuel depth, mass density, heat of combustion), and environmental components (variables determined from wind speed, moisture content, and slope). These two groups of components were separated to define a fuel variable (F_v) with the dimensions of kilowatts per metre and weather variable (E_v) that when >1 magnifies the rate in F_v and when <1 reduces the rate in F_v. Thus:

$$I = E_v \cdot F_v. \tag{5}$$

The fuel variable (F_v) can be described as the intensity at which a fire would burn if $E_v = 1$, which occurs when there is no wind and fuels are completely dry. The fuel variable included the constant heat of preignition of dry fuels (Q_d: 581 kJ/kg) such that the fuel variable had the same units as intensity (kilowatts per metre):

$$F_v = \frac{(\eta_s \Gamma h W_n)^2 \xi t_r}{\rho_b \epsilon Q_d}. \tag{6}$$

The weather variable (dimensionless) included the effects of fuel moisture content and windspeed (and slope, which is held constant at zero slope) on surface fire intensity:

$$E_v = (\eta_m)^2 (1 + \phi_w + \phi_s) \frac{Q_d}{Q_{\text{ig}}}. \tag{7}$$

Notice that Q_d, for dimensional purposes, appears in both F_v and E_v so that it cancels when multiplied. For E_v to equal 1, the effect of fuel moisture must balance the effects of wind and slope.

Crown fire initiation model

Crown fire initiation involves two steps. First, crown fuel ignition from a burning surface fire must occur. Second, rate of spread must allow direct crown-to-crown fire spread. The first step alone results in a *passive crown fire* with the surface fire largely affecting the spread rate. If both steps are achieved, the fire becomes an *active crown fire* with the burning crowns largely affecting the spread rate; the flaming front is a wall of flames (Van Wagner 1977). Passive crown fire intensity will be somewhat higher than surface fire intensity due to additional consumption of crown fuels; active crown fire intensity is 10–100 times higher than surface fire intensity due to increased fuel consumption and higher spread rates (Van Wagner 1980). This model of crown fire initiation is incorporated in the Canadian Forest Fire Behavior Prediction System (Fire Danger Group 1992).

Crown fuel ignition occurs when the surface fire intensity exceeds the critical surface intensity (I_p: kilowatts per metre):

$$I_p = (0.01zQ_c)^{\frac{3}{2}}, \qquad (8)$$

where

z = lower crown base height (m)
Q_c = heat of crown foliage ignition (kJ/kg).

The value 0.01 is an empirical constant of complex dimensions (cf. Van Wagner 1977). The heat of foliage ignition (Q_c) is assumed to be constant at 3060 kJ/kg, assuming foliage at 100% moisture (dry mass). A minimum critical intensity value is set at 200 kW/m. Eq. 8 states that crowning could occur when intensity is *very* small and crown height is zero. This is, however, not very reasonable, so we have chosen arbitrarily the 1 m crown height which gives an intensity of ≈200 kW/m. Fire intensity predictions are then compared to the critical intensity to predict passive crown fire initiation.

A passive crown (fire initiation) fuel variable (C_p) is defined as:

$$C_p = \frac{F_v}{I_p}, \qquad (9)$$

where

C_p = passive crown fuel variable (dimensionless)
F_v = surface fuel variable (kW/m)
I_p = critical intensity (kW/m).

When $C_p > 1$, surface fuels prduce enough heat to cause crowning.

Crown-to-crown fire spread (active crown fire initiation) is achieved when crown fire rate of spread exceeds the critical rate of spread (R_a: m/s):

$$R_a = \frac{S_0}{\rho_c}, \qquad (10)$$

where

S_0 = critical mass flow rate ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
ρ_c = crown fuel bulk density (kg/m^3).

A critical mass flow rate for conifer forests was empirically determined to be 0.05 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Van Wagner 1977). The critical rate of spread is compared to an estimate of crown fire rate of spread to determine whether the crown fire should be classed as active.

An active crown (fire initiation) fuel variable (C_a) is defined by first converting the critical crown rate of spread (R_a) to a surface rate of spread value. This conversion uses the empirical relationship (Rothermel 1991) between predicted surface fire rate of spread (R, Eq. 1) and active crown fire rate of spread (R_c):

$$\frac{R_c}{3.34} = R. \qquad (11)$$

Since we have no model to predict crown fire rate of spread for comparison to R_a (to determine crowning), we make the assumption that R_a can be substituted for R_c to give an approximate surface fire critical rate of spread that can be compared to R from Rothermel's (1972) model. Using this reasoning, the critical surface rate of spread ($R_a/3.34$) is multiplied by heat of combustion (h) and the net surface fuel load (W_n) to give a second critical intensity value that pertains to active crowning:

$$I_a = \frac{R_a}{3.34} h W_n, \qquad (12)$$

where

I_a = critical intensity for active crowning (kW/m)
R_a = critical rate of spread (m/s)
h = low heat of combustion (12 700 kJ/kg)
W_n = net surface fuel load (kg/m^{-2}) from Rothermel's model.

Note that both I_a and I_p pertain to surface fire conditions and therefore only results from Rothermel's model are required to determine when crowning will occur. Finally, substitution of I_a for I_p in Eq. 9 gives the active crown fuel variable (C_a).

$$C_a = \frac{F_v}{I_a}, \qquad (13)$$

following Van Wagner's (1977) criteria for active crowning.

The initiation of passive or active crown fires (I/I_p or I/I_a) is the appropriate crown fuel variable (C_p or C_a) multiplied by the weather variable (E_v, Eq. 6):

$$C_p E_v = \frac{I}{I_p}; \qquad C_a E_v = \frac{I}{I_a}. \qquad (14)$$

When $I/I_p < 1$, the fire is a surface fire. When $I/I_p \geq 1$ but $I/I_a < 1$, the fire is a passive crown fire. When $I/I_p \geq 1$ and $I/I_a \geq 1$, the fire is an active crown fire.

METHODS

Study area

Forty-seven stands were sampled to obtain estimates of surface and crown fuel properties for input to the fire models. Stands are representative of fuel types that cover >95% of the study area. Stand locations and characteristics (elevation, age, aspect, density, basal area, slope, and overstory tree percentages) are listed in Table 1. Forty-four stands were located in the Kananaskis Valley of southwest Alberta situated in the front and main ranges of the southern Canadian Rocky Mountains, ≈100 km west of Calgary, Alberta. Three additional young stands (22 yr) were sampled in the Vermillion Pass area of Banff and Kootenay National Parks (Table 1). All sampled stands were upland subalpine conifer forests and represent the range of principal vegetation types. These forests consist of *Pinus contorta* Loud. var *latifolia* Engelm., *Picea engelman-*

TABLE 1. Characteristics of 47 forest stands that influence surface and crown fuel properties. Age is time since last fire, density is stems ≥1.5 m tall. Pine, spruce, and fir frequency are given as percentage of total overstory trees.

Stand no.	Elevation (m)	Age (yr)	Aspect (degree)	Density (no./ha)	Basal area (m^2/ha)	Slope (degrees)	Pine (%)	Spruce (%)	Fir (%)
1	1675	101	314	1230	31.2	22	60	17	23
2	1450	125	356	2530	47.4	9	97	3	0
3	1425	81	232	2170	48.7	16	98	2	0
4	1575	54	0	7230	40.3	0	100	0	0
5	1575	70	0	3770	55.1	5	100	0	0
6	1600	70	100	3330	47.1	8	97	3	0
7	1650	109	60	1070	92.5	15	16	84	0
8	1750	258	120	1900	74.6	25	45	43	12
9	1475	54	300	2100	33.5	21	100	0	0
10	1450	54	206	3130	43.6	7	100	0	0
11	1575	99	0	1730	74.3	5	100	0	0
12	1625	202	320	1270	55.8	13	9	41	50
13	1550	109	264	730	22.6	12	67	33	0
14	1775	216	360	730	43.8	21	0	53	47
15	2250	211	57	1670	60.7	22	0	68	32
16	1500	99	0	1970	55.5	6	98	0	0
17	1925	224	96	1330	48.9	27	20	30	50
18	1725	120	68	2000	47.8	27	20	60	20
19	1700	57	0	1770	17.8	2	87	13	0
20	2025	112	45	1700	25.1	23	94	6	0
21	1825	70	246	1470	33.1	5	100	0	0
22	2000	132	212	1800	72.6	16	0	45	55
23	1700	86	0	3900	58.6	10	100	0	0
24	1650	100	0	870	46.2	1	42	59	0
25	1650	100	200	7000	46.5	8	100	0	0
26	1825	86	216	1400	45.3	15	74	26	0
27	1425	125	320	1570	34.3	5	100	0	0
28	1825	86	234	600	30.1	16	56	39	6
29	1700	57	0	1870	40.0	3	100	0	0
30	1750	132	0	1900	42.0	3	4	63	33
31	2000	150	0	1870	66.9	4	14	89	0
32	1575	220	320	900	57.2	13	4	81	15
33	1375	125	290	1930	44.6	8	100	0	0
34	2400	212	216	1570	95.7	9	5	37	59
35	2175	23	250	2270	8.4	26	100	0	0
36	2175	23	192	230	3.6	29	0	100	0
37	2000	120	140	500	18.8	36	53	27	20
38	1875	92	230	1800	37.0	19	8	82	10
39	1600	120	290	1070	31.0	8	85	11	0
40	1750	124	70	2270	49.8	33	2	66	32
41	1600	22	180	0	2.3	34	100	0	0
42	1600	22	105	0	8.6	18	100	0	0
43	1600	22	0	1870	38.9	6	100	0	0
44	1725	132	0	2930	37.6	7	86	14	0
45	1425	81	100	1500	54.2	7	89	11	0
46	1900	216	132	630	59.9	12	0	59	41
47	1650	202	200	1530	75.5	6	68	32	0

nii Parry ex. Engelm., *Abies lasiocarpa* (Hook.) Nutt., and occasionally *Populus tremuloides* Michx. Most conifer stands in the Kananaskis Valley originate from stand-replacing fire disturbances with a fire cycle of 90 yr (Johnson and Larsen 1991), which result in even-aged fire cohorts of *Pinus contorta* or *Picea engelmannii* trees (Johnson and Fryer 1989). The main lightning fire season (area burned) is July and August. In the last 100 yr, fires >400 ha have almost always been caused by lightning (E. A. Johnson and D. R. Wowchuk, *personal communication*).

Fuel inventory and calculations

Surface fuels were measured by methods of McRae et al. (1979) and Brown et al. (1982) along an equilateral triangle with each side 30 m long (90 m total). *Downed wood fuels* were measured by the line intersect technique (Van Wagner 1968). *Shrub, herb, litter, and moss fuels* were measured in quadrats evenly spaced along the transect. Shrubs (by species) had basal diameter measured in nine (1 m^2) quadrats at 10-m intervals. Litter (L layer) and moss depth, herbaceous plant cover, height, and percentage dead were measured in 27 (0.06 m^2) quadrats at 3 m intervals. Fuel loads were calculated from equations determined from fuel samples collected in the Kananaskis Valley (Appendix 1).

The surface fuel components were divided into the following classes: litter, moss/lichen, live herbs, live shrubs, 1-h time-lag fuels (dead wood, dead shrub wood, dead herbs), 10- and 100-h fuels (dead wood and dead shrub wood). Each fuel class was assigned a standard surface-area-to-volume ratio (cf. Brown and Bevins 1986) and a fuel depth based on field estimates (see Appendix).

Crown fuels were measured in three 100-m^2 quadrats per stand by measuring each tree's diameter at breast height (dbh). Crown foliage biomass was predicted from dbh using published empirical equations (see Appendix 1). Crown top and base heights were measured on a 2 m wide strip transect until three dominant and three subdominant trees per species were measured. Mean crown heights (top and base) were determined by weighting tree heights of dominant and subdominant trees by population densities in the three quadrats. Fuel loads were divided by crown depth to give the crown bulk density.

Weather data source and calculations

Daily noon weather data (temperature, precipitation, wind speed, and relative humidity) for 1954–1988 were obtained from the Atmospheric Environment Service for Banff, Alberta and represented subalpine fire-weather for the southern Canadian Rockies (cf. Johnson and Wowchuk 1993). July and August were chosen since these are the largest area burned months (Johnson and Wowchuk 1993). Herb, shrub, and dead wood moisture contents were predicted for each stand from National Fire Danger Rating System equations (Bradshaw et al. 1984). The conversion from moisture contents to Q_{ig} and η_m (Eqs. 1 and 2) is accomplished via equations from Rothermel (1972). Litter moisture was predicted from the Fine Fuel Moisture Code (Van Wagner 1987). Lichen moisture was predicted from equations by Pech (1989). As no equations were available for moss, the lichen moisture was used as an approximation since moss is also a passive (i.e., no cuticle) fuel.

Surface fire intensity analyses

1. *Relative importance of fuel and weather.*—Surface fire intensity predictions from Rothermel's (1972) model (Eq. 4) were made using the fuel loads from 47 forest stands and the weather representing *each day in July and August for the 35-yr* weather record. Log transformation of the rearranged model (Eq. 5) would give $\log(I) = \log(F_v) + \log(E_v)$. However, in order to determine the relative importance of the fuel (F_v) and weather (E_v) variables, the following model was used:

$$\log(I) = b_1'\log(F_v) + b_2'\log(E_v), \qquad (15)$$

where

I = intensity
F_v = fuel variable
E_v = weather variable
b_1' = standardized partial regression coefficients.

In this model, the sum of squares of the logarithm of intensity was partitioned between the two variables such that the standardized partial regression coefficients $b_1' = b_1(\text{SS}_{\log F_v}/\text{SS}_{\log I})$ and $b_2' = b_2(\text{SS}_{\log E_v}/\text{SS}_{\log I})$ provide an estimate of the proportional change in variation in intensity produced *by a unit change in variance* of either the fuel or weather variable where b_i is the partial regression coefficient (see Snedecor and Cochran 1967: 398 ff.). The relative size of these standardized partial regression coefficients indicates how strongly each variable (fuel or weather) influences surface fire intensity.

2. *Comparison between large and small fire years.*—The amount of variation in fire intensity prediction in relation to large and small area burned years was tested using the following ANOVA model:

$$\log(I) = b_0 + b_1 \text{ group} + b_2 \text{ year(group)} \qquad (16)$$

where

I = intensity predictions from Rothermel's model
group = large or small area burned years (1 or 0)
year(group) = year nested within groups.

Large area burned years had $>$50–100 ha of forested area burned by lightning fires in the combined areas of Kootenay, Yoho, and Banff National Parks, and the Bow-Crow Forest of Alberta for the period 1954–1988 (Johnson and Wowchuk 1993). The hypothesis tested was that large area burned years have higher fire intensity predictions throughout the entire July–August period than do small area burned years.

Crown fire initiation analyses

1. *Relative importance of fuels and weather.*—The relative importance of the crown fuel and weather variables in crown fire initiation was determined using crown fire initiation predictions from the 47 sampled stands and 1968 summer weather. The year 1968 was chosen because it had the largest areas burned and thus represented a wide range of fire weather conditions from fire-free to actual crown fire conditions. Fire type (crown vs. surface fire) was related to the crown fuel variables (C_p: passive crown fuel variable, and C_a: active crown fuel variable) and weather variable (E_v) using multiple logistic regression:

$$\text{Type} = \frac{\exp[b_0 + b_1(C_x) + b_2(E_v)]}{1 + \exp[b_0 + b_1(C_x) + b_2(E_v)]}, \qquad (17)$$

where

Type = crown fire type probability
C_x = passive or active crown fuel variable
E_v = weather variable

The initiation of passive crown fires from surface fires was related to C_p and E_v. The initiation of active crown fires was examined in relation to C_a and E_v in two ways: first by excluding all surface fire predictions from the

TABLE 2. Standardized logarithmic multiple regression analysis of the relative importance of surface fuel (F_v) and weather (E_v) on surface fire intensity (I).*

Variable	Std. coeff.	t	P
Log(E_v)	0.9121	31 000	<0.001
Log(F_v)	0.3883	31 000	<0.001

Source	SS	df	MS	F	P
Regression	257 276.5	2	128 638.2	0.565E+09	<0.001
Log(E_v)	213 897.8	1	213 897.8	0.940E+09	<0.001
Log(F_v)	38 768.6	1	38 768.6	0.170E+09	<0.001
Residual	16.828	73981	0.0002		

* Sample size ($N = 73984$) is not all days but only those with intensity >0. The coefficients here have been standardized; actual coefficients were both equal to one. $R^2 = 1.00$; $\text{SE}_e = 0.0151$.

data, and second by including them. The first test examined only the transition from passive to active crown fire, whereas the second test examined the entire transition from surface to passive to active crown fire as a single step. The relative importance of crown fuel and weather variables was determined from the *standardized* partial logistic regression coefficients that indicated the relative effect of each variable on each initiation examined. The weather variable is not a time series in the equation since the fire fuel moisture and wind speed are not highly autocorrelated from one day to the next.

2. *Crown fire initiation: graphical model.*—A logarithmic contour plot of the crown fire initiation relationship of Eq. 13 was defined with the logarithm of the weather variable on the abscissa and crown fuel variable on the ordinate. This graph, by definition, had a crown fire initiation line running along the diagonal from upper left to lower right, which represented the point of passive or active crown fire initiation for each combination of the crown fuel and weather variables. Upper and lower boundary values of the passive and active crown fuel variables (C_p and C_a) were plotted on the ordinate and interpolated through the transition line to predict the weather variable ranges at which crowning will: (a) occur in no stands; (b) occur in some stands; or (c) occur in all stands. The values chosen to represent the upper and lower boundaries of stand conditions were the 10th and 90th percentiles of each of the variables C_p and C_a. These percentiles were chosen so that extremely high or low conditions that do not commonly occur in forest stands would not bias the results away from the central tendency of conditions. The percentages of days in those types were then compared between large and small area burned years.

Weather variable frequencies in large and small fire years

The weather variable (E_v) was predicted for all stands for July and August 1954–1988 for large and small area burned years. The weather variable values were fitted to a negative exponential density distribution of the form: percent frequency = $\alpha \exp(-\beta E_v)$. The distributions of large and small area burned years were then compared using a heterogeneous slope t test (Zar 1984). This analysis tested whether there were differences in the frequency distribution of weather variable values between large and small area burned years.

Fuel variables vs. stand age

Regression analysis was used to determine whether there was an increase in any of the three fuel variables with time-since-fire age, as would be expected if the forest's potential fire intensity was changing with forest age. The regression model used was a log-log transformed model, since this stabilized the variances across the range of ages and best met the linear model assumption of regression. The fuel variables were tested in two sets: (a) all stands; and (b) all stands over 25 yr of age. This examined whether the young stands had a significant influence on the observed trends. Twenty-five years was chosen since this is the approximate age at which crown closure occurred in the observed stands.

RESULTS

Surface fire intensity analysis

1. *Relative importance of fuel and weather.*—The standardized partial regression coefficients give the relative importance of the weather and fuel variability by estimating the change in intensity (as the proportion of the variation in intensity) produced by a unit change in variance of the weather or fuel variable. The weather variable had a standardized partial regression coefficient of 0.91 and explained 83% of the regression sum of squares ($\text{SS}_{\log E_v}/\text{SS}_{\text{reg}}$) (Table 2). The fuel variable's standardized coefficient was 0.39 and this variable explained 15% of the model sum of squares. Therefore variation in surface fire intensity was determined more by the weather variable than the fuel variable.

2. *Comparison between large and small area burned years.*—Mean fire intensity predictions for all days in large area burned years were different from all days in small area burned years (Table 3, $P < 0.001$), although there was also significant variation between the means for individual years within each group ($P < 0.001$). The mean intensities (± standard deviations) were 41.4 ± 17.26 kW/m in small area burned years, and 105.8

TABLE 3. Analysis of variance comparison of intensity predictions between large and small area burned years. Intensity was predicted from Rothermel's model for 47 forest stands and 35 yr of summer weather (1 July–31 August) data. Years were nested within the large and small area burned categories to account for variation in individual years. Intensity was log-transformed (log intensity + 1).

Source	df	MS	F	P
Group*	1	17 728.1	2246.5	<0.001
Year(group)†	33	1087.7	137.8	<0.001
Error	101 955	7.8		

* Group = Large or small area burned years.

† Year(group) = Years nested within groups.

± 15.16 kW/m in large area burned years. Means for each individual year, with large and small area burned categories indicated, are shown in Fig. 1. The mean intensity predictions do not indicate how fires would burn, since they included low intensity days as well as high days. Instead the means indicated that large area burned years generally had more days when high intensity fires could have occurred than small area burned years.

Crown fire initiation analyses

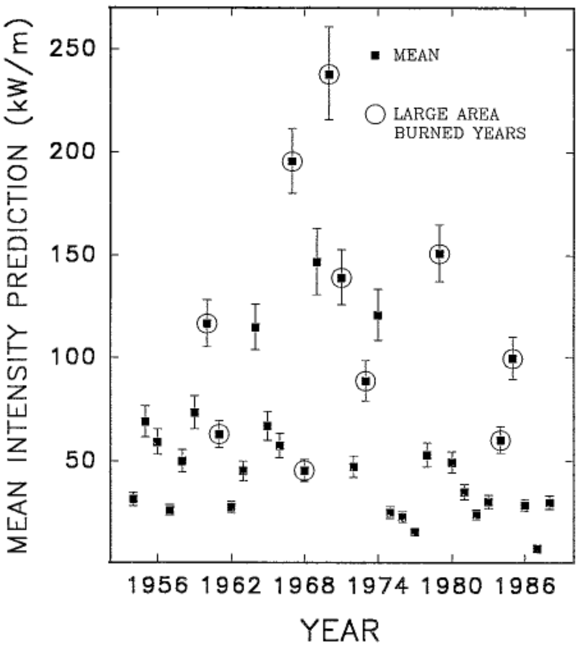

FIG. 1. Mean intensity predictions with 95% confidence limits for each summer fire season (1 July–31 August) from 1954–1988. Large area burned years are circled to demonstrate the difference between the categories. Means and confidence limits were calculated from log-transformed values (log intensity + 1), used in the analysis of variance, and were then transformed back to the original scale, resulting in asymmetric confidence limits.

TABLE 4. Multiple logistic regression results for crown fire initiation vs. crown fuel and weather variables for 47 stands and weather data from 1968 for (a) passive crown fires vs. surface fires, (b) active crown fires vs. passive crown fires only, (c) active crown fires vs. surface or passive crown fires.

	Std. coef.	Wald χ^2	P
a) Passive Initiation: $n = 2914$,* −2LL† $\chi^2 = 1684$, $P < 0.0001$			
Intercept	0.0	893.87	0.0001
C_p	−0.38	196.24	0.0001
E_v	−1.80	611.20	0.0001
b) Active Initiation: $n = 992$, −2LL $\chi^2 = 842$, $P = 0.0001$			
Intercept	0.0	106.26	0.0001
C_a	−4.51	107.87	0.0001
E_v	−2.95	75.50	0.0001
c) Active Initiation: $n = 2914$, −2LL $\chi^2 = 1715$, $P < 0.0001$			
Intercept	0.0	701.85	0.0001
C_a	−0.39	136.80	0.0001
E_v	−1.85	606.15	0.0001

* n = number of samples: days when passive or active crown fire initiation was possible, multiplied by the 47 tree stands.

† −2LL = negative two log likelihood.

1. *Relative importance of fuel and weather.*—Crown fire initiation (determined from the models) was also primarily influenced by weather rather than fuels (Table 4). In the passive crown fire initiation test, standardized slopes were −1.80 for the weather variable and −0.38 for the passive crown fuel variable. In the first active crown fire initiation test (for only those stands that achieved passive crowning), standardized slopes were −4.51 for the active crown fuel variable and −2.95 for the weather variable. However, most stands that achieved passive crown fire criteria also achieved active crown fire status. For the entire transition from surface to active crown fires, the standardized coefficients were −1.85 for the weather variable and −0.39 for the fuel variable. Thus, the first step (crown ignition) is mainly dependent on weather, and the second step (crown spread) slightly more dependent on fuels. However, the entire transition is mainly dependent on weather.

2. *Crown fire initiation: graphical model.*—The crown fire initiation graph (Fig. 2) demonstrated three weather variable ranges: (a) the range for which the models predict only surface fires among the sampled forest stands; (b) the range for which the models predict crown fires for every forest stand; (c) the transitional range between the two. Fig. 2A shows the weather variable ranges that correspond to the 10th and 90th percentiles of the passive crown fuel values; Fig. 2B shows the ranges for the 10th and 90th percentiles of the active crown fuel values. The surface fire weather variable range was >0 to 1, since the passive crown transition occurred in all stands >1. The transition weather range was 1 to 10, and the crown fire range was >10. The ranges were very similar for both active and passive fuel values. The crown fire weather range shows that, once these weather values are achieved, all

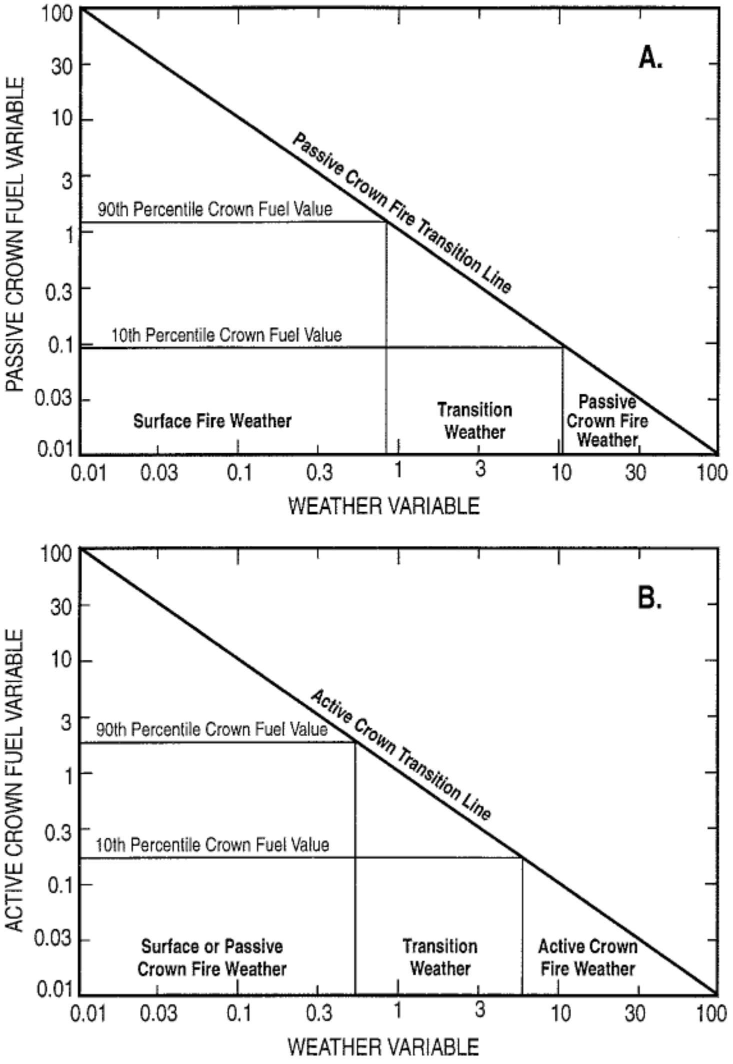

FIG. 2. Crown fire initiation chart which demonstrates the weather and crown fuel variables at which conifer forest stands will achieve passive or active crown fire initiation according to Eq. 17 of the crown fire model. (A) Passive crown fuel variable (C_p) 10th and 90th percentile values, and (B) active crown fuel variable (C_a) 10th and 90th percentile values. The three resultant weather variable ranges were defined as the surface fire zone, crown fire zone, and the transition zone.

stands will support crown fires. Thus, fuels play no further role in determining whether or not a stand will crown. Fuels only play a significant role within the transition range. Although not shown on the graphs, the weather value of 0 is important. It defined conditions in which fire intensity would be zero, and thus no fires would be able to occur.

Weather variable frequencies in large and small fire years

For all years combined the weather variable was found to decline exponentially (% frequency = $0.433(E_v)^{-0.566}$, $r^2 = 0.98$, $P < 0.01$). The negative exponential relationship meant that most days had low weather variable values (from 0–1), while there were very few extreme weather (>10) days. Large and small area burned years had significantly different weather variable distributions (Fig. 3, $t = 2.99$, $P < 0.05$). Both large and small area burned years had similar numbers of days of low to moderate weather values, but high to extreme values were progressively more common in large area burned years.

Based on the crown fire initiation graph and the frequency of weather values, for the average summer 18.5% of days would allow no fires ($E_v = 0$), 45.6% of days would allow only surface fires ($0 < E_v < 1$), 35.7% of days would support a mix of surface and crown types ($1 \leq E_v < 10$) (days in the transition weather range), while only 0.2% of days would support crown fires in all stands ($E_v > 10$). Although the fewest days are accounted for in the crown fire weather ($E_v > 10$) range, this is where the greatest difference between

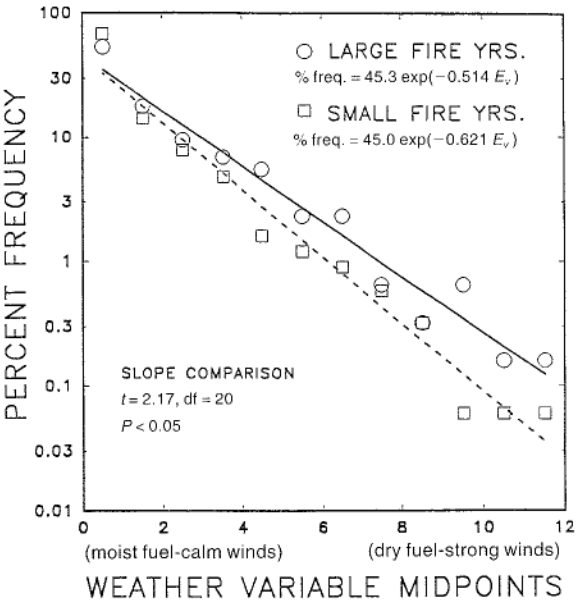

FIG. 3. Weather variable frequency distributions (percent frequency of days with weather values within each range class, vs. weather variable midpoints of the range classes) for large and small area burned years with predicted regression lines. Note that the y axis was log-transformed, indicating that these distributions were negative exponentials. Slopes were compared using t tests following Zar (1984).

large and small area burned years occurs. Large area burned years had three times as many days in the crown fire range compared to small area burned years. Thus, the weather variable distribution was shifted in large area burned years such that a few days in those years are much more likely to sustain high intensity/crown fires.

Fuel variables vs. stand age

Regression coefficients between each fuel variable and stand age are presented in Table 5 for all stands and for only stands >25 yr of age. The surface fuel variable (F_v) was unrelated to age for stands >25 yr (Fig. 4A). However, among all stands there was a positive relationship (Table 5) with age, which explains 18% of the regression sum of squares. The difference between the two results shows that there is an initial increase in the fuel variable, but this does not continue after 25 yr. There is, however, substantial scatter of points in the older stands that reflects the very wide range of surface fuel differences in the stands. This scatter was unrelated to any of the other stand features listed in Table 1.

The passive crown fuel variable was unrelated to age if all ages were examined or if stands <25 yr of age were removed (Table 5; Fig. 4B). However, the active crown fuel variable was very low in the stands <25 yr of age (Fig. 4C), so that a significant relationship to age was seen if these were included, but no relationship was found in stands >25 yr. The five stands <25 yr of age differed from the others in having very low crown fuel loads and thus very high critical rates of spread (and low active crown fuel variable values). Thus, passive crowning is unrelated to age, while active crowning is less likely in stands <25 yr of age.

TABLE 5. Partial regression coefficients of surface and crown fuel variables (log-transformed) vs. stand age (log-transformed) in two sets: all stands, and stands with trees >25 yr old removed.

	Years	Coeff.	No. stands	t	P
$\log(F_v)$	All	0.47	47	3.136	<0.005
$\log(F_v)$	>25 yr removed	0.10	42	0.537	>0.5
$\log(C_p)$	All	−0.29	47	−1.065	>0.25
$\log(C_p)$	>25 yr removed	0.21	42	0.581	>0.5
$\log(C_a)$	All	0.97	47	5.194	<0.001
$\log(C_a)$	>25 yr removed	0.33	42	1.393	>0.1

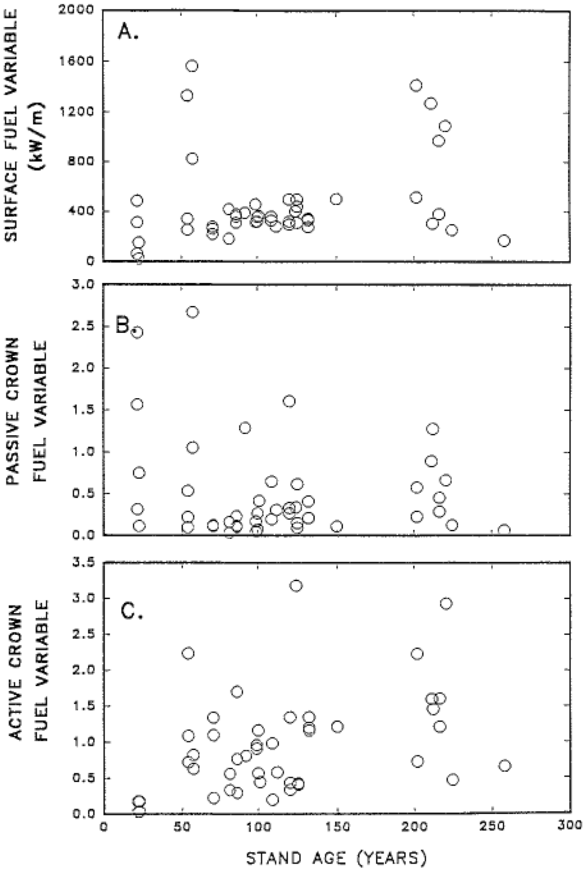

FIG. 4. Surface and crown fuel variables plotted against stand age. (A) Surface fuel variable (F_v), (B) passive crown fuel variable (C_p) (dimensionless), (C) active crown fuel variable (C_a) (dimensionless).

DISCUSSION

Predicted forest fire behavior in the subalpine forests of the southern Canadian Rocky Mountains is more strongly related to weather variation (over time) than to fuel variation (among stands). The weather variable set the lower threshold below which surface fire cannot occur (i.e., when the value of the weather variable was zero, conditions were too wet for burning to occur in the models). The weather also set the upper threshold beyond which only crown fires occur. In comparison, the fuel variable was always >zero and therefore could not be controlling whether or not fires could burn. Of course, fuels play an important role in fire behavior—this is not disputed. However, the range of fuels among sampled stands in this study was overwhelmed by the variation in weather, such that in a relative sense, fuel moisture and wind speed were the main features controlling variation in fire behavior.

Under extreme weather conditions, the crown fire model predicts that all stands will exhibit crown fires, regardless of the range of fuel conditions. Only in moderate weather will differences in crowning behavior due to fuels be achieved. Furthermore, most large fires occur in years when there are elevated weather variable values. Since fires in those years account for >99% of the area burned, it is unlikely that fuel variation is strongly influencing fire behavior over the entire forested landscape.

Two basic reasons explain why weather is more important than fuel in fire behavior. First, weather is more strongly associated with the mechanisms of fire behavior than fuel: wind speed strongly affects heat transfer rates by increasing both radiative heat transfer (due to flame tilt) and convective heat transfer; fuel combustibility and heat loss rates depend strongly on fuel moisture content; fuel primarily acts as the burn substrate, providing the heat of combustion for the fire (Rothermel 1972). Second, as shown by the values of the standardized partial regression coefficients for the weather (0.91) and fuel (0.39) variables, the weather variable explained 83% of the variance in intensity while the fuel variable explained only 15%. The explanation for the differences in these standardized coefficients is the fact that fire weather is much more variable over time than fuels are among stands. Surface fuel moisture contents may range from ≈5 to >100% (based on dry mass). Wind speed may range from 0 to >100 km/h. These changes can occur over very short time scales, hours to weeks, due to very fast drying rates of fine fuels and highly variable wind speeds. Thus, the range of weather effects on fire behavior potential is quite great. High variability and strong ties to the fire behavior mechanisms in the models combine so that the weather variable (and thus variation in intensity due to weather) ranges over four orders of magnitude (i.e., 10^4).

Fuel variation within stands occurs over such long time scales (years to decades) that it may be ignored at any individual time period (see Van Wagner 1965). The only important variation in fuel loads exists among stands of differing forest type and history (stand age, developmental stage, past disturbance, etc.). However, the amount of variation among stands is still generally low. For the stands in this study, total burnable fuel loads ranged from 0.5 to 3.6 kg/m^2, which amounts to only a sevenfold difference among stands. These fuel loads are not substantially different from ones in similar *Pinus contorta* forests (e.g., Kiil 1968, Muraro 1971, Lawson 1973, Fischer 1981, Romme 1982, Brown and Bevins 1986). Often larger biomass components such as the duff layer and large logs are observed to vary over a much greater range than the smaller fuels (Fischer 1981, Romme 1982, Lotan et al. 1985, Spies et al. 1988), but large fuel components play a lesser role in the active spread rate and intensity at the fire front than fine dead or cured fuels (Rothermel 1972, Brown 1983). However, it can be argued that large fuels (particularly the duff layer) do play a much greater role in high intensity (crown) fires. Rothermel (1993) points out that Albini's (1976) burnout model, which could increase reaction intensity 2–3 fold within the 1st min of combustion at the flaming front, is one method to incorporate this effect. This higher reaction intensity could increase the role of larger fuels in surface/transition weather (Fig. 2) conditions such that high fuel loading stands more easily achieve passive or active crown fires. Since duff is not incorporated in this study, we have a conservative estimate of high-intensity fires.

The lower variability of fuel loads and weaker relationships to intensity in the models combined so that there was less than two orders of magnitude between the highest and lowest fuel variables among stands in this study. Therefore, fuel variation among stands may result in up to two orders of magnitude variation in the fire intensities. Although this may seem like a large amount of variation attributed to fuels, it is comparable to 1% of the variation in intensity due to the weather.

Why are fuels thought to be so important to fire behavior? The first reason is the belief that fire behavior is mainly an attribute of the plant community. Mutch (1970) gave a clear statement of this hypothesis. Thus, as plant communities change due to growth of individuals, senescence, etc., the fire behavior is thought to change concurrently. This appears to be the main reason behind the notion that older forests are more likely to sustain a high-intensity fire than a younger forest (e.g., Heinselman 1973). It has also led to the notion that fire suppression in natural reserves such as Yellowstone National Park has resulted in unnatural fuel accumulation that will (or did) result in more catastrophic fires (e.g., Romme and Despain 1989). These arguments lack a fire behavior mechanism by which community change should affect fires. Fire behavior depends on only certain fuel structural components that change over time, not on all fuels and all structural changes.

The second reason that some ecologists believe that fuels are so important comes from a misunderstanding of the pattern of fire occurrence. Studies must distinguish between fires burning during marginal or extreme fire weather (small and large area burned years). In marginal fire weather, the role of fuel differences among forest stands will appear to be more important. For example, a crown fire burning in a spruce woodland with a low crown base may change to a surface fire in a lodgepole pine forest because of the pines' elevated crown base (e.g., Despain and Sellers 1977). Under these conditions, different fuel types can show differences in fire behavior and area burned. However, the total area burned (the ecologically meaningful variable) by fires in marginal weather will be small because the fires will be more easily extinguished (by rain or by man) and have lower rates of spread than fires during extreme weather conditions. In extreme weather, areas burned will be much larger and the role of fuel much smaller.

CONCLUSION

Rothermel's (1972) fire behavior model, along with empirical fuel and weather data for 35 yr, predicts that variation in surface fire intensity in subalpine forest stands in the southern Canadian Rockies would be primarily determined by weather (fuel moisture and wind speed) rather than by variation due to fuels. Fires that occur in low to moderate weather conditions remain small surface fires or intermittent crown fires, while those in extreme conditions often become large crown fires. In these weather conditions, crown fires will initiate from all surface fires largely independent of fuel conditions or stand type. Extreme weather occurs most commonly in large area burned years compared to small area burned years.

Fire behavior should be directly related to regional patterns of weather that influence fuel moisture contents and wind speeds, rather than ecosystem properties that affect fuel loads and structure. Thus, fire behavior should not vary strongly with stand age or with species composition types. Fire behavior research should be directed toward understanding weather phenomena and their relationship to fire behavior events as well as to regional fire patterns.

The lack of any strong relationships between fuel variables (and thus fire behavior) and stand age, and the overall larger importance of weather than fuel in fire behavior, support the assumption of independence of the hazard of burning to stand age found in the negative exponential model of fire frequencies (Johnson et al. 1990*b*, Masters 1990, Johnson and Larsen 1991).

The lack of a significant fuel importance is also consistent with the relationship of large area burned years in the southern Canadian Rockies with mid-tropospheric anomalies, i.e., surface-blocking higher pressure systems (Johnson and Wowchuk 1993).

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APPENDIX

Methods and equations for calculating surface fuels (downed wood fuels, shrubs, herbs, litter, and moss) and crown fuels, together with the fuel characteristics used in the surface fire intensity and crown fire initiation models. Fuel load calculations for downed wood inventoried by the line intersect method was done using the following equation (Van Wagner 1968).

$$W = \frac{\rho \pi^2 \sum d^2}{8L},$$

where

W = fuel load (kg/m^2)
ρ = mass density (kg/m^3)
d = diameter (m)
L = transect length (m)

The equation required wood mass density and quadratic mean diameters for each size class and species of wood. Wood samples were collected throughout Kananaskis and measured for diameter and mass density (cf. ASTM 1988). Diameters were squared, means obtained, and then transformed back to linear values. Mean diameters, mass densities, and sample length over which the size class is measured are presented in Table A1. Species sampled were pine (*Pinus contorta*), spruce (*Picea engelmannii*), fir (*Abies lasiocarpa*), aspen (*Populus tremuloides*).

Fuel load calculations for shrubs were made by estimating biomass from the following empirical equations calculated from samples collected in Kananaskis. All equations predict dry mass in grams from diameter in centimetres (Table A2). Fuel load was then determined by dividing the mass by the quadrat area, which was, in this inventory, 1 m^2. For live shrubs, log(mass) = log(a) + b log(diameter); dead branch mass was transformed as log(mass + 1).

Fuel load calculations for herbaceous classes used in the inventory predicted fuel load directly from cover, height, and percent dead. All equations were of the form: Load = a + b1(% cover) + b2(height[cm]) + b3(cover·height) + b4(% dead). Note that the maximum % dead value permitted for prostrate shrubs was 20.

Fuel load calculations for litter and moss were made from depth, based on samples collected throughout the Kananaskis Valley. The litter depth was taken to the fermentation layer. Moss depth was taken to the extent of living material.

Wood fuel loads were divided among the 1, 10, and 100 h time-lag size classes (0–0.63 cm, 0.64–2.54 cm, and 2.55–7.62 cm diameter, cf. Bradshaw et al.1984) based on conversion factors determined from wood diameters collected in Kananaskis (Table 4a). Dead shrub wood was also divided into the three time-lag size classes based on an expected distribution of stem sizes (Table 4b) for stems of a certain basal diameter (cf. Brown et al. 1982). Each fuel class was then assigned a characteristic surface-area-to-volume ratio (cf. Sylvester and Wein 1981, Brown and Bevins 1986), and a fuel depth based on field estimates (Table 5).

Crown foliage fuel loads were predicted from previously published equations. As a number of choices were available, the selection criteria for a useable equation was that it covered the appropriate range of tree sizes, provided a good fit to the data used to make the equation, and was applicable to the study area. Table A7 lists the equations chosen and their authors. All equations predict foliage load from dbh, with the exception of the equations for small trees, which are based on height.

TABLE A1. Downed wood mass density, quadratic mean diameters, sample line length for downed wood measurements in Kananaskis, Alberta.

Size* class	Mean size (cm)	Line distance (m)	Mass densities (kg/m^3)					
			Pine	Spruce	Fir	Aspen	Shrub†	Other‡
1	0.28	10	420	380	450	480	450	N.A.
2	0.71	20	490	450	460	470	500	N.A.
3	1.73	20	540	540	510	350	430	N.A.
4	3.74	30	460	490	390	420	470	N.A.
5	5.92	30	450	510	410	420	470	N.A.
6S	N.A.	30	450	460	360	430	430	426
6R	N.A.	30	N.A.	N.A.	N.A.	N.A.	N.A.	310

* 1 = 0–0.49 cm, 2 = 0.5–0.99 cm, 3 = 1.0–2.9 cm, 4 = 3.0–4.9 cm, 5 = 5.0–6.9 cm, 6S = sound wood 7+ cm, 6R = rotten wood 7+ cm. N.A. = not applicable.

† Shrubs were the mean of *Alnus tenuifolia, Shepherdia canadensis, Rosa* spp., *Salix* spp., and *Potentilla fruticosa.*

‡ "Other" was the mean of pine, spruce, fir, aspen.

TABLE A2. Shrub and seedling equations for Kananaskis, Alberta which estimate fuel mass of foliage and stems from basal stem diameter.

Species	Composition*	log(a)	b	MSE	N	r^2	Maximum diameter (cm)†
Salix spp.	Fol.	−0.266	1.801	.139	37	0.73	3
	Dbr.	0.627	1.101	.147	37	0.84	
	Lst.	1.326	2.600	.142	37	0.50	
	Dst.	1.300	2.993	.111	51	0.93	
Populus tremuloides	Fol.	0.042	0.938	.051	38	0.63	3
	Dbr.	1.412	1.917	.180	38	0.67	
	Lst.	0.445	0.981	.104	38	0.48	
	Dst.	1.279	2.098	.058	38	0.86	
Shepherdia canadensis	Fol.	−0.160	1.916	.067	23	0.88	2
	Dbr.	0.545	1.061	.178	23	0.46	
	Lst.	1.337	3.118	.122	23	0.92	
	Dst.	1.393	2.496	.123	29	0.87	
Rosa spp.	Fol.	−0.474	0.714	.061	29	0.33	1
	Dbr.	0.439	0.542	.067	29	0.20	
	Lst.	0.970	1.714	.087	29	0.66	
	Dst.	1.306	2.052	.181	22	0.62	
Alnus tenuifolia	Fol.	0.378	1.260	.133	19	0.42	3
	Dbr.	0.114	0.480	.029	19	0.32	
	Lst.	1.492	2.567	.054	19	0.88	
	Dst.	1.178	2.567	.076	11	0.89	
Potentilla fruticosa	Fol.	−0.445	1.081	.188	19	0.28	1
	Dbr.	0.628	0.892	.060	19	0.46	
	Lst.	1.288	2.345	.208	19	0.63	
	Dst.	1.153	1.346	.116	22	0.49	
Betula spp.	Fol.	0.309	1.883	.275	27	0.33	2
	Dbr.	0.522	1.124	.070	27	0.41	
	Lst.	1.596	2.387	.066	27	0.77	
	Dst.	1.441	2.076	.096	21	0.52	
Amelanchier alnifolia	Fol.	0.100	1.747	.272	31	0.53	3
	Dbr.	0.383	0.635	.079	31	0.34	
	Lst.	1.351	2.938	.159	31	0.85	
Viburnum edule	Fol.	−0.117	1.868	.136	16	0.61	1
	Dbr.	0.231	0.363	.013	16	0.38	
	Lst.	1.463	3.191	.270	16	0.70	
Pinus contorta	Fol.	0.950	2.171	.156	26	0.57	1.5
	Lst.	1.307	1.872	.100	26	0.61	
Picea engelmannii	Fol.	1.327	1.924	.059	25	0.89	3
	Dbr.	0.093	0.244	.036	25	0.17	
	Lst.	1.224	2.194	.083	25	0.88	
Abies lasiocarpa	Fol.	1.446	2.085	.163	8	0.52	3
	Lst.	1.374	2.523	.143	8	0.64	
Juniperus communis	Fol.	1.347	0.954	.046	25	0.63	2
	Lst.	1.243	1.440	.063	25	0.74	

* Fol. = foliage, Dbr. = dead branches on live plants, Lst. = live stem, Dst. = mass of dead plants.
† Maximum stem diameter permitted for each equation.

TABLE A3. Herbaceous plant equations for Kananaskis, Alberta, which predict fuel load (kg/m^2) from height (cm), cover (%), and percent dead.

	Multiple regression coefficients							
Class*	a	$b1$	$b2$	$b3$	$b4$	MSE	N	r^2
L. Shrub	−.015	.00119	.0101	.000473	⋯	.00423	52	0.81
D. Shrub	−.00232	.000212	⋯	⋯	.000518	.00004	52	0.59
L. Broad	.00209	.000783	.000507	⋯	⋯	.00030	92	0.61
L. Grass	.00685	−.000022	.000242	.000033	−.000089	.00006	108	0.74
D. Grass	.0128	.00189	.000699	−.000039	.000178	.00018	108	0.87
L. Lich.	.0180	−.000362	−.0110	.00319	⋯	.00065	18	0.97

* For two classes, live (L.) and dead (D.) predictions were made. The classes were prostrate shrubs (Shrub), broadleaf herbs (Broad), grasses and sedges (Grass), and lichens (Lich.).

TABLE A4. Litter and moss equations for Kananaskis, Alberta which predict fuel load (kg/m^2) from D, depth (cm).

Type*	Equation^2	MSE	N	r^2
Needle	$W = 0.733 + 0.447(D)$	0.451	45	0.68
Leaf	$\log(W) = -0.294 + 0.620 \cdot [\log(D)]$	0.044	41	0.30
Cone	$W = 1.208 + 1.040(D)$	2.990	5	0.88
Moss	$\log(W) = -0.0318 + 0.276 \cdot [\log(D)]$	0.032	42	0.20

* The categories of litter sampled were: conifer needle litter (needle), deciduous leaf litter (Leaf), cone scale litter (Cone).

TABLE A5. Conversion percentages to calculate fuel loads in time-lag fuel classes from (a) shrub basal stem diameter classes and (b) dead wood in measured size classes.

a) Shrubs

Shrub class (cm)	Class % in 1-h	% in 10-h	% in 100-h
0.0–0.5	100	0	0
0.5–1.0	80	20	0
1.0–1.5	70	30	0
1.5–2.0	60	40	0
2.0–3.0	50	40	10
3.0–5.0	25	25	50

b) Downed wood

Diam. size class (cm)	Class % in 1-h	% in 10-h	% in 100-h
0.0–0.5	100	0	0
0.5–1.0	48	52	0
1.0–3.0	0	92	8
3.0–5.0	0	0	100
5.0–7.0	0	0	100

TABLE A6. Standardized values of surface area to volume ratio (cm^{-1}) and fuel layer depth for each surface fuel category.

Fuel component	Surface area/volume (cm^{-1})	Depth (cm)	Source (for surface area/volume)*
Litter	50	5	1
1-h wood	13	30	3
10-h wood	3	30	1
100-h wood	1	30	1
Moss	100	5	1,2
Herbs	50	30	1
Shrub foliage	75	100	2
Shrub stems	15	100	2

* Sources. 1: Brown and Bevins 1986; 2: Sylvester and Wein 1981; 3: This study, based on calculations in Brown 1970.

TABLE A7. Conifer tree equations to predict foliage mass (kg) from diameter at breast height (cm) and/or tree height (m).

Equation*	r^2	MSE	N (sample size)	Range†	Source ‡
Pinus contorta					
$T = 0.152(h^2)$	0.96	0.045	12	$d < 5$	1
$F = 0.38(T)$				$h \leq 3.05$	
$F = 0.31(T)$				$h > 3.05$	
$F = 0.0525(d^{1.6057})$	0.83	432.6	27	$d \geq 5$	2
Picea engelmannii					
$T = 0.4535(e^{-0.878+2.57 \cdot \ln(h)})$	0.94	1.499	12	$d < 5$	1
$F = 0.40(T)$				$h \leq 3.05$	
$F = 0.33(T)$				$h > 3.05$	
$F = 0.6373(d^{1.1457})$	0.69	216.1	23	$d \geq 5$	2
Abies lasiocarpa					
$T = 0.4535(e^{-0.599+2.30 \cdot \ln(h)})$	0.90	0.276	13	$d < 5$	1
$F = 0.40(T)$				$h \leq 3.05$	
$F = 0.33(T)$				$h > 3.05$	
$M = 3.66 - 1.02(d) + .091(d^2) - 0.0011(d^3)$	0.79	35.28	60	$d \geq 5$	3
$F = 0.5(M)$					

* T = total tree mass (kg), F = needle mass (kg), M = foliage + small twig mass, d = diameter at breast height (cm), h = tree height (m). For *Abies lasiocarpa* it was assumed that $F = 0.5 \times M$.

† Tree sizes applicable for equations.

‡ 1: Brown 1978; 2: Johnson et al. 1990*a*; 3: Singh 1982.

TABLE A8. The stand fuel characteristics used in the surface fire intensity (Rothermel 1972) and crown fire initiation (Van Wagner 1977) models. The column headings "1-h," "10-h," and "100-h" refer to time-lag fuel classes.

Site	Age (yr)	Litter (kg/m^2)	1-h (kg/m^2)	10-h (kg/m^2)	100-h (kg/m^2)	Moss (kg/m^2)
1	101	0.58	0.09	0.05	0.11	0.65
2	125	0.94	0.05	0.13	0.42	0.47
3	81	0.59	0.08	0.29	1.70	0.84
4	54	0.85	0.07	0.13	0.06	0.21
5	70	0.62	0.06	0.12	0.49	0.63
6	70	0.48	0.05	0.25	0.63	0.80
7	109	0.56	0.17	0.03	0.06	0.64
8	258	0.88	0.14	0.17	1.59	0.46
9	54	1.38	0.10	0.15	0.22	0.04
10	54	0.71	0.06	0.11	0.13	0.44
11	99	0.53	0.09	0.11	0.62	0.80
12	202	0.04	0.10	0.05	0.21	1.31
13	109	0.92	0.18	0.32	0.53	0.33
14	216	0.21	0.09	0.07	0.15	1.13
15	211	2.00	0.13	0.10	0.11	0.38
16	99	0.93	0.09	0.09	0.13	0.47
17	224	0.88	0.13	0.15	0.69	0.40
18	120	0.40	0.08	0.08	0.70	1.09
19	57	1.15	0.05	0.05	0.12	0.04
20	112	0.95	0.11	0.11	0.41	0.34
21	70	1.02	0.08	0.17	0.89	0.37
22	132	0.63	0.07	0.02	0.09	0.58
23	86	0.54	0.07	0.19	0.61	0.86
24	100	0.79	0.07	0.05	0.17	0.65
25	100	0.73	0.04	0.48	0.19	0.87
26	86	0.81	0.09	0.11	0.17	0.58
27	125	1.20	0.05	0.13	0.55	0.21
28	86	0.96	0.05	0.06	0.05	0.48
29	57	1.96	0.04	0.02	0.18	0.17

TABLE A8. Continued.

Site	Age (yr)	Litter (kg/m^2)	1-h (kg/m^2)	10-h (kg/m^2)	100-h (kg/m^2)	Moss (kg/m^2)
30	132	0.56	0.11	0.03	0.15	0.73
31	150	0.38	0.05	0.08	0.40	1.06
32	220	0.13	0.05	0.04	0.32	1.20
33	125	0.23	0.05	0.26	1.23	1.24
34	212	0.52	0.05	0.04	0.19	0.74
35	23	0.50	0.06	0.14	0.90	0.03
36	23	0.15	0.08	0.12	0.07	0.00
37	120	0.68	0.03	0.02	0.15	0.04
38	92	1.14	0.21	0.15	0.20	0.36
39	120	0.69	0.06	0.08	0.94	0.74
40	124	0.63	0.15	0.10	0.31	0.76
41	22	0.22	0.21	0.73	0.93	0.00
42	22	1.07	0.06	0.23	0.81	0.05
43	22	0.88	0.03	0.21	0.51	0.12
44	132	0.92	0.07	0.10	0.21	0.53
45	81	1.06	0.05	0.06	0.25	0.62
46	216	0.57	0.12	0.13	0.56	0.94
47	202	0.72	0.06	0.08	0.43	0.97

Site	Herbs (kg/m^2)	Shrub (kg/m^2)	Total fuel (kg/m^2)	Bulk density	Fuel depth (kg/m^3)	Surf. area/ distance (m^2/m)
1	0.05	0.05	1.57	3.55	0.44	82.6
2	0.04	0.01	2.07	5.40	0.38	73.8
3	0.06	0.03	3.58	9.27	0.39	83.9
4	0.09	0.10	1.52	3.30	0.46	65.2
5	0.10	0.01	2.03	5.62	0.36	81.5
6	0.07	0.00	2.29	6.47	0.35	86.3
7	0.02	0.01	1.48	3.97	0.37	82.8
8	0.04	0.04	3.32	8.20	0.41	72.6
9	0.04	0.11	2.04	3.92	0.52	51.7
10	0.05	0.01	1.52	4.18	0.36	76.5
11	0.06	0.04	2.24	5.49	0.41	85.1
12	0.09	0.17	1.96	3.83	0.51	95.7
13	0.04	0.38	2.70	4.02	0.67	64.9
14	0.03	0.04	1.72	3.93	0.44	94.0
15	0.06	0.08	2.85	6.29	0.45	62.8
16	0.05	0.18	1.94	3.36	0.58	72.4
17	0.06	0.07	2.37	5.42	0.44	71.4
18	0.04	0.02	2.40	6.31	0.38	90.5
19	0.10	0.02	1.52	4.08	0.37	54.8
20	0.17	0.24	2.34	4.78	0.49	67.9
21	0.08	0.07	2.68	6.21	0.43	68.9
22	0.10	0.02	1.50	4.08	0.37	81.0
23	0.06	0.08	2.42	5.33	0.46	85.3
24	0.06	0.02	1.81	4.69	0.39	79.9
25	0.08	0.00	2.38	6.71	0.35	83.5
26	0.13	0.12	2.01	4.45	0.45	76.9
27	0.06	0.02	2.22	5.88	0.38	62.3
28	0.11	0.03	1.73	4.53	0.38	74.3
29	0.10	0.07	2.55	5.94	0.43	57.8
30	0.12	0.10	1.81	4.15	0.44	83.1
31	0.09	0.00	2.05	5.86	0.35	90.8
32	0.06	0.07	1.87	4.10	0.45	95.4
33	0.07	0.01	3.09	8.60	0.36	93.3
34	0.20	0.09	1.84	4.52	0.41	84.1
35	0.03	0.03	1.69	4.19	0.40	53.4
36	0.03	0.03	0.49	1.16	0.42	49.2
37	0.09	0.00	1.01	2.89	0.35	57.6
38	0.13	0.14	2.33	5.23	0.45	66.9
39	0.07	0.11	2.70	5.64	0.48	81.4
40	0.08	0.23	2.26	4.07	0.55	81.3
41	0.05	0.19	2.33	4.57	0.51	39.5
42	0.11	0.10	2.43	5.58	0.44	54.1
43	0.09	0.03	1.87	4.81	0.39	60.4
44	0.10	0.05	1.97	4.84	0.41	75.4
45	0.04	0.01	2.09	5.47	0.38	76.0
46	0.08	0.05	2.46	6.00	0.41	85.8
47	0.03	0.03	2.32	5.41	0.43	85.2

TABLE A8. Continued.

Site	Crown depth (m)	Crown base (m)	Tree fol. (kg/ m^2)	Fuel var. (kW/ m)	Crit. intens. (kW/ m)	Crit. R.O.S. (ms^{-1})	Pass. crown var.	Active crown var.
1	7.9	3.0	1.04	365	871	0.38	0.419	0.
2	7.1	7.2	1.12	310	3256	0.32	0.095	0.
3	4.7	10.1	1.16	183	5463	0.20	0.033	0.
4	2.1	4.4	1.40	342	1553	0.08	0.220	2.
5	4.6	4.7	2.42	219	1729	0.10	0.127	1.
6	3.2	5.5	2.05	260	2206	0.08	0.118	1.
7	11.2	2.1	3.56	330	508	0.16	0.649	0.
8	5.7	6.4	2.52	170	2733	0.11	0.062	0.
9	5.3	6.0	0.94	1330	2492	0.28	0.534	1.
10	3.9	6.0	1.08	252	2501	0.18	0.101	0.
11	7.5	4.9	2.85	317	1847	0.13	0.172	0.
12	6.0	5.9	2.03	1416	2450	0.15	0.578	2.
13	12.3	4.9	0.77	360	1825	0.80	0.197	0.
14	4.1	5.4	1.23	973	2147	0.17	0.453	1.
15	6.8	4.1	2.25	1275	1429	0.15	0.892	1.
16	4.6	13.7	1.06	460	8553	0.21	0.054	0.
17	6.9	5.1	1.40	253	1959	0.25	0.129	0.
18	6.3	4.3	2.89	499	1513	0.11	0.330	1.
19	5.9	1.5	0.77	825	309	0.38	2.671	0.
20	3.7	3.1	0.83	283	918	0.22	0.308	0.
21	7.4	6.1	0.73	279	2533	0.51	0.110	0.
22	5.8	3.9	2.44	277	1326	0.12	0.209	1.
23	3.7	7.2	2.20	379	3243	0.08	0.117	1.
24	8.9	9.4	1.72	358	4850	0.26	0.074	0.
25	3.7	3.7	1.90	322	1200	0.10	0.269	1.
26	6.4	6.8	1.73	311	3030	0.18	0.103	0.
27	5.6	2.8	0.73	498	807	0.38	0.617	0.
28	10.6	4.4	1.04	361	1554	0.51	0.232	0.
29	7.6	4.3	1.14	1563	1484	0.33	1.054	0.
30	5.9	2.9	2.56	345	843	0.11	0.409	1.
31	8.2	9.0	3.23	502	4555	0.13	0.110	1.
32	4.7	4.6	2.47	1093	1644	0.09	0.655	2.
33	4.9	6.6	0.94	442	2897	0.26	0.152	0.
34	3.8	1.3	2.00	306	240	0.10	1.278	1.
35	3.1	0.1	0.26	151	7	0.58	0.753	0.
36	1.6	0.2	0.05	23	11	1.55	0.114	0.
37	6.7	0.2	0.66	321	13	0.51	1.607	0.
38	9.2	1.5	2.55	392	305	0.18	1.288	0.
39	6.7	3.5	1.19	298	1112	0.28	0.268	0.
40	4.0	3.7	3.80	405	1198	0.05	0.338	3.
41	4.5	0.2	0.10	63	18	2.21	0.314	0.
42	4.9	0.3	0.26	485	28	0.96	2.427	0.
43	5.8	0.5	0.38	314	66	0.77	1.569	0.
44	3.9	4.4	1.68	332	1558	0.12	0.213	1.
45	7.2	6.2	1.36	419	2598	0.26	0.161	0.
46	5.0	3.9	2.28	381	1322	0.11	0.288	1.
47	8.9	5.6	1.97	517	2261	0.23	0.229	0.