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The Relative Importance of Fuels and Weather on Fire Behaviour in Subalpine Forests in the Southern Canadian Rocky Mountains

by

Wayne Christopher Bessie

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Relative Importance of Fuels and Weather on Fire Behaviour in Subalpine Forests in the Southern Canadian Rocky Mountains" submitted by Wayne Christopher Bessie in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

The relative roles of fuel and weather variation in influencing fire behaviour variation was examined using data from subalpine forest stands. Fire behaviour (intensity and crown fire initiation) was predicted from Rothermel's (1972) and Van Wagner's (1977) models. Weather variation was many times more influential than fuel variation in influencing the predicted fire behaviour. Besides considerable seasonal variation, weather also varied importantly among years. Previous large-area-burned years had more days with extreme weather (very dry fuels/high windspeeds) which could lead to high intensity/crown fires, than small-area-burned years. Fuel component variation was much less variable than weather variation. This fuel variation was poorly related to stand age or species composition. Furthermore, this fuel variation has no influence over crowning behaviour once extreme weather conditions are achieved. These relationships demonstrated that fire behaviour and large fire occurrence are influenced primarily by weather conditions rather than fuels.

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SYMBOL	MEANING	UNITS
Greek Symbols		
Γ	optimum combustion rate	s^{-1}
ε	effective heating number	dimensionless
η_m	moisture damping function	dimensionless
η_s	mineral damping function	dimensionless
ξ	propagating flux ratio	dimensionless
ρ	wood mass density	kg m^{-3}
ρ_b	fuel bulk density	kg m^{-3}
ρ_c	fuel bulk density (crown)	kg m^{-3}
ϕ_s	slope coefficient	dimensionless
ϕ_w	wind coefficient	dimensionless
English Symbols		
C_p	passive crown fuel variable	dimensionless
C_a	active crown fuel variable	dimensionless
E_v	environment (weather) variable	dimensionless
F_v	fuel variable	kW m^{-1}
h	heat of combustion	kJ kg^{-1}
I	intensity	kW m^{-1}

I_p	passive crown critical intensity	kW m^{-1}
I_a	active crown critical intensity	kW m^{-1}
I_R	reaction intensity	kW m^{-2}
Q_f	forward heat flux	kW m^{-2}
Q_{ig}	heat of pre-ignition	kJ kg^{-1}
Q_d	heat of pre-ignition of dry fuel	kJ kg^{-1}
Q_c	foliar heat of ignition (crown)	kJ kg^{-1}
Q_r	dry to wet heat of preignition ratio	dimensionless
Q_s	fuel heat sink	kJ m^{-3}
R	rate of spread	m s^{-1}
R_c	rate of spread (crown fire)	m s^{-1}
R_o	critical rate of spread (crown fire)	m s^{-1}
S_o	critical crown fire mass flow rate	kg m^{-2} s^{-1}
t_r	flame residence time	s
W_n	net fuel load	kg m^{-2}
z	lower crown base height	m

INTRODUCTION

A traditional theory in forest fire ecology holds that fire behaviour (*e.g.* rate of spread and intensity) is a plant community attribute (Mutch 1970). Fuel load increases and structural changes which occur as stands age are believed to increase the intensity of surface fires and/or lead to increased crown fire occurrence (Despain 1990, Lotan *et al.* 1985, Romme and Knight 1981, Despain and Sellers 1977, Heinselman 1973, Habeck and Mutch 1973), but there is no formalized mechanism which explains these ideas. Fire behaviour is also believed to vary among stand types within the closed-canopy subalpine forest due to differences in tree architecture and/or fuel accumulation (*e.g.* Renkin and Despain 1992). Furthermore, fuel differences which are thought to lead to increased fire intensity are also thought to increase the probability of occurrence of fires and the fire frequency in older stands or various stand types (Despain 1990, Clark 1988). By avoiding the quantitative mechanisms which link fuels to fire behaviour, the above beliefs discount the important role played by weather in fires. Fire behaviour and fire frequency are closely related to temporal or regional variation in fuel moisture (Johnson and Wowchuk 1993, Johnson and Larsen 1991, Masters 1990, Swetnam and Betancourt 1990, Clark 1989) and high intensity wildfires are strongly associated with high winds and low moisture, such that fire spread patterns appear unrelated to fuel (or age) differences among stands during large fire events (Fryer and Johnson 1988, Johnson and Larsen 1991, Simard *et al.* 1983).

The purpose here is to assess the relative roles played by weather (fuel moisture content and windspeed) and fuel (fuel loads by size classes) in forest fire behaviour. Empirical fuel and weather data from lower subalpine forests in the southern Canadian Rocky Mountains are used to model fire intensity and crown fire initiation with Rothermel's (1972) surface fire intensity model and Van Wagner's (1977) crown fire initiation model. These models are chosen because both models allow the roles of fuel components to be quantitatively separated from the role of weather components. After separation, the fuel and weather components are used to define collective fuel and weather variables which are used to determine the relative contribution of variation in fuel loads, crown structure, and weather on the variation in predicted surface fire intensity and crown fire initiation. The variables also permit the quantitative examination of the role of weather in determining annual area burned classes (large and small-area-burned years *sensu* Johnson and Wowchuk 1993), and the relationship between stand age or stand composition and fuel induced changes to fire behaviour. Fire behaviour modelling provides an objective approach to determine the role of fuel and weather in fire behaviour because of the direct linkages made to the fire behaviour mechanisms. Also, unlike some previous studies (Keane *et al.* 1990, Agee and Huff 1987), fire behaviour is determined over a full range of weather possibilities rather than a single weather condition, such that the variation in the weather is properly expressed in the analyses performed.

The objective of this thesis is to answer the following three questions:

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

2. Why is weather variation so important in determining fire behaviour in the subalpine forest?

3. How important is fuel variation associated with stand age or stand type on the fire behaviour in the subalpine forest?

In what follows, it is assumed that the reader is familiar with concepts of forest fire behaviour; if not, refer to Van Wagner (1980) for a discussion.

Surface Fire Intensity Model

Rothermel's (1972) model predicts surface forest fire rate of spread (m s^{-1}) and intensity (kW m^{-1}). Fire spread is modelled as a series of particle ignitions at an optimum rate determined by the interaction of fuels, weather, and slope. Fuel loads (mass per area) of various categories (litter, moss, herbs, shrubs, dead wood) and size classes, and fuel bed depth are determined from field measurements and input to the model; however, fuel heat content, ash fraction, and particle density are generally held constant (Rothermel 1983). Moisture contents (for each fuel category) and windspeeds are also model inputs.

Rate of spread (R) is determined by an energy budget:

$$R = \frac{Q_f}{Q_s} \tag{1}$$

Q_f = forward heat flux (kW m^{-2} or kJ m^{-2} s^{-1})
Q_s = fuel heat sink (kJ m^{-3}).

Heat flux (Q_f) is the forward heat transfer rate to new fuels:

$$Q_f = I_R \xi (1+\phi_w+\phi_s) \tag{2}$$

ξ = propagating flux ratio (dimensionless)
ϕ_w = wind coefficient (dimensionless)
ϕ_s = slope coefficient (dimensionless)
I_R = reaction intensity (kW m^{-2})

The propagating flux ratio (ξ) is the fraction of the reaction intensity (I_R) which transfers heat to new fuel particles. Wind and slope coefficients (ϕ_w, ϕ_s) modify this heat flux to account for increased radiative and convective heat transfer.

Reaction intensity is the total rate of heat release <u>per unit area in the combustion zone</u>:

$$I_R = \eta_m \eta_s \Gamma h W_n \tag{3}$$

η_m = moisture damping function (dimensionless)
η_s = mineral damping function (dimensionless)
Γ = optimum combustion rate (s^{-1})
h = heat of combustion (kJ kg^{-1})
W_n = net fuel load (kg m^{-2})

Reaction intensity differs from (fire front) intensity (I), which is the forward heat flux <u>per unit length at the fire front</u>. Reaction intensity is the product of the rate of combustion, the fuel heat content (h), and the net fuel load (W_n). The optimum combustion rate (Γ) is the rate at which fuels would burn under ideal conditions. This rate is reduced by the fuel moisture and fuel mineral damping functions.

The heat sink (Q_s) is the heat required to raise a unit volume of fuels within the fuel bed to ignition temperature:

$$Q_s = \rho_b \varepsilon Q_{ig} \tag{4}$$

ρ_b = fuel bulk density (kg m^{-3})
ε = effective heating number (dimensionless)
Q_{ig} = heat of pre-ignition (kJ kg^{-1})

The heat of pre-ignition is the energy needed to vaporize moisture from the fuel and then increase fuel temperature to the ignition temperature (~ 300 °C). Only a fraction of the fuel bulk density (ρ_b) needs to reach the ignition temperature before ignition occurs: this fraction is the effective heating number (ε).

Rate of spread (R: m s^{-1}) is found by substitution of Q_f and Q_s in equation 1:

$$R = \frac{I_R \xi (1+\phi_w+\phi_s)}{\rho_b \varepsilon Q_{ig}} \tag{5}$$

Intensity (I: kW m^{-1}) is the product of rate of spread (R) and the heat release of the fire (kJ m^{-2}), where heat release is the product of reaction intensity (I_R) and flame residence time (t_r; Albini 1976):

$$I = I_R R t_r \tag{6}$$

I_R = reaction intensity (kW m^{-2})
R = rate of spread (m s^{-1})
t_r = flame residence time (s)

The rate of heat release over a unit area is essentially summed over the entire time that the flame exists at any location. This assumes that reaction intensity is constant as fuel particles are consumed by the combustion process.

Substitution and rearrangement produces the following intensity equation:

$$I = \frac{(\eta_m \eta_s \Gamma h W_n)^2 \xi (1+\phi_w+\phi_s) t_r}{\rho_b \varepsilon Q_{ig}} \tag{7}$$

Fuel and weather components in the intensity equation were separated to define two new variables. The heat of pre-ignition was also split into two parts, a constant value for dry fuels (Q_d) and the total value for wet fuels (Q_{ig}), with the ratio of the dry to wet values shown as Q_r. The fuel variable (F_v : kW m^{-1}) has the same units as intensity, and thus specifies the collective role of fuels in intensity:

$$F_v = \frac{(\eta_s \Gamma h W_n)^2 \xi t_r}{\rho_b \varepsilon Q_d} \tag{8}$$

The environment variable (E_v: dimensionless) includes the remaining effects of fuel moisture content, windspeed, and slope on surface fire intensity:

$$E_v = (\eta_m)^2 (1+\phi_w+\phi_s) Q_r \tag{9}$$

Since slope was held constant E_v was renamed the weather variable.

Crown Fire Initiation Model

Van Wagner's (1977) model of crown fire initiation involves two steps, first crown fuel ignition must occur and second, the crown fire must burn fuel (and release heat) at a rate sufficient to allow direct crown-to-crown fire spread. When only the first step is achieved the fire is a passive crown fire, because the crown fire passively follows the surface fire at its rate of spread. When both steps are achieved, the fire will become an active crown fire, because the crown component dictates the fire spread rate. Passive crown fires have somewhat elevated intensities (compared to surface fires) due to the addition of crown fuels; active crown fires have intensities 10-100 times greater than surface fires due to the combination of increased fuel consumption and higher rates of spread (Van Wagner 1980).

The first step, crown fuel ignition, occurs when the heat flux from the surface to the crown exceeds the critical intensity (I_p: kW m^{-1}):

$$I_p = (0.01 z Q_c)^{\frac{3}{2}} \tag{10}$$

z = lower crown base height (m)
Q_c = heat of crown foliage ignition (kJ kg^{-1})

The value 0.01 is an empirical constant of complex dimensions (*cf.* Van Wagner 1977). The heat of foliage ignition (Q_c) depends on foliage moisture content, but moisture content generally remains constant throughout the late summer months ranging from 90 - 110 percent (Springer and Van Wagner 1984). This variation in moisture contents represents a seasonal shift due to physiology of the trees and not a weather-caused phenomena. Thus, it was unnecessary to include moisture content variation in this study comparing weather and fuel effects on fires, and the value of Q_c was held constant at 3060 kJ kg^{-1} which corresponds to 100 percent moisture (by dry mass). The minimum critical intensity value was set as 200 kW m^{-1}. It is unlikely that crown ignition could occur at any intensities less than this amount (*cf.* Fire Danger Group 1992).

The second step in crown fire initiation, active crown spread, occurs when the total crown heat flux is sufficient to ignite nearby crown fuels allowing direct flame transfer between crowns. This occurs only if the rate of crown fuel consumption (mass flow rate) surpasses a critical value. Van Wagner (1977) empirically determined the critical mass flow rate to be 0.05 kg m^{-2} s^{-1}. This value equals the product of the rate of spread and crown fuel bulk density. Critical rate of spread (R_a: m s^{-1}) is determined by dividing the mass flow rate by crown bulk density:

$$R_a = \frac{S_o}{\rho_c} \tag{11}$$

S_o = critical mass flow rate (kg m^{-2} s^{-1})
ρ_c = crown fuel bulk density (kg m^{-3})

The critical rate of spread is then compared to an estimate of crown fire rate of spread (R_c) to determine if active crowning is achieved. A procedure to estimate crown fire rate of spread from predicted surface fire rate of spread is given by Rothermel (1991). This empirical relationship predicts crown fire rate of spread for wind-driven fires:

$$R_c = 3.34\,R \tag{12}$$

R_c = crown fire rate of spread (m s^{-1})
R = predicted surface fire rate of spread (m s^{-1})

This empirical equation is as yet untested and consequently serves here only as a guide to the conditions in which R_a may be achieved.

The surface fuel variable (F_v) is then combined with critical intensity and rate of spread to define fuel variables for crown fire initiation. This combination reflects the influence of both surface and crown fuels in crown fire initiation.

The passive crown (fire initiation) fuel variable (C_p: dimensionless) is:

$$C_p = \frac{F_v}{I_p} \tag{13}$$

F_v = surface fuel variable (kW m^{-1})
I_p = critical intensity (kW m^{-1})

Definition of the active crown (fire initiation) fuel variable (C_a) first involves conversion of the critical crown fire rate of spread to a critical surface fire rate of spread value (via equation 12). This critical spread rate is then multiplied by heat of combustion and the net surface fuel load (as in Byram's 1959 equation) to predict the active crown fire critical surface fire intensity (I_a: kW m^{-1}).

$$I_a = \frac{R_a}{3.34} h \, W_n \tag{14}$$

R_a = critical rate of spread (m s^{-1})
h = low heat of combustion (12700 kJ kg^{-1})
W_n = net surface fuel load (kg m^{-2}) from Rothermel's model

Substitution of I_a for I_p into equation 13 gives the active crown fuel variable (C_a).

$$C_a = \frac{F_v}{I_a} \tag{15}$$

The crown fuel variables and the surface fire weather variable relate directly to passive or active crown fire initiation according to the following formulae:

$$C_p E_v = \frac{I}{I_p} \; ; \; C_a E_v = \frac{I}{I_a} \tag{16}$$

C_p = passive crown fuel variable (dimensionless)
C_a = active crown fuel variable (dimensionless)
E_v = weather variable (dimensionless)
I = surface fire intensity (kW m^{-1})
I_p = passive crowning critical fire intensity (kW m^{-1})
I_a = active crowning critical fire intensity (kW m^{-1})

All fire behaviour predictions, fuel and weather variables are calculated with a FORTRAN program (Appendix 2). Modelling fire behaviour is simpler than gathering data from actual fires, and this approach allowed every stand to be tested in every possible weather condition, whereas any real fire would be a non-repeatable event. The reliability of this approach clearly depends on the ability of the models to capture the fundamental processes of fire behaviour. Given the widespread use of Rothermel's (1972) model in fire danger rating (Bradshaw *et al.* 1984) throughout the United States, it is clear that the general processes of the model are generally well accepted. Van Wagner's (1977) model is also used in fire danger rating in Canada (Fire Danger Group 1992). Reliability of Rothermel's (1972) model predictions for a number of fuel types have been published by Rothermel (1983). A field test of Van Wagner's (1977) model is provided in the original reference.

METHODS

Study Area

The Kananaskis Valley of S.W. Alberta is situated in the front and main ranges of the southern Canadian Rocky Mountains (115° 0-20' W, 50° 30'-51° N) approximately 100 km west of Calgary, Alberta (Fig. 1). All sampled stands were located in the Kananaskis Valley except for three 22-year-old stands in the Vermilion Pass of Banff and Kootenay National Parks (Table 1). Lower subalpine forest (1200 - 1700 m elevation) primarily consists of lodgepole pine (*Pinus contorta* Loudon var *latifolia* Engelm.) and Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) canopy trees. Aspen (*Populus tremuloides* Michx.) stands occur occasionally in the lower subalpine zone, but were not sampled. The upper subalpine forest (1700 m - c. 2300 m) consists of Engelmann spruce and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests (Johnson and Miyanishi 1991). The stands sampled in this study represent approximately 95% of the stand types in the Kananaskis Valley. Most conifer stands in the Kananaskis Valley originate from fire disturbances (Johnson and Larsen 1991) which result in even-aged fire cohorts of lodgepole pine or Engelmann spruce trees (Johnson and Fryer 1989).

The fire cycle of the Kananaskis Valley (90 years) is mainly affected by areas burnt from infrequent stand-replacing crown fires (Johnson and Larsen 1991). The main season for large fires is July and August due to a combination of thunderstorms which produce numerous fire ignitions and dry fuel conditions resulting from many days with high temperature and low relative humidity.

FIGURE 1. Map of study area in the Kananaskis Valley, with points indicating locations of sampled stands. Inset: forest reserves and national parks in the southern Canadian Rocky Mountains in southwest Alberta and southeast British Columbia.

KANANASKIS VALLEY, ALBERTA

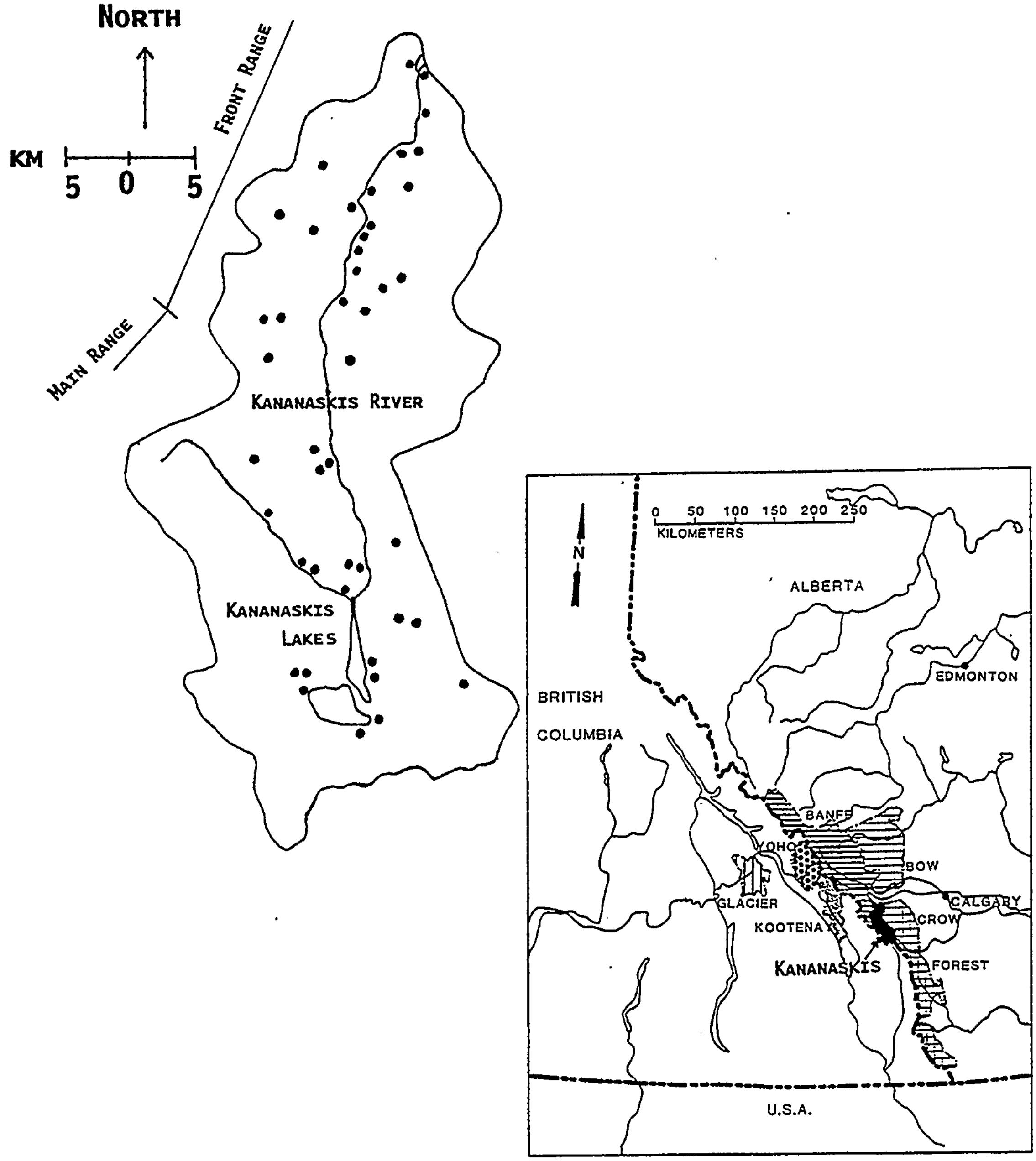


TABLE 1. Sampled forest stands listing location, elevation, age (time-since-fire), aspect, density, basal area, slope, overstorey tree percentage composition (by tree density), and stand composition classes.

No.	Location	Elev. m	Age y	Asp. deg	Dens. #/ha	B.A. m^2/ha	Slope deg	Pine %	Spr. %	Fir %	Comp Class[1]
1	Barrier 1	1675	101	314	1230	31.2	22	60	17	23	2
2	Barrier 2	1450	125	356	2530	47.4	9	97	3	0	1
3	Porcupine	1425	81	232	2170	48.7	16	98	2	0	1
4	Lower Wedge	1575	54	0	7230	40.3	0	100	0	0	1
5	Lower Fortress 1	1575	70	0	3770	55.1	5	100	0	0	1
6	Lower Fortress 2	1600	70	100	3330	47.1	8	97	3	0	1
7	Middle Fortress 1	1650	109	60	1070	92.5	15	16	84	0	3
8	Middle Fortress 2	1750	258	120	1900	74.6	25	45	43	12	2
9	Nakiska Sign	1475	54	300	2100	33.5	21	100	0	0	1
10	Skogan Trail	1450	54	206	3130	43.6	7	100	0	0	1
11	Evan Thomas 1	1575	99	0	1730	74.3	5	100	0	0	1
12	Ribbon Creek 1	1625	202	320	1270	55.8	13	9	41	50	3
13	Boundary Trail	1550	109	264	730	22.6	12	67	33	0	2
14	Galatea Creek 1	1775	216	360	730	43.8	21	0	53	47	3
15	Upper Wedge	2250	211	57	1670	60.7	22	0	68	32	3
16	Ranger Station	1500	99	0	1970	55.5	6	98	0	0	1
17	Middle Nakiska	1925	224	96	1330	48.9	27	20	30	50	3
18	Rocky Creek	1725	120	68	2000	47.8	27	20	60	20	3
19	Boulton Creek 1	1700	57	0	1770	17.8	2	87	13	0	1
20	Upper Opal Creek	2025	112	45	1700	25.1	23	94	6	0	1
21	Lower Opal Creek	1825	70	246	1470	33.1	5	100	0	0	1
22	Elbow Trailhead	2000	132	212	1800	72.6	16	0	45	55	3
23	L. Lake Peninsula	1700	86	0	3900	58.6	10	100	0	0	1
24	Spillway	1650	100	0	870	46.2	1	42	59	0	2
25	K. River Outflow	1650	100	200	7000	46.5	8	100	0	0	1
26	Sm. Dor. Highw. 1	1825	86	216	1400	45.3	15	74	26	0	2
27	Field Station	1425	125	320	1570	34.3	5	100	0	0	1
28	Sm. Dor. Highw. 2	1825	86	234	600	30.1	16	56	39	6	2
29	Boulton Creek 2	1700	57	0	1870	40.0	3	100	0	0	1
30	Hydroline Trail	1750	132	0	1900	42.0	3	4	63	33	3
31	Sawmill	2000	150	0	1870	66.9	4	14	89	0	3

TABLE 1. Continued.

No.	Location	Elev. m	Age y	Asp. deg	Dens. #/ha	B.A. m^2/ha	Slope deg	Pine %	Spr. %	Fir %	Comp Class
32	Wasootch 1	1575	220	320	900	57.2	13	4	81	15	3
33	Wasootch 2	1375	125	290	1930	44.6	8	100	0	0	1
34	Chester	2400	212	216	1570	95.7	9	5	37	59	3
35	Indefatiguable 1	2175	23	250	2270	8.4	26	100	0	0	1
36	Indefatiguable 2	2175	23	192	230	3.6	29	0	100	0	3
37	Evan Thomas 2	2000	120	140	500	18.8	36	53	27	20	2
38	King Creek	1875	92	230	1800	37.0	19	8	82	10	3
39	Evan Thomas 3	1600	120	290	1070	31.0	8	85	11	0	1
40	Upper Lake	1750	124	70	2270	49.8	33	2	66	32	3
41	Vermilion Pass 1	1600	22	180	0 *	2.3	34	100	0	0	1
42	Vermilion Pass 2	1600	22	105	0	8.6	18	100	0	0	1
43	Vermilion Pass 3	1600	22	0	1870	38.9	6	100	0	0	1
44	Point Campground	1725	132	0	2930	37.6	7	86	14	0	1
45	Jewel Pass	1425	81	100	1500	54.2	7	89	11	0	1
46	Galatea Creek 2	1900	216	132	630	59.9	12	0	59	41	3
47	Ribbon Creek 2	1650	202	200	1530	75.5	6	68	32	0	2

[1] Stand Composition Classes		Species Composition
1.	Pine	>85% pine by density
2.	Pine-spruce mix	15-85% pine, 15-85% spruce
3.	Spruce (fir)	>85% spruce or spruce/fir

* stands with all trees under 1.5 m tall were classed as having no canopy density

47 subalpine forest stands were chosen for sampling based on a stand origin map of the Kananaskis valley. This method was employed to attain a maximum stratification of samples among the ages and tree species compositions among the valley stands. Stand ages were confirmed by examining annual ring cores of overstorey trees. A stand was defined as an area of contiguous forest at least 1.5 ha area, with generally uniform species composition and a minimum of 20 m from any clearing, road, or trail in any direction. Stand characteristics: elevation, age, aspect, density, basal area, slope, overstorey tree percentages, and stand types are listed in Table 1. Stand ages (*i.e.* time since last fire) ranged from 22 to 258 years. Stand types (pine, spruce, and mixed species) were classified according to the percentage of overstorey species (Table 1).

Fuel Inventory and Calculations

Surface fuel loads were measured by methods of McRae *et al.* (1979) and Brown (1974, 1983) along a 90 m transect in the shape of an equilateral triangle (30 m sides). Downed wood fuels in five diameter classes (0-0.25 cm, 0.26-1.0 cm, 1.1-3.0 cm, 3.1-5.0 cm, and 5.1-7.0 cm) were measured using the line intersect technique and calculated into fuel loads according to Van Wagner (1968):

$$W = \frac{\rho \pi^2 \Sigma d^2}{8L} \tag{17}$$

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 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 square roots were taken to transform these means back to linear values. This determined the quadratic mean diameter required in the calculation of wood volume in the equation. Mean diameters and mass densities for the fuel load calculations are given in Table 2.

Shrub, herb, litter and moss fuels were measured in evenly spaced quadrats along the 90-m transect. Shrub basal diameters were measured in nine (1 m^2) quadrats at 10-m intervals. Each shrub species was recorded individually, and the number of dead stems per shrub plant was estimated visually. Litter and moss depth, and herbaceous plant cover, height, and percent dead were measured in 27 (0.06 m^2) quadrats at 3-m intervals along the transect (corners excluded). "Herbaceous" fuels were classified as grass, broadleaf herbs, prostrate shrubs (*e.g. Arctostapholous uva-ursi*) and lichens. Fuel load estimates for the above fuel components were calculated from regression equations (Table 3) estimated from fuel samples collected in the Kananaskis Valley. Above-ground masses for shrub species (live stem, dead stem, and foliage) were estimated from basal stem diameter (Table 3a) and were split into live and dead shrub categories based on the percent dead estimate. Live and dead herbaceous fuel loads were predicted from cover, height, and percent dead (Table 3b). Litter and moss fuel loads were predicted from depth (Table 3c).

The estimated surface fuel components were then divided into the following

TABLE 2. Downed wood mass density, quadratic mean diameters, and sample line length for downed wood measurements in Kananaskis, Alberta.

Size[1] Class	Mean Diam. (cm)	Line[2] Dist. (m)	Mass Densities (kg m^{-3}) Pine[3]	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] 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.

[2] Length on each 30-m side of a 90-m triangular transect in which each size class of wood was counted.

[3] Pine = *Pinus contorta*
Spruce = *Picea engelmannii*
Fir = *Abies lasiocarpa*
Aspen = *Populus tremuloides*
Shrub = mean of *Alnus tenuifolia*, *Shepherdia canadensis*, *Rosa* spp., *Salix* spp., and *Potentilla fruticosa* L.
Other = mean of pine, spruce, fir, aspen.

TABLE 3a) Regression equations for shrubs and seedlings in the Kananaskis Valley, Alberta estimating mass of foliage and stems from basal stem diameter.

SPECIES	[1]COMP	[2]log(a)	b	MSE	N	r^2	[3]MAX
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	

TABLE 3a) Shrub component equations continued.

SPECIES	COMP	log(a)	b	MSE	N	r^2	MAX
Amelanchier	FOL.	0.100	1.747	.272	31	0.53	3
alnifolia	DBR.	0.383	0.635	.079	31	0.34	
	LST.	1.351	2.938	.159	31	0.85	
Vibernum	FOL.	-0.117	1.868	.136	16	0.61	1
edule	DBR.	0.231	0.363	.013	16	0.38	
	LST.	1.463	3.191	.270	16	0.70	
Pinus	FOL.	0.950	2.171	.156	26	0.57	1.5
contorta	LST.	1.307	1.872	.100	26	0.61	
Picea	FOL.	1.327	1.924	.059	25	0.89	3
engelmannii	DBR.	0.093	0.244	.036	25	0.17	
	LST.	1.224	2.194	.083	25	0.88	
Abies	FOL.	1.446	2.085	.163	8	0.52	3
lasiocarpa	LST.	1.374	2.523	.143	8	0.64	
Juniperus	FOL.	1.347	0.954	.046	25	0.63	2
communis	LST.	1.243	1.440	.063	25	0.74	

[1] FOL = foliage, DBR. = dead branches on live plants, LST. = live stem, DST. = mass of dead plants.

[2] For shrub equations log(mass) = log(a) + b log(diam), where diameter was in cm and mass was in g. Dead branch mass was transformed as log(mass+1). If there was no dead stem equation for a species, the live stem value was used.

[3] MAX = maximum stem diameter (cm) permitted for each equation.

TABLE 3b) Regression equations for herbaceous plants and prostrate shrubs in the Kananaskis Valley, Alberta estimating fuel load (kg m^{-2}) from height (cm), cover (%), and percent dead.

	Multiple Regression Coefficients [2]							
TYPE[1]	a	b_1	b_2	b_3	b_4	MSE	N	r^2
L. SHRUB	-.015	.00119	.0101	.000473	.	.00432	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	-.00362	-.0110	.00319	.	.00065	18	0.97

1 L. = live, D. = dead. SHRUB = prostrate shrubs. BROAD = broadleaf herbs. GRASS = grasses and sedges. LICH = lichens.

2 Herbaceous plant equations are of the form:
Load = a + b_1(%cover) + b_2(height(cm)) + b_3(cov*ht) + b_4(%dead).
Note: The maximum % dead value permitted for prostrate shrubs was 20.

TABLE 3c) Regression equations for litter and moss in the Kananaskis Valley, Alberta estimating fuel load (kg m^{-2}) from depth in cm.

TYPE[1]	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 [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 [log(D)]	0.032	42	0.20

1 NEEDLE = conifer needle litter

LEAF = deciduous leaf litter

CONE = cone scale litter

MOSS = live moss plants

2 W = fuel load (kg m^{-2})

D = depth to fermentation layer or to dead moss tissues (cm).

classes: litter, moss/lichen, live herbs, live shrubs, 1-hour time-lag fuels (0.00-0.63 cm: dead wood, dead shrub wood, dead herbs), 10-hour (0.64-2.54 cm) and 100-hour (2.55-7.62 cm) fuels (dead wood and dead shrub wood). Wood fuel loads were divided among the three time-lag size classes 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.* Brown and Bevins 1986, Sylvester and Wein 1981), and a fuel depth based on field estimates (Table 5).

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 empirical equations from various literature sources (Table 6). 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 then divided by crown depth to get crown bulk density.

Weather Data Source and Calculations

Daily weather data (temperature, precipitation, windspeed, and relative humidity) for 1954-1988 were obtained from the Atmospheric Environment Service,

TABLE 4. 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)	Shrub Class (cm)	% in 1-h Class[1]	% in 10-h Class	% In 100-h Class
	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. Class (cm)	% in 1-h Class	% In 10-h Class	% In 100-h Class
	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

1 1-hour class = 0.00 - 0.63 cm, 10-hour class = 0.64 - 2.54 cm, 100-hour class = 2.55 - 7.62 cm.

TABLE 5. Standardized values of surface area to volume ratio (cm^{-1}) and fuel layer depth for each surface fuel category.

Fuel Component	Depth (cm)	SA/VOL (cm^{-1})	Source [1] (for SA/VOL)
Litter	5	50	1
1-h Wood	30	13	3
10-h Wood	30	3	1
100-h Wood	30	1	1
Moss	5	100	1,2
Herbs	30	50	1
Shrub Foliage	100	75	2
Shrub Stem	100	15	2

[1] Sources 1. Brown and Bevins (1986)

2. Sylvester and Wein (1981)

3. This study, based on calculations in Brown (1970)

TABLE 6. Regression equations predicting foliage mass (kg) from diameter at breast height (cm) and/or tree height (m) for conifer trees.

Equation[1]	r^2	MSE	N	Range[2]	Source[3]
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					
$T=0.4535\ (e^{-0.878+2.57*\ln(h)})$	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					
$T=0.4535\ (e^{-0.599+2.30*\ln(h)})$	0.90	0.276	13	$d < 5$	1
$F=0.40\ (T)$				$h \leq 3.05$	
$F=0.33\ (T)$				$h > 3.05$	
$N=3.66-1.02(d)+.091(d^2)-.0011(d^3)$	0.79	35.28	60	$d \geq 5$	3
$F=0.5\ (N)$					

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

2 Tree sizes applicable for equations.

3 1. Brown (1978); 2. Johnson, Woodard, and Titus (1990); 3. Singh (1982).

Environment Canada, Banff, Alberta (115° 30' W, 51° 10' N). This station's weather represented typical fire-weather for the southern Canadian Rockies (Johnson and Wowchuk 1993). Wind speed at 10-m was adjusted to mid-flame height using the adjustment factor of 0.37. This value was equivalent to the standard value of 0.40 at 6.1-m height (Bradshaw *et al.* 1984) for an assumed logarithmic wind profile.

Daily moisture contents for surface fuel components (litter, dead timelag class fuels, herbs, shrubs, and moss/lichens) were calculated for the fire seasons of 1954-1988 using a FORTRAN program (Appendix 3). Herb, shrub, and dead-wood moisture contents were predicted from National Fire Danger Rating System equations for Climate Class 3 (Bradshaw *et al.* 1984). Litter moisture was predicted from the Fine Fuel Moisture Code of the Fire Weather Index System (Van Wagner 1987). Moss/lichen moisture was predicted from equations by Pech (1989).

Surface Fire Intensity Analysis

Surface fire intensity predictions from Rothermel's (1972) model were made using fuel loads from 47 forest stands and weather representing each day in July and August from 1954-1988. Remember that intensity (kW m^{-1}) is the product of the fuel variable (kW m^{-1}) and the weather variable (dimensionless). Variation in intensity predictions was partitioned between the fuel and weather variables using multiple regression for the log transformed model:

$$\log(I) = b_0 + b_1 \log(F_v) + b_2 \log(E_v) \quad \textbf{(18)}$$

I = intensity
b = partial regression coefficients
F_v = fuel variable
E_v = weather variable

In this analysis, regression was used to partition the sums of squares of intensity between the two variables rather than to predict an empirical relationship, since by definition this equation will have a perfect fit with each coefficient equal to 1. The relative roles of fuel and weather variables were then determined from the standardized partial regression coefficients which determine how strongly each variable (fuel variable or weather variable) influences the dependent variable intensity). Thus, this test was used as a kind of a sensitivity analysis with actual fuel and weather data, to see which of those two classes more strongly affected the fire intensity predictions.

Crown Fire Initiation Analyses

The relative importance of the crown fuel and weather variables in crown fire initiation were determined using predictions from the 47 sampled stands and 1968 summer weather. The year 1968 was chosen because it had a wide range of weather variable values, especially in the upper end of the range, due to a blocking high pressure system in July. These high values were needed to ensure that the logistic model would have a number of points for the upper asymptote (*i.e.* predicted crown fires). However, any other year with a high range of weather values would have given similar results in this analysis.

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:

$$Type = \frac{\exp(b_0 + b_1(C_x) + b_2(E_v))}{1 + \exp(b_0 + b_1(C_x) + b_2(E_v))} \qquad \textbf{(19)}$$

Type	=	Crown Fire Type: a binary variable
C_x	=	Passive or Active Crown Fuel Variable
E_v	=	Weather Variable

The logistic regression curve has asymptotes at zero and one, in which zero corresponds to fires which do not exceed the crowning criteria and one corresponds to crowning fires. The shape of the curve between the asymptotes is sigmoidal. The initiation of passive crown fires from surface fires was related to C_p and E_v. Initiation of active crown fires was examined in relation to C_a and E_v in two ways. Active crown fire initiation was examined first by excluding all surface fire predictions from the data and second, the surface fire predictions were included. The first test examined only passive to active crown fire transition, whereas the second test examined the entire surface to passive to active crown fire transition as if it were a single transition. The relative importance of crown fuel and weather variables was determined from the standardized partial logistic regression coefficients which indicated the magnitude of importance of the two variables in each analysis. Thus, this test again was a sensitivity-type analysis to show the importance of actual fuel and weather variation among crown fire initiation variation.

Graphical crown fire initiation model

A graphical representation of equation 16 was developed to show the ranges of weather at which the different types of fire behaviour could be expected for a set of normal forest stand crown fuel conditions (normal here meant all stands between the 10^{th} and 90^{th} percentiles of the two crown fuel variables). The fire behaviour classes determined were: no fires, all surface fires, all crown fires, and the transition range from surface to crown (*i.e.* some stands achieve crowning status while others remain as surface fires due to differences in fuels/crown structure). A separate graph was prepared for each of passive and active crowning. The purpose of this exercise was to demonstrate how the variability in the weather variable would affect crowning behaviour given the range of fuel conditions among stands. This graph will explain the results of the previous analysis by showing which ranges of the overall behaviour are controlled by weather versus fuel variation. Also, as the weather becomes more extreme, the relative role of the fuel variables in influencing fire behaviour will be demonstrated.

Weather Variable Analyses

As noted earlier in the model sections, the weather variable represents the effect of weather conditions on the potential magnitude of fire intensity for all forest stands of a forest region. The tests employed in this section examined how daily variation in the weather variable among fire seasons would affect the variation in predicted fire behaviour.

The weather variable (E_v) was predicted for all stands for each day of July and August, 1954-1988, and daily mean weather variable values (among stands) were determined. Frequency distributions of the weather variable were compared between year classes representing annual area burned in the southern Canadian Rockies. Large-area-burned years were years in which much greater than 30 ha of forest was burned in the combined area of Kootenay National Park, Yoho National Park, Banff National Park, and the Bow Crow Forest Reserve, Alberta. From 1954-1988, large areas burned during 10 years, while small areas (<< 30 ha) burned in 25 years (Johnson and Wowchuk 1993).

The first analysis was a comparison of weather variable frequency distributions between large and small-area-burned years, to determine if the difference between the two classes was related to weather variation as expressed in the fire models. The null hypothesis was that large-area-burned years had the same weather variable frequencies as small-area-burned years. Accepting this hypothesis would imply either that all years have an equal frequency of suitable conditions for large fires to develop, or that the fire-year classes differ but cannot be explained by the weather variable since the weather mechanism which relates to annual area burned is unrelated to the weather variable. The alternative hypothesis was that the weather variable distribution was shifted in large-area-burned years, such that those years were more likely to sustain large rather than small area fires. The frequency distributions were negative exponentials when the continuous weather variable was classed into discrete ranges. The frequency distributions of the weather variable were compared using a heterogeneity of slopes t-test (Zar 1984).

Intensity comparison between large and small fire years

The importance of large and small fire years on fire behaviour was also tested directly using the following ANOVA model:

$$\log(I) = b_0 + b_1\ group + b_2\ year(group) \tag{20}$$

I	= intensity predictions
group	= large or small-area-burned years
year(group)	= year nested within groups

Year nested within groups accounted for intensity variation among years. The significance of the group factor determined whether large and small-area-burned years differed in their mean predicted intensities.

The purpose of this test was to show the importance of weather variation among years on fire intensity predictions directly. Although the previous test examined the weather variable frequencies, there was still a possibility that a significantly different frequency distribution would not lead to significantly higher intensity predictions, because most values in the negative exponential weather frequency would still result in mainly low intensity predictions. Thus, the null hypothesis was that large-area-burned years and small-area-burned years had the same mean intensity predictions.

Fuel Variable Analyses

These analyses tested whether the potential for high intensity or crown fires, in lower subalpine conifer forests, was a function of fuel variation associated with either stand age or stand species composition (pine versus spruce stands). Remember from the model sections, that the surface and crown fuel variables were defined such that they related directly to surface fire intensity predictions from Rothermel's (1972) model or to crown fire initiation from the combination of Rothermel's (1972) and Van Wagner's (1977) models. These variables were independent of the weather and thus they provided the best method to examine the independent role of factors which affect fuel variation in terms of the potential for affecting fire behaviour variation among sampled forest stands.

Fuel variables and stand age

Regression was used to determine whether any or all of the three fuel variables increased with stand age, as would be predicted based on the belief that fire behaviour increases in older stands due to fuel build-up or crown structural changes (see Introduction). Scatter plots of each variable versus age were first examined to see whether a linear model would be appropriate. Other potential models could have been substituted (*e.g.* quadratic) if the plots indicated a non-linear relationship. The model chosen was the log-log transformed model, since this stabilized the fuel variable variances across the range of ages and better met the linearity assumption of regression.

The role of site features in influencing the fuel variables were also considered. These features were elevation (m), aspect (° : cosine transformed to make it a noncircular variable) and slope (°). Thus a multiple regression model was used to analyze each fuel variable:

$$VAR = b_0 + b_1(AGE) + b_2(ELEV) + b_3(ASP) + b_4(SLOPE) \tag{21}$$

The fuel variables were tested in two sets: a) all stands ; and b) all stands over 25 years of age. The reason for this split was that crown development was not observed in the stands less than 25 years of age, which may affect the surface fuel variable and should certainly affect the crown fuel variables. If the younger stands significantly alter the relationship between age and the fuel variables it may imply that as stands < 25 years of age become older, the fuel conditions may increase from a relatively lower intensity or crown fire potential state to a higher intensity/crowning potential state, as is also believed by some fire ecologists.

Fuel variables and stand types

The role of stand composition on the fuel variables was examined using one way analysis of variance. The stand composition classes were pine, spruce (fir), and pine/spruce mix as defined in Table 1. As in the regression analysis above, log-transformed values were used for all variables. For each analysis, the null hypothesis being tested was that the mean fuel variable value (and thus the potential fire behaviour independent of weather conditions) was no different between the pine and spruce classes. Note that stands less than 25 years of age were excluded from this analysis based on the disjunctions determined in the data set between the stands greater than and less than 25 years in the previous analysis. Thus, only stands with a developed crown were compared in these tests. Multiple comparison (Tukey) tests were performed when required. Fuel variable means with 95 % confidence limits for each significantly different compositional class were reported after each test.

RESULTS

Surface Fire Intensity Analysis

The relative role of weather was found to be much greater than the role of fuels in determining surface fire intensity (predicted from Rothermel's (1972) model). As expected, the logarithmic regression model found partial slopes of $\log(F_v)$, $\log(E_v)$, and also found R^2 equal to 1 (Table 7). The weather variable explained 83 percent of the regression sum of squares ($SS_{\log(Ev)}/SS_{reg}$), and had a standardized partial regression coefficient of 0.912. The fuel variable explained 15 percent of the model sum of squares and the standardized coefficient was 0.388. Due to rounding errors in the analysis, these values do not add up to 100%. A small residual sum-of-squares indicates a possible slight (non-significant) interaction between the two variables.

Crown Fire Initiation Analyses

Predicted crown fire initiation (determined from the models) was also mainly influenced by weather rather than fuels. All three multiple logistic regression models were significant at $p < 0.001$ (Table 8). In the passive crown fire initiation test, standardized regression coefficients were -1.80 for the weather variable and -0.38 for the passive crown fuel variable (Table 8a). In the first active crown fire initiation

TABLE 7. Multiple regression analysis of predicted surface fire intensity for 35 years of summer weather data and 47 forest stands in Kananaskis, Alberta, comparing the roles of the surface fuel and weather variables in intensity.

Dep. Var.: Log(I)		N=73984	$R^2 = 1.00$	$SE_E = 0.0151$	
Variable	Coeff.	S.E.	STD. COEFF.	t	P
Constant	0.001	0.001	0.0000	1.213	> 0.2
$Log(E_v)$	1.000	0.326E-04	0.9121	31000	< 0.001
$Log(F_v)$	1.000	0.766E-04	0.3883	31000	< 0.001

ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F	P
Regression	257276.5	2	128638.2	0.565E+09	0.000
$Log(E_v)$	213897.8	1	213897.8	0.940E+09	0.000
$Log(F_v)$	38768.6	1	38768.6	0.170E+09	0.000
Residual	16.9	73981	0.0002		

(for only those stands which achieved passive crowning; Table 8b) standardized regression coefficients were similar in magnitude (-4.51 for the active crown fuel variable and -2.95 for the weather variable). When active crowning was contrasted with all surface/passive fires, the standardized coefficients differed greatly in magnitude (-1.85 for the weather variable and -0.39 for the fuel variable; Table 8c). The similarity in the regression coefficients between the passive crown fire analysis and the second active crown fire analysis indicated that passive crown initiation was the main threshold to be surpassed to attain an active crown fire. That is, once this threshold was surpassed most stands had surpassed the active crown fire threshold.

Graphical crown fire initiation model

Figure 2a demonstrates the range of weather at which crown fires will ignite in normal stands in the Kananaskis Valley. Not shown on the graph, is the point where the weather variable equals 0, and correspondingly no fires are possible. At this point, weather completely dominates the possible range of fire behaviour, since none is allowed. This single point actually represents a very common set of weather conditions, as will be seen in the next section. The weather range from > 0 to approximately $E_v = 1$, is the surface fire range. Within this range all fires will remain as surface fires; this again demonstrates a range in which weather dominates the fire behaviour by being too moist/calm for crown fires to develop. The next range, from $1 < E_v < 10$, there will be a difference in crowning status among stands due to fuel/crown structural differences; within this transitional range, fuel differences

TABLE 8. Multiple logistic regression results for crown fire initiation versus crown fuel and weather variables for 47 stands and weather data from 1968 for a) passive crown fires versus surface fires, b) active crown fires versus passive crown fires only, and c) active crown fires versus surface or passive crown fires.

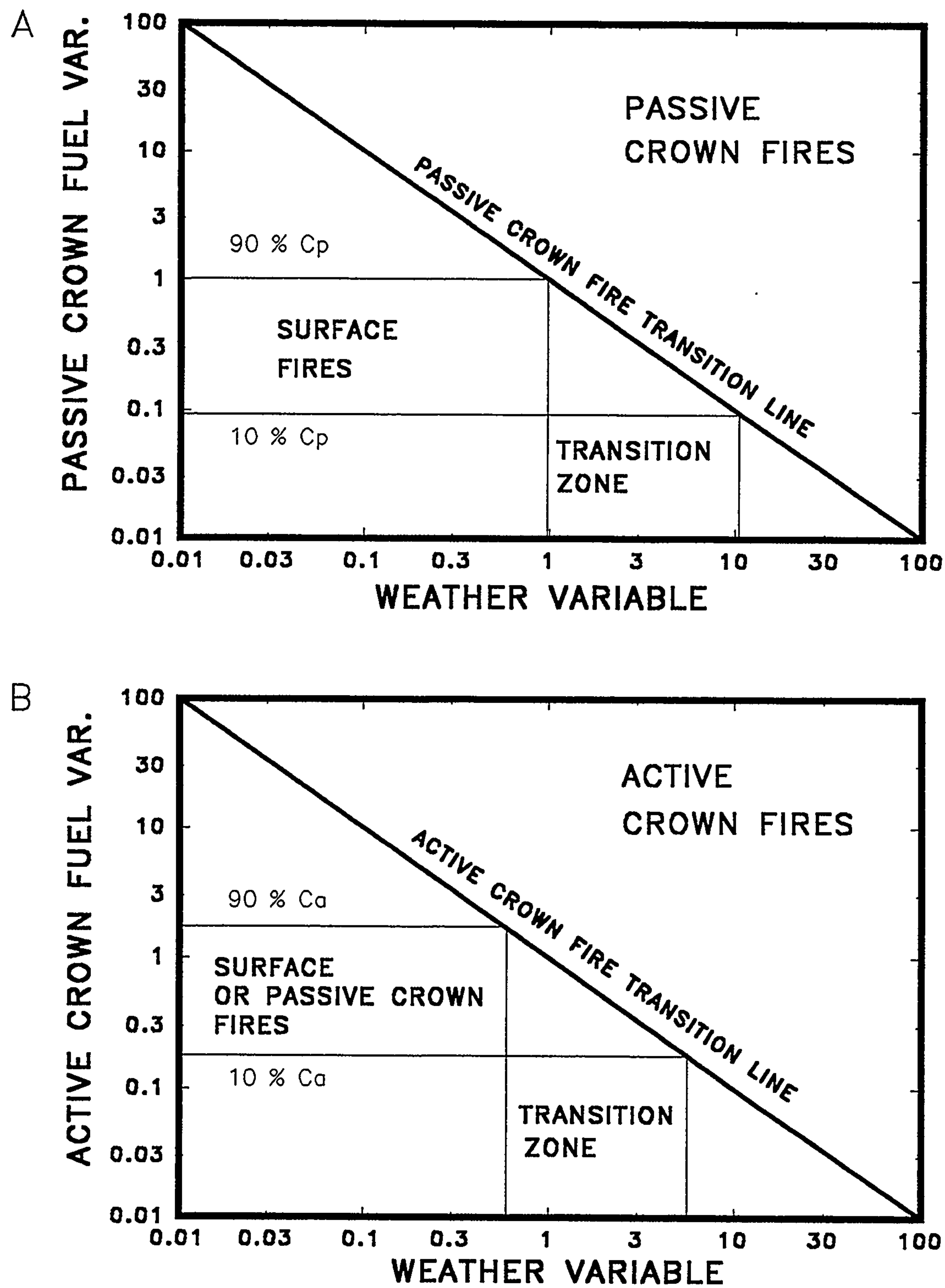
a) Passive Init.		n = 2914	-2LL χ^2 =1684	p<0.0001	
	Coef.	S.E.	Std. Coef.	Wald χ^2	p
Intercept	2.7027	0.0904	.	893.87	0.0001
PCFV	-0.1324	0.0095	-0.3768	196.24	0.0001
Weather	-0.5249	0.0212	-1.7988	611.20	0.0001

b) Active Init.		n = 992	-2LL χ^2 = 842	p=0.0001	
	Coef.	S.E.	Std. Coef.	Wald χ^2	p
Intercept	7.0158	0.6806	.	106.26	0.0001
ACFV	-10.8505	1.0447	-4.5109	107.87	0.0001
Weather	- 0.6654	0.0766	-2.9532	75.50	0.0001

c) Active Init.		n = 2914	-2LL χ^2 = 1715	p<0.0001	
	Coef.	S.E.	Std. Coef.	Wald χ^2	p
Intercept	4.2055	0.1587	.	701.85	0.0001
ACFV	-1.0165	0.0869	-0.3859	136.80	0.0001
Weather	-0.5385	0.0219	-1.8453	606.15	0.0001

-2LL = Negative two log likelihood
Active Init. = Active crown fire ignition
Passive Init. = Passive crown fire ignition
PCFV = Passive crown fuel variable
ACFV = Active crown fuel variable
Weather = Weather Variable

FIGURE 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 equation 16 of the crown fire model section. Both figures show the range for stands in which crown fuel variables range between the 10^{th} and 90^{th} percentiles of all crown fuel values. A) Passive crown fuel variable (C_p); B) Active crown fuel variable (C_a).


A
100
30
10
3
1
0.3
0.1
0.03
0.01
PASSIVE CROWN FUEL VAR.
PASSIVE
CROWN FIRES
PASSIVE CROWN FIRE TRANSITION LINE
90 % Cp
SURFACE
FIRES
10 % Cp
TRANSITION
ZONE
0.01 0.03 0.1 0.3 1 3 10 30 100
WEATHER VARIABLE
B
100
30
10
3
1
0.3
0.1
0.03
0.01
ACTIVE CROWN FUEL VAR.
ACTIVE
CROWN FIRES
ACTIVE CROWN FIRE TRANSITION LINE
90 % Ca
SURFACE
OR PASSIVE CROWN
FIRES
10 % Ca
TRANSITION
ZONE
0.01 0.03 0.1 0.3 1 3 10 30 100
WEATHER VARIABLE

have their relatively greatest influence on fire behaviour. However, as the weather reaches progressively higher values within the transition range, more and more stands achieve crowning status, meaning that the weather is still playing an important role within this range. Once $E_v > 10$, weather again is the only influential factor on fire behaviour since all stands are crowning, and thus there are no differences among stand fuel conditions. Crowning is dominated by weather for all conditions except the transition range, in which case both fuels and weather play an important role. Once extreme weather conditions ($E_v > 10$) are achieved fuels play no further role in the determination of crown initiation since all stands have achieved the threshold intensities required for crown initiation.

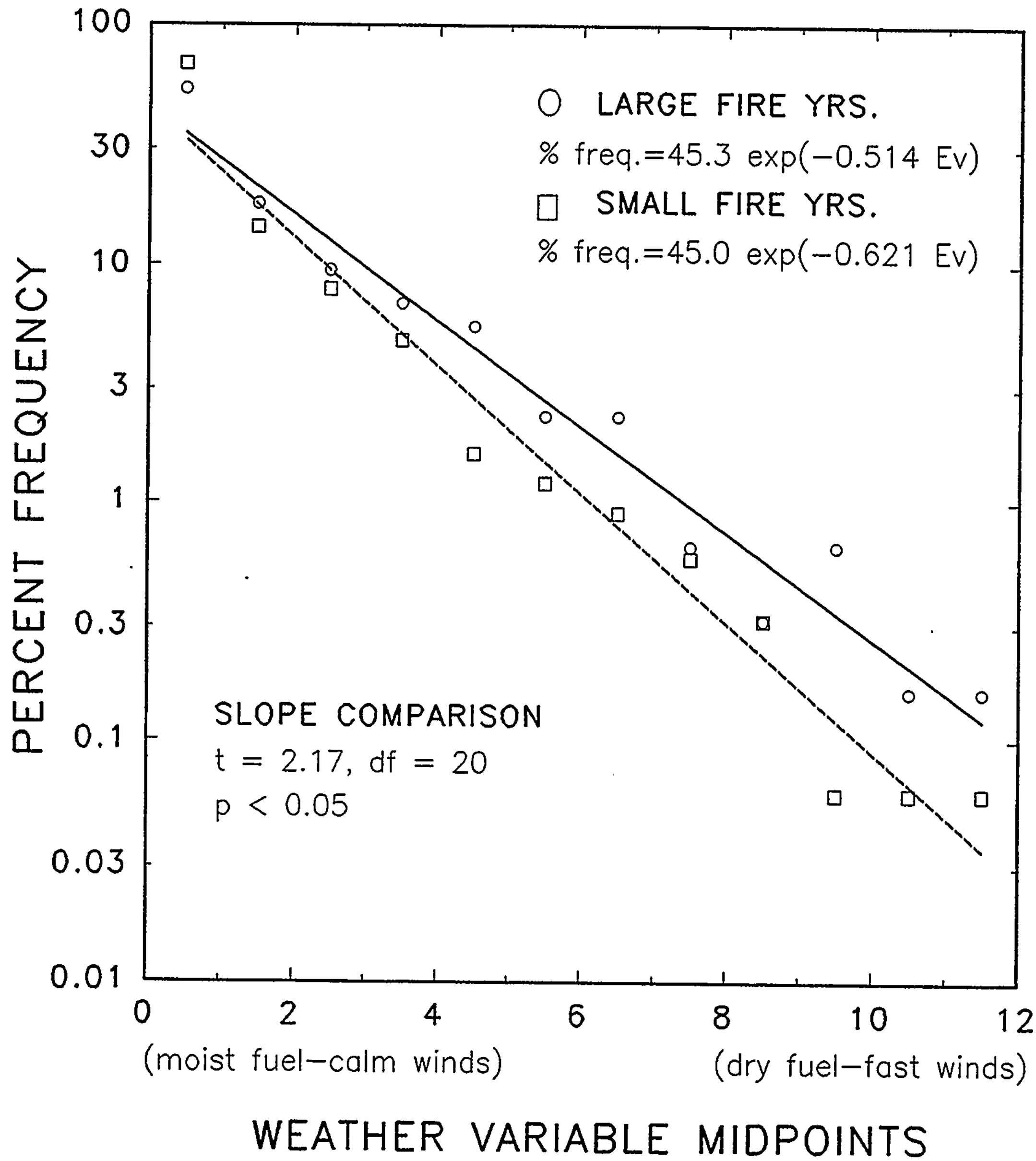
Figure 2b shows the corresponding lines for active crown fires. Since the passive crown fire threshold must be achieved prior to the active crown fire threshold, and since the minimum and maximum values of the passive crown variable exceed the minimum and maximum for the active crown variable, the ranges described above will also pertain to active crown fires.

Weather Variable Analyses

The tests employed in this section examined how daily variation in the weather variable among fire seasons would affect the variation in predicted surface fire intensity and crown fire initiation. The first analysis was a comparison of weather variable frequency distributions between large and small-area-burned years. The null hypothesis was that large-area-burned years had the same weather variable frequencies as small-area-burned years. The percent frequency distribution of the daily values of the weather variable for July and August 1954-1988, was shown to decline exponentially (% Freq. = 0.433 $(E_v)^{-0.566}$, $r^2=0.98$, df=10, $p<0.01$). This negative exponential relationship explains that the daily weather variation is slanted towards mostly low values (days in which fires are unlikely to burn intensely) and that very few days reach extreme conditions which can result in high intensity fires.

Large and small-area-burned years had significantly different weather variable distributions (Figure 3, df=20, t=2.99, $p<0.05$). Note from the figure that the difference between the frequency of days at the low end of the weather distribution, for the two year classes, was slight, while the difference between the two classes in the frequency of extreme weather values was great (>3 times higher for weather variable values of 10 or more, which includes all weather which will cause crowning in normal stands in the study area). The null hypothesis stated above was rejected. Thus, the weather variable distribution was shifted in large-area-burned years, such that some days in those years were much more likely to sustain high intensity fires than days in small-area-burned years. It cannot be directly shown that high intensity fires will be larger fires, but this seems to be a plausible connection, since higher intensity fires will have greater rates of spread, and therefore cover greater area within a unit time span. Large-area-burned years exist most likely because the weather is much more extreme than normal for only a few days in those years, not due to slightly dryer/windier conditions over the entire summer.

FIGURE 3. Weather variable frequency distributions (percent frequency of days with weather values within each range class, versus 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).



100
30
10
3
1
0.3
0.1
0.03
0.01
PERCENT FREQUENCY
O LARGE FIRE YRS.
% freq.=45.3 exp(−0.514 Ev)
□ SMALL FIRE YRS.
% freq.=45.0 exp(−0.621 Ev)
SLOPE COMPARISON
t = 2.17, df = 20
p < 0.05
0
2
4
6
8
10
12
(moist fuel—calm winds)
(dry fuel—fast winds)
WEATHER VARIABLE MIDPOINTS

Fire intensity comparison between large and small fire years

Mean intensity predictions for large-area-burned years were different from small-area-burned years (Table 9, $p < 0.001$: see Figure 4), although there was also significant variation between the means for individual years within each class ($p < 0.001$). The mean intensities ($\pm$ standard deviations) were 41.4 ± 17.26 kW m^{-1} in small-area-burned years, and 105.8 ± 15.16 kW m^{-1}. The mean intensity predictions were not highly informative as to how fires would burn, because they included all low intensity days as well as high days. Instead the means indicated that large-area-burned years generally had greater fire behaviour potential than small-area-burned years. Thus, the null hypothesis that fire behaviour potential (due to differences in weather) was no different between the two categories was not accepted. Note from Figure 4 that most large-area-burned years have much higher means than most small-area-burned years, but also that there is some overlap. This overlap indicated that some large-area-burned years have weather similar to small-area-burned years and vice-versa. These could possibly indicate years in which large fires occurred during short-lived extreme weather periods, and alternatively years which had the kind of weather typical of large-area-burned years but during which no large wildfires occurred due to "missed opportunity".

TABLE 9. 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 years of summer weather (July 01 - August 31) 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).

N = 101990 R-SQUARED = 0.062

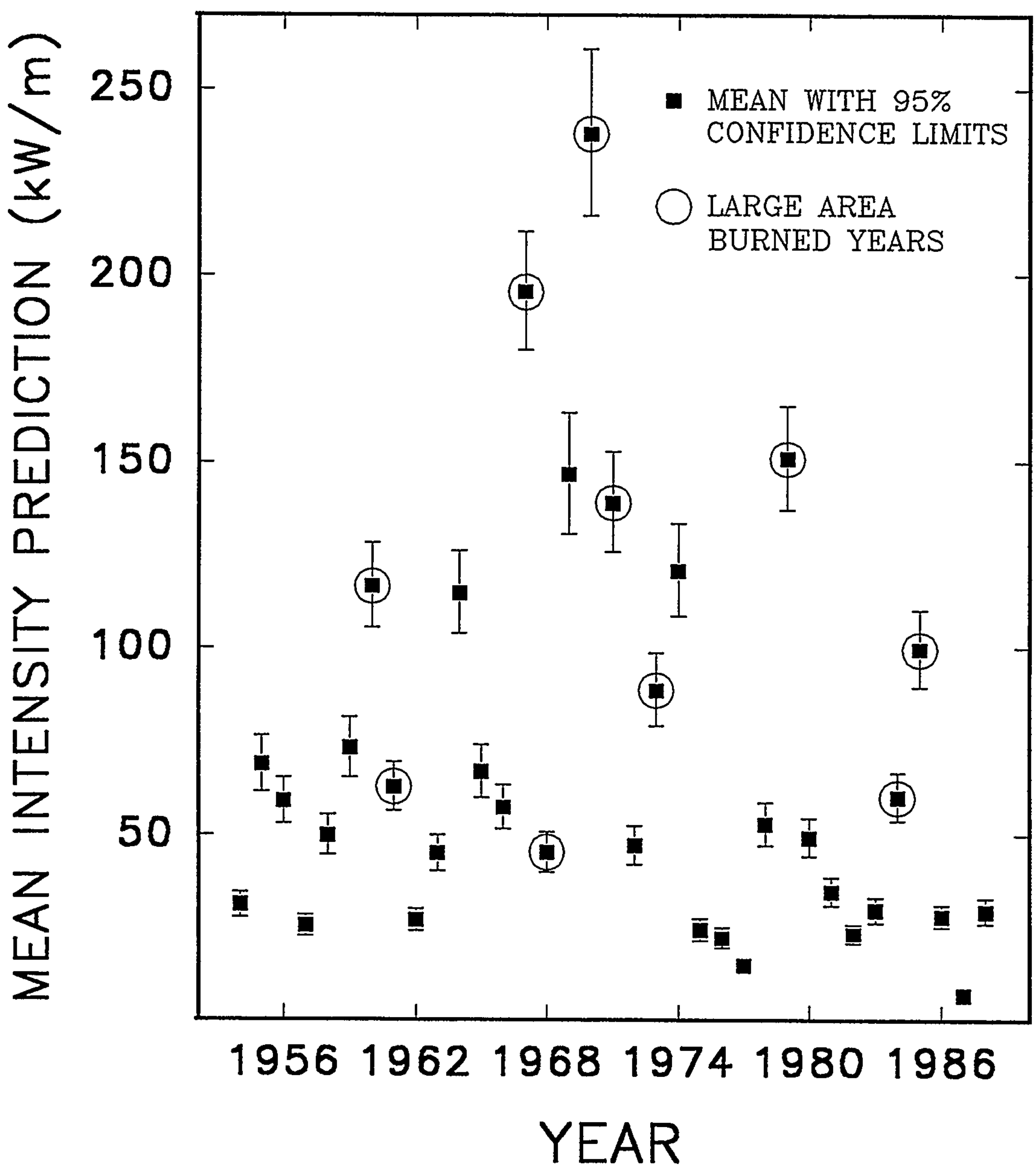
ANALYSIS OF VARIANCE TABLE

SOURCE	DF	MS	F	P
GROUP[1]	1	17728.1	2246.5	< 0.001
YEAR(GROUP)[2]	33	1087.7	137.8	< 0.001
ERROR	101955	7.8		

1 Group = Large or small-area-burned years.

2 Year(Group) = Years nested within groups.

FIGURE 4. Mean intensity predictions with 95% confidence limits for each summer fire season (July 01 - August 31) from 1954-1988. Large-area-burned years are circled to demonstrate the difference between the two year 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.


MEAN WITH 95% CONFIDENCE LIMITS
LARGE AREA BURNED YEARS
MEAN INTENSITY PREDICTION (kW/m)
50
100
150
200
250
1956
1962
1968
1974
1980
1986
YEAR

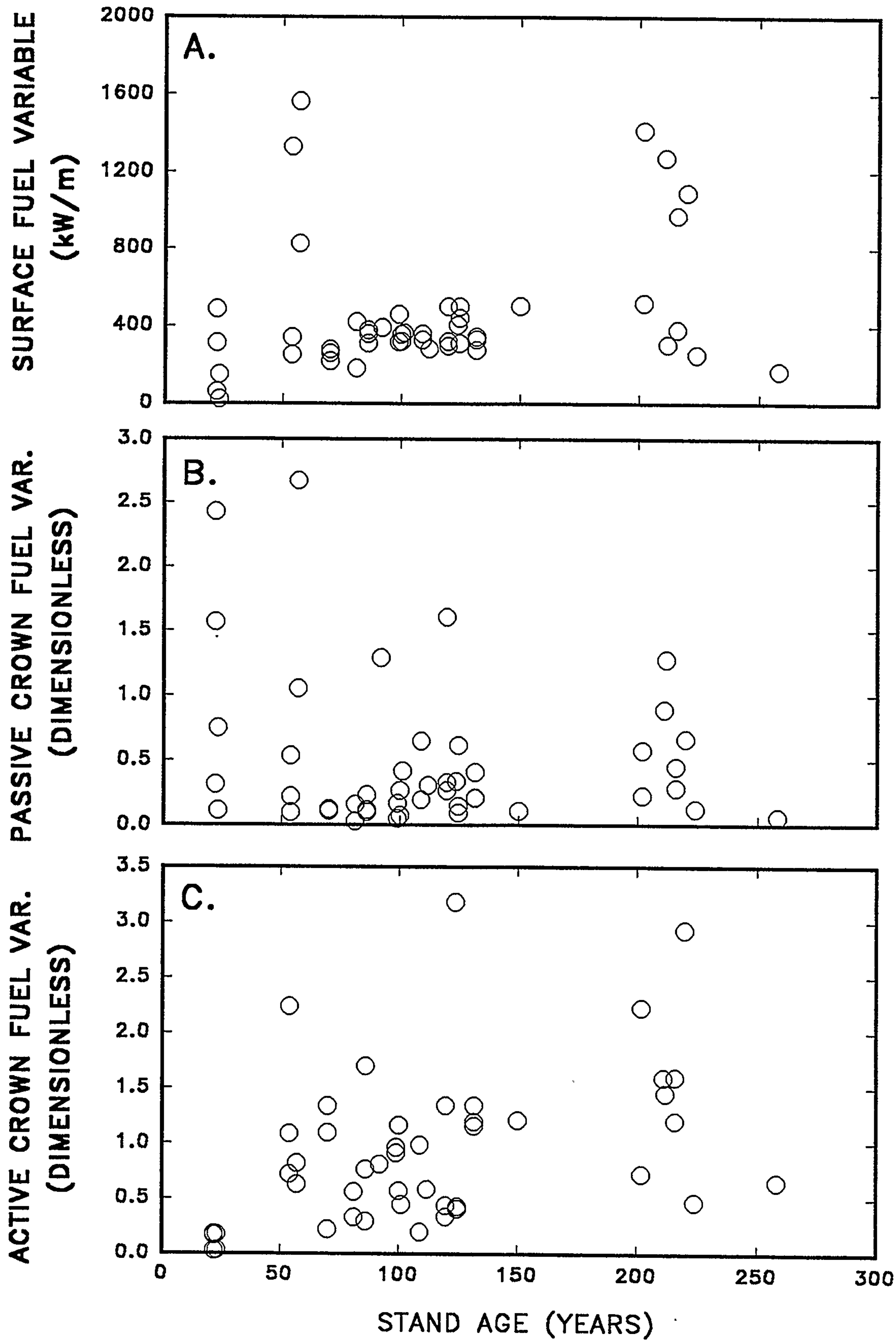
Fuel Variable Analyses

Fuel variables and stand age

None of the three fuel variables (F_v: surface fuel variable, C_p: passive crown fuel variable, and C_a: active crown fuel variable) had a significant relationship with any of the stand covariates (elevation, aspect, or slope) so these were dropped from the multiple regression model via the backward elimination procedure, leaving simple regression analyses between the fuel variables and stand age (Figure 5). The simple regression coefficients between each fuel variable and stand age are presented in Table 11. Note that the analysis was split into two sets: stands with ages less than 25 years were alternatively included or excluded from the analysis.

The surface fuel variable (F_v) was unrelated to age for stands older than 25 years (Table 10). However, among all stands there was a positive relationship with age which explained 18% of the regression sum of squares. However, this latter regression analysis was seriously affected by outliers and only the two lowest fuel variable values were causing the slope to become significant. The plot of surface fuel variable versus age (Figure 5a) indicated two distinct populations of stands with regard to the fuel variable: those with values below 600, and those above 800. The latter stands were found to differ from the others by having high fuel loads comprised of litter or moss, rather than an even mix of these two fuel components. The results of this regression analysis were that stand age was poorly related to the fuel variable, and thus the potential fire intensity (independent of weather's influence) was not

FIGURE 5. Surface and crown fuel variables plotted against stand age. a) surface fuel variable (F_v), b) passive crown fuel variable (C_p), c) active crown fuel variable (C_a).



SURFACE FUEL VARIABLE (kW/m)
2000
1600
1200
800
400
0
A.
PASSIVE CROWN FUEL VAR. (DIMENSIONLESS)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
B.
ACTIVE CROWN FUEL VAR. (DIMENSIONLESS)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
C.
0
50
100
150
200
250
300
STAND AGE (YEARS)

TABLE 10. Simple regression coefficients of surface and crown fuel variables (log transformed) versus stand age (log transformed) in two sets: all ages and ages < 25 y removed.

DEP. VAR.	YEARS	COEFF.	N	t	p
$\log(F_v)$	ALL	0.473	47	3.136	0.003
$\log(F_v)$	> 25	0.104	42	0.537	0.594
$\log(C_p)$	ALL	-0.294	47	-1.065	0.292
$\log(C_p)$	> 25	0.205	42	0.581	0.564
$\log(C_a)$	ALL	0.966	47	5.194	0.000
$\log(C_a)$	> 25	0.326	42	1.393	0.171

F_v: Surface Fuel Variable (kW m^{-1})
C_p: Passive Crown Fuel Variable (dimensionless)
C_a: Active Crown Fuel Variable (dimensionless)

strongly related to stand age.

The passive crown fuel variable was unrelated to age if all ages were examined or if stands less than 25 years of age were removed (Table 10; Figure 5b). These results arise from the wide variation in mean lower crown base heights (see Appendix 1). Thus, passive crown fire initiation does not relate to age. Like the surface fuel variable, the active crown fuel variable was very low in stands younger than 25 y (Figure 5c) so that a significant relationship to age was seen if these were included, but no relationship was found for ages greater than 25 y alone. The five stands younger than 25 y did not have a closed-crown and thus crown fuel loads and bulk densities were much lower and critical rates of spread were disproportionately higher (Appendix 1). Thus, like the surface fuel variable, the active crown fire initiation variable was unrelated to stand age throughout most of the age of the stands, but showed a significant increase if stands less than 25 years of age were included. This may indicate that fuel variables undergo an initial increase from sometime between 0 and 50 years (or during closed-crown development), followed by no further increases throughout the age of the stand.

Fuel variables and stand types

In this analysis, the three fuel variables were examined using analyses of variance between the three stand types (pine, spruce, and pine-spruce mix: Table 11). The 5 stands less than 25 y were excluded from this analysis so as not to affect the results. The surface fuel variable did not differ among the three stand types (ANOVA:

$p > 0.1$). The mean value for the fuel variable (back transformed from the logarithmic form) was 412 kW m^{-1} (lower 95% confidence limit (lcl) = 348, upper 95% confidence limit (ucl) = 488). The passive crown fuel variable also did not differ significantly among stand types (ANOVA $p > 0.25$). The mean value was found to be 0.37 (lcl=0.25, ucl=0.49). The active crown fuel variable, however, was significantly different ($p < 0.001$) among classes. Tukey test results indicated that spruce differed from both pine and the pine/spruce mix classes, while the pine and mix classes did not differ. The means of the active crown fuel variable for each of the three stand types were: pine: 0.81 (lcl=0.61, ucl=1.03); mix: 0.49 (lcl=0.32, ucl=0.68); spruce: 1.44 (lcl=1.07, ucl=1.88).

TABLE 11. Analysis of variance model results followed by Tukey tests where appropriate, comparing the three fuel variables among the 3 stand types.

A. Surface Fuel Variable

Test Performed	D.F.	F	P	Conclusion
ANOVA	2,39	1.805	>0.1	No differences

Tukey: N.A.

B. Passive Crown Fuel Variable

Test	D.F.	F	P	Conclusion
ANOVA	2,39	1.103	>0.25	No differences

Tukey: N.A.

C. Active Crown Fuel Variable

Test	D.F.	F	P	Conclusion
ANOVA	2,39	11.498	<0.001	Classes differ

Tukey	Mean 1	Mean 2	q	D.F.	P
pine vs spruce	0.257	0.388	4.890	39, 3	< 0.005
pine vs mix	0.257	0.172	2.592	39, 3	> 0.1
mix vs spruce	0.172	0.388	6.290	39, 3	< 0.001

DISCUSSION

Predicted forest fire behaviour in lower subalpine *Pinus contorta - Picea engelmannii* forests of the southern Canadian Rocky Mountains, based on Rothermel's (1972) and Van Wagner's (1977) models, is much more strongly related to weather variation (over time) than to fuel variation (among stands). 83% of the variation in surface fire intensity was explained by the weather variable, whereas only 15% was explained by the fuel variable. Likewise, variation in crown fire initiation was much more strongly related to the weather variable than to the active or passive crown fuel variables. Furthermore, the weather variable controlled conditions in which fires could or could not burn, (*i.e.* when the value of the weather variable was zero, conditions were too wet for burning to occur in the models). In comparison, the fuel variable was always greater than zero and therefore could not be controlling whether or not fires could burn.

Weather is much more important than fuel in fire behaviour for two reasons. First, weather is more strongly associated with the mechanisms of fire behaviour than fuel. For example, windspeed strongly affects heat transfer rates by increasing both radiative heat transfer (due to flame tilt) and convective heat transfer (Rothermel 1972). Fuel combustibility and heat loss rates are also strongly dependent on the moisture content of the fuels (Rothermel 1972). In contrast, fuel primarily acts as the burn substrate which provides the heat of combustion for the fire, and fuels also determine the base rate of combustion as a function of the size class distribution and packing ratio of fuel particles (Rothermel 1972). Thus, fuels set the base rates or base intensity which is modified up or down by many orders of magnitude depending on the moisture content and wind speed. This can be seen directly via the fuel and weather variables whose product is intensity. Each stand has a static fuel variable value which dictates the intensity the fire would burn under conditions of no weather (no weather here means 0 % moisture content and 0 m s^{-1} wind speed). The fuels determine a single, static value, which can be modified down (by weather variable values from 0 to 0.99) to much lower intensities, or up (by weather variable values from 1 to 30 or more) to much higher intensities.

The second reason that fuels are less important than weather is that the rates of change of weather (moisture content and windspeed) within a forest stand greatly exceeds the rates of change of fuel loads, size class distribution, or packing ratio within stands. Fuel moisture contents may range from approximately 5 to over 100 percent (by dry mass) and fine fuel moisture which is most important in Rothermel's (1972) model have a 1 hour response time in which they can lose approximately 2/3 of their moisture (Bradshaw et al 1984), hence the name 1 hour time-lag fuels. Windspeed may range from 0 to over 100 km h^{-1} and can change within a few minutes to a few hours. Some of the most spectacular wildfire runs have occurred when windspeed suddenly increases by 2-3 times its previous speed (Simard et al 1983, Fryer and Johnson 1988) indicating the strong role of variation in this component.

Fuel variation within stands occurs over such long periods (years to decades) that it may almost be ignored. The only important variation in fuel loads exists among stands of differing forest type and history (stand age, developmental stage, past disturbance, *etc.*). This could affect a fire which passes from one stand type to another, especially if their were large differences in crown base height or surface fuel load. However, the amount of variation among stands is still generally low. In the stands sampled in Kananaskis, Alberta, total burnable fuel loads ranged from 0.5 to 3.6 kg m^{-2} (Appendix 1), which amounts to only a 7-fold difference among stands, and crown base heights (for stands which had closed crown development) ranged from 1.3 to 13.7 m or a 10-fold difference. The fuel loads reported here are not substantially different from ones in similar *Pinus contorta* forests (*e.g.* Brown and Bevins 1986, Romme 1982, Fischer 1981, Lawson 1973, Muraro 1971, Kiil 1968). Fuel loads represent a balance between new inputs and decomposition, which explains why the fuel loads are constrained from increasing to extremely high values or from decreasing until no fuel remains (Turner and Long 1975). 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 (Spies *et al.* 1988, Lotan *et al.* 1985, Romme 1982, Fischer 1981), but large fuel components play only a minor role in the active spread rate and intensity at the fire front compared to the role of fine dead or cured fuels (Brown 1983, Rothermel 1972). Although the amount of variation in the fuels reported above may seem high, remember that this must be compared to the variation in the weather variable. The fuel variable did not reach values below 20 kW m^{-1} or above 1600 kW m^{-1} meaning that fire behaviour predictions were constrained to an approximate 80-fold difference related to fuel variation, compared to a 10 000-fold difference related to variation in the weather variable.

More important to the understanding of the comparative role of fuels in fire behaviour stems from the relationship shown in the crown fire graphical model (Figure 2) and the relationship between this result and the weather variable analyses. The first result showed that the crown fire initiation threshold can be achieved by most conifer stands at the weather variable value of 10 or more. The weather variable analysis showed, however, that values in excess of 10 are extremely rare, occurring only in 0.2 percent of days on average for the July-August fire season. However, the likelihood of crown fire weather was 3 times higher in large-area-burned years when compared to small-area-burned years. Predicted weather variable values throughout the entire range of this variable, and more importantly, predicted intensity for fires occurring in large-area-burned years were also substantially higher than values in small-area-burned years. In combination, these two results support the idea that weather differences (at very high to extreme values) between the two year-classes are driving the occurrence of large and small-area-burned years, and thus, that fires which burn during those years are typically high intensity/crown fires in which the role of fuel variation in determining fire behaviour variation is relatively unimportant. (The hypothesized mechanism which relates large area burned fires to crown fires is that crown fires have much greater rates of spread than surface fires (Van Wagner 1980), such that larger areas burn within a given time period.) The importance of this connection is made more clear by the relative importance of the area of fires which burn (in large crown fires) in large-area-burned years as opposed to the area of small fires which burn in marginal weather during large or small-area-burned years; 99 percent of the area burned by non-intentionally set fires occurs in the large fires of large-area-burned years, while only 1 percent of the total area is burned by all other non-intentional fires (J. Weir and E. Johnson pers. comm.). Thus, fires which are significantly affected by fuel variation are not important in the fire cycle of the Canadian Rocky Mountains. These areas may still be important as mortality agents in localized areas, but are unimportant forces of mortality over the entire forested landscape when compared to larger fires.

In this study, fuels were not found to be strongly related to age or stand composition class with two notable exceptions. First, stands less than 25 years of age have considerably lower surface fuel variable values and active crown fuel variable values. This reflects the lack of closed crown development in these stands and also little source for fuel input other than herbaceous regrowth. Nevertheless, it is unlikely that these stands will differ substantially in fires in large-area-burned years because the passive crown fuel variable is still unrelated to age in these young stands and because the passive crown fuel variable is the more important variable in the determination of crown fire initiation. Differences due to age would only be prominent in fires which burn during marginal weather in small-area-burned years. Second, spruce stands have much higher active crown fuel variable values than pine or mixed pine/spruce stands. This reflects the much greater basal areas of spruce stands which results in greater crown fuel volumes than seen in pine forests. Again, the same argument as used above is applied to show that this is not a likely factor affecting fire behaviour in large-area-burned years. Independent of the weather reasons, though, it can be seen that other than the exception noted, there is very low relationship between stand age and fuels, and thus for all fires, large or small, fire behaviour will be essentially unrelated to age.

Why do so many ecologists think that fuels are highly important to fire behaviour in coniferous forests? A simple answer to this may be that some fire ecologists believe that fire is mainly a plant community attribute (*e.g.* Heinselman 1973, Mutch 1970). Fuels are also easily measured and can be more easily managed as compared to fuel moisture content or windspeed. These reasons have probably been partially responsible for numerous studies on fuel loading in coniferous forests (*e.g.* Fischer 1981). Fuel loading as stands age has also been shown in some ecosystem types, notably surface fire affected systems such as chaparral (Riggan *et al.* 1988), to be key to understanding the fire regime in those types, and this has been extrapolated to conifer systems as a working model of fire behaviour even though this age-fuel relationship does not hold for closed canopy coniferous subalpine forests in this study or others (Romme 1982, Fahnestock 1976). Thus, changes in plant structure and fuel loads over time are assumed to play an important role in fire behaviour and frequency in coniferous forests of different ages (Romme and Despain 1989) even if evidence for this is not strong (Renkin and Despain 1992). Finally, it seems clear that many ecologists have misunderstood the role of weather in determining the patterns of fire occurrence and area burned. Fires which occur in marginal weather may often be strongly affected by age, fuel load or crown structural differences while those which burn during extreme weather are unaffected by these factors (Fryer and Johnson 1988, Johnson and Larsen 1991). For example, during moderate weather a fire burning in a spruce dominated stand with low crown bases can more easily maintain crown fire status than the fire which passes out of the spruce stand into a pine stand with elevated crown bases (*e.g.* Despain and Sellars 1977), while in extreme weather conditions spruce and pine stands will burn equally well as crown fires (*e.g.* Fire Danger Group 1992). Unfortunately, it is still the opinion of some ecologists that large fires such as the Yellowstone fires of 1988 (Romme and Despain 1989) were not normal fire events and that most fires have behaviour determined by fuel variation among stand ages and types (D. Despain pers. comm., W. Romme pers. comm.). Given the arguments above about the areas burned by large and small fires, it is more likely that the reverse is true.

CONCLUSION

Variation in surface fire intensity in lower subalpine forest stands in the southern Canadian Rockies (predicted from Rothermel's 1972 model), was primarily determined by weather (fuel moisture and windspeed), rather than by variation due to fuels. Fires which 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 independent of fuel conditions or stand type.

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

The lack of any strong relationships between fuel variables (and thus fire behaviour) and age or stand classes, and the overall larger importance of weather than fuel in fire behaviour supports the use of the negative exponential model for determining fire frequencies from stand age distributions (Johnson and Larsen 1991, Masters 1990, Johnson, Fryer, and Heathcott 1990). This is because the negative exponential model assumes the fire hazard to be constant with age, and to affect all stands with equal probability (Johnson and Van Wagner 1985).

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APPENDIX 1.

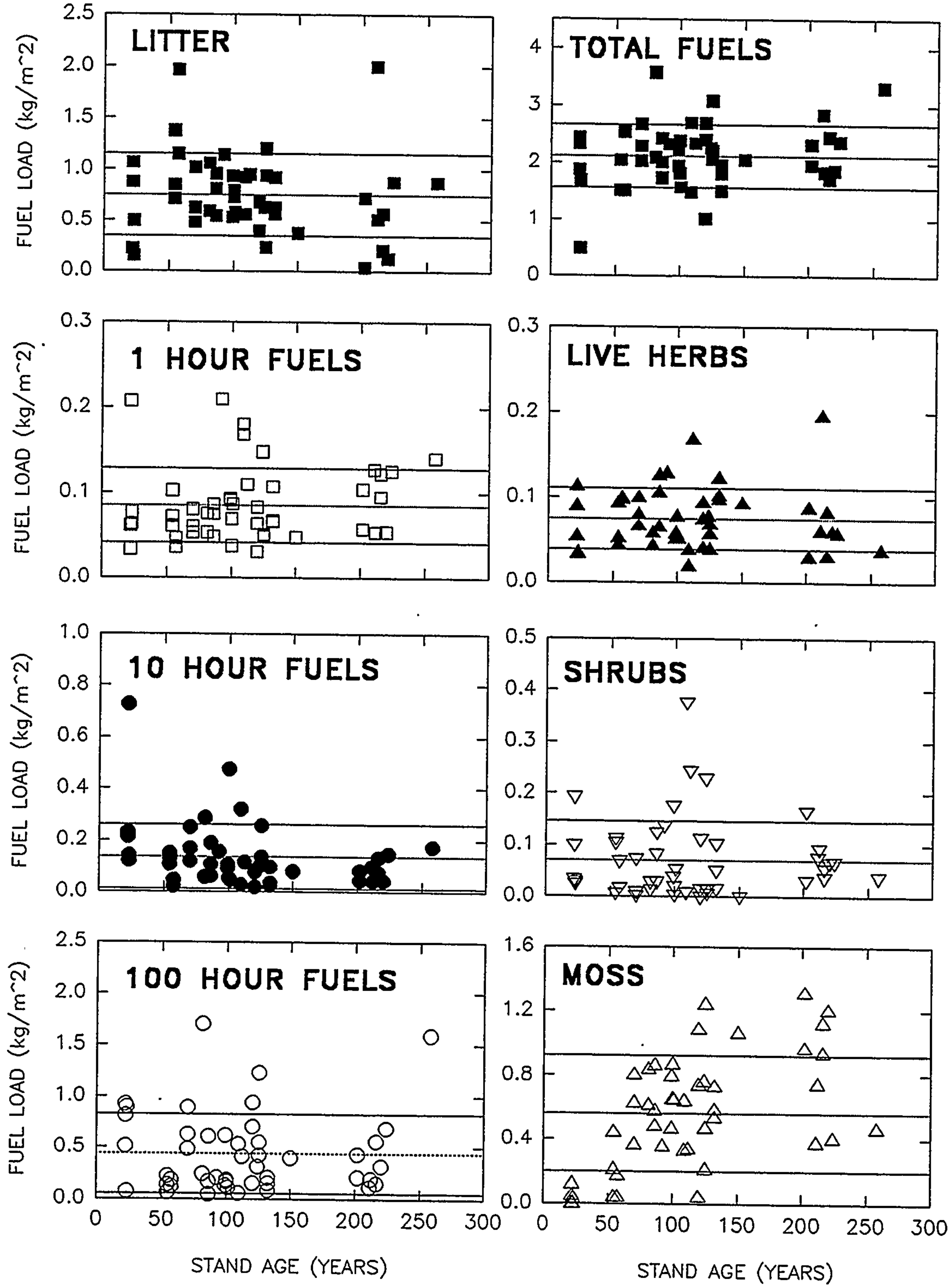
Stand fuel data the 47 lower subalpine stands including stand age, mean fuel component loads and crown heights. Also included there are the calculated mean depths and surface area to volume ratios from Rothermel's (1972) model, the fuel variable, critical intensity and critical rate of spread, and crown fuel variables.

SITE	AGE (y)	LITTER (kg m^{-2})	TIME-LAG CLASS FUEL LOADS 1 HOUR (kg m^{-2})	10 HOUR (kg m^{-2})	100 HOUR (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
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	FUEL LOADS (CONT'D) HERBS (kg m^{-2})	SHRUB (kg m^{-2})	TOTAL FUEL (kg m^{-2})	BULK DENSITY (kg m^{-3})	FUEL DEPTH (m)	SA/ VOL. (cm^{-1})
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

SITE	CROWN DEPTH (m)	CROWN BASE (m)	TREE FOL. (kg m^{-2})	FUEL VAR (kW m^{-1})	CRIT. INTENS. (kW m^{-1})	CRIT. R.O.S. (m s^{-1})	PASS. CROWN VAR.	ACTIVE CROWN VAR.
1	7.9	3.0	1.04	365	871	0.38	0.419	0.447
2	7.1	7.2	1.12	310	3256	0.32	0.095	0.405
3	4.7	10.1	1.16	183	5463	0.20	0.033	0.334
4	2.1	4.4	1.40	342	1553	0.08	0.220	2.240
5	4.6	4.7	2.42	219	1729	0.10	0.127	1.096
6	3.2	5.5	2.05	260	2206	0.08	0.118	1.342
7	11.2	2.1	3.56	330	508	0.16	0.649	0.968
8	5.7	6.4	2.52	170	2733	0.11	0.062	0.651
9	5.3	6.0	0.94	1330	2492	0.28	0.534	1.090
10	3.9	6.0	1.08	252	2501	0.18	0.101	0.724
11	7.5	4.9	2.85	317	1847	0.13	0.172	0.966
12	6.0	5.9	2.03	1416	2450	0.15	0.578	2.228
13	12.3	4.9	0.77	360	1825	0.80	0.197	0.202
14	4.1	5.4	1.23	973	2147	0.17	0.453	1.603
15	6.8	4.1	2.25	1275	1429	0.15	0.892	1.595
16	4.6	13.7	1.06	460	8553	0.21	0.054	0.913
17	6.9	5.1	1.40	253	1959	0.25	0.129	0.470
18	6.3	4.3	2.89	499	1513	0.11	0.330	1.343
19	5.9	1.5	0.77	825	309	0.38	2.671	0.630
20	3.7	3.1	0.83	283	918	0.22	0.308	0.585
21	7.4	6.1	0.73	279	2533	0.51	0.110	0.222
22	5.8	3.9	2.44	277	1326	0.12	0.209	1.164
23	3.7	7.2	2.20	379	3243	0.08	0.117	1.701
24	8.9	9.4	1.72	358	4850	0.26	0.074	0.573
25	3.7	3.7	1.90	322	1200	0.10	0.269	1.168
26	6.4	6.8	1.73	311	3030	0.18	0.103	0.768
27	5.6	2.8	0.73	498	807	0.38	0.617	0.410
28	10.6	4.4	1.04	361	1554	0.51	0.232	0.296
29	7.6	4.3	1.14	1563	1484	0.33	1.054	0.822
30	5.9	2.9	2.56	345	843	0.11	0.409	1.346
31	8.2	9.0	3.23	502	4555	0.13	0.110	1.213
32	4.7	4.6	2.47	1093	1644	0.09	0.665	2.930
33	4.9	6.6	0.94	442	2897	0.26	0.152	0.427
34	3.8	1.3	2.00	306	240	0.10	1.278	1.454
35	3.1	0.1	0.26	151	200	0.58	0.753	0.176
36	1.6	0.2	0.05	23	200	1.55	0.114	0.036
37	6.7	0.2	0.66	321	200	0.51	1.607	0.337
38	9.2	1.5	2.55	392	305	0.18	1.288	0.816
39	6.7	3.5	1.19	298	1112	0.28	0.268	0.438
40	4.0	3.7	3.80	405	1198	0.05	0.338	3.183
41	4.5	0.2	0.10	63	200	2.21	0.314	0.030
42	4.9	0.3	0.26	485	200	0.96	2.427	0.167
43	5.8	0.5	0.38	314	200	0.77	1.569	0.180
44	3.9	4.4	1.68	332	1558	0.12	0.213	1.200
45	7.2	6.2	1.36	419	2598	0.26	0.161	0.561
46	5.0	3.9	2.28	381	1322	0.11	0.288	1.207
47	8.9	5.6	1.97	517	2261	0.23	0.229	0.729

Figure A1. Fuel loads (kg m^{-2}) of the litter, 1 hour time-lag fuels, 10 hour timelag fuels, 100 hour time-lag fuels, moss/lichen, live herbs, and live shrubs versus stand age (years). Each graph has lines representing the mean, upper and lower standard deviations.


LITTER
TOTAL FUELS
1 HOUR FUELS
LIVE HERBS
10 HOUR FUELS
SHRUBS
100 HOUR FUELS
MOSS
FUEL LOAD (kg/m^2)
STAND AGE (YEARS)
0
50
100
150
200
250
300

APPENDIX 2.

Fire behaviour program followed by symbol list. This program was written in Fortran and compiled using a WATFOR77[1] compiler. Fire intensity was predicted using Rothermel's (1972) model, as converted to metric by Wilson (1980)[2] with corrections to the metric conversion by the author. Note one major change is that fuel bed depth is calculated in which each fuel component has a characteristic depth, and the mean depth is determined using component fuel load as the weighting factor. Crown fire initiation calculations determine values of 0 when there is no initiation, and values of 1 when there is initiation, for both crown fire types. The program also determines fuel and weather variables as defined in the model section of the introduction.

---

[1]Coschi, G. and J.B. Schuler. 1987. WATFOR-77. Users Guide for the IBM PC with DOS. Watcom Publications Ltd. Waterloo, Ontario.

[2]Wilson, R. 1980. Reformulation of Forest Fire Spread Equations in S.I. Units. USDA Forest Service Research Note INT-292.

```
C       FIRE BEHAVIOUR PROGRAM

        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        INTEGER SITE,PCF,ACF
        REAL IR
        OPEN(10,FILE='(T:120)FUELS.DAT')
        OPEN(12,FILE='(T:100)OUTPUT.DAT')

C       FUEL CONSTANTS, SA/VOL RATIOS AND DEPTHS

        FMX=0.3                     VM=100
        H=20000                     VF=75
        SM=0.42                     VS=15
        P=500                       DDEAD=30
        S=0.0555                    DH=30
        VL=50                       DS=100
        V1=13                       DL=5
        V10=3
        V100=1

C       WIND ADJUSTMENT FACTOR AND SLOPE
        WAF=0.37
        SL=0

C       OUTSIDE LOOP
10      CONTINUE
        I=0

C       READING FUELS DATA
        READ (10,*) SITE,ZL,Z1,Z10,Z100,ZM,ZF,ZS,CI,CR,ZN
        IF (ZL .EQ. 9999) THEN
              WRITE (6,*) 'PROCESSING COMPLETE'
              STOP
        END IF
        WRITE(6,*)'PROCESSING SITE:',SITE

C       CALCULATION OF WEIGHTING FACTORS
        AL=VL*ZL
        A1=V1*Z1
        A10=V10*Z10
        A100=V100*Z100
        AM=VM*ZM
        AF=VF*ZF
        AS=VS*ZS
        ADEAD=AL+A1+A10+A100
        ALIVE=AM+AF+AS
        AT=ADEAD+ALIVE
        BL=AL/ADEAD
        B1=A1/ADEAD
        B10=A10/ADEAD
        B100=A100/ADEAD
```

```
      BM=AM/ALIVE
      BF=AF/ALIVE
      BS=AS/ALIVE
      BDEAD=ADEAD/AT
      BLIVE=ALIVE/AT

C     CALCULATION OF MINERAL ADJUSTED FUEL LOADS
      WL=ZL*(1-S)
      W1=Z1*(1-S)
      W10=Z10*(1-S)
      W100=Z100*(1-S)
      WM=ZM*(1-S)
      WF=ZF*(1-S)
      WS=ZS*(1-S)
      WDEAD=BL*WL+B1*W1+B10*W10+B100*W100
      WLIVE=BM*WM+BF*WF+BS*WS

C     CALCULATION OF FUEL BED SURFACE AREA TO VOLUME RATIO
      VDEAD=BL*VL+B1*V1+B10*V10+B100*V100
      VLIVE=BM*VM+BF*VF+BS*VS
      VT=BDEAD*VDEAD+BLIVE*VLIVE

C     CALCULATION OF FUEL BED DEPTH
      DR=(A1+A10+A100)/(A1+A10+A100+AF+AS)
      DLIVE=(DH*BF+DS*BS)/(BF+BS)
      D=(DL+DDEAD*DR+DLIVE*(1-DR))/100

C     PACKING RATIO, REACTION RATE, AND PROP. FLUX RATIO
      W=ZL+Z1+Z10+Z100+ZM+ZF+ZS
      PB=W/D
      BETA=PB/P
      BOP=0.20395*VT**(-0.8189)
      BB=BETA/BOP
      TM=1./(0.0591+2.926*VT**(-1.5))/60
      A=8.9033*VT**(-0.7913)
      T=TM*(BB*EXP(1-BB))**A
      PF=((192+7.9095*VT)**(-1))*EXP((0.792+3.7597*VT**0.5)*(BETA+0.1))

C     START OF INTERNAL LOOP
      OPEN(11,FILE='(T:100)WEATHER.DAT')
20    CONTINUE

C     READ DATE AND WEATHER DATA
      READ (11,*) JY,JD,FML,FM1,FM10,FM100,FMM,FMF,FMS,U
      IF (JY .EQ. 9999) THEN
            CLOSE(11)
            GO TO 10
      END IF

C     CONVERSION OF UNITS
      FML=FML/100.
```

```
      FM1=FM1/100.
      FM10=FM10/100.
      FM100=FM100/100.
      FMM=FMM/100.
      FMF=FMF/100.
      FMS=FMS/100.

C     LIVE FUEL MOISTURE OF EXTINCTION
      FMXL=(1.45*(1.-((10./3.)*FML)))-0.226
      IF (FMXL .LT. 0.3) FMXL=0.3
      IF (FMXL .GT. 1.0) FMXL=1.0

C     FUEL BED MOISTURE CONTENT
      FDEAD=BL*FML+B1*FM1+B10*FM10+B100*FM100
      FLIVE=BM*FMM+BF*FMF+BS*FMS
      FT=BDEAD*FDEAD+BLIVE*FLIVE
      FRD=FDEAD/FMX
      FRL=FLIVE/FMXL
      FDD=1-2.59*FRD+5.11*FRD**2-3.52*FRD**3
      IF (FDD .LT. 0) FDD=0.
      FDL=1-2.59*FRL+5.11*FRL**2-3.52*FRL**3
      IF (FDL .LT. 0) FDL=0

C     REACTION INTENSITY
      IR=T*SM*H*(BDEAD*WDEAD*FDD+BLIVE*WLIVE*FDL)

C     WIND AND SLOPE VARIABLE CALCULATION
      UE=U*WAF
      C=7.47*EXP(-0.8711*VT**0.55)
      B=0.15988*VT**0.54
      E=-1*(0.715*EXP(-0.01094*VT))
      UC=(C*(3.28084*UE*60)**B)*BB**E
      SLC=5.275*BETA**(-0.3)*(TAN(SL))**2

C     HEAT SINK CALCULATION
      QL=581+2594*FML
      Q1=581+2594*FM1
      Q10=581+2594*FM10
      Q100=581+2594*FM100
      QM=581+2594*FMM
      QF=581+2594*FMF
      QS=581+2594*FMS
      X=-4.528
      QD=BL*EXP(X/VL)*QL+B1*EXP(X/V1)*Q1+B10*EXP(X/V10)
     *     *Q10+B100*EXP(X/V100)*Q100
      QLIVE=BM*EXP(X/VM)*QM+BF*EXP(X/VF)*QF+BS*EXP(X/VS)*QS
      ED=BL*EXP(X/VL)+B1*EXP(X/V1)+B10*EXP(X/V10)+B100*EXP(X/V100)
      EL=BM*EXP(X/VM)+BF*EXP(X/VF)+BS*EXP(X/VS)
      EMIX=BDEAD*ED+BLIVE*EL
      Q=PB*(BDEAD*QD+BLIVE*QLIVE)
```

```
C       RESIDENCE TIME
        TR=755.66/VT

C       FINAL SURFACE FIRE CALCULATIONS
        R=IR*PF*(1+UC+SLC)/Q
        IPR=I
        I=IR*R*TR
        WMIX=BDEAD*WDEAD+BLIVE*WLIVE

        SURFACE FUEL AND WEATHER VARIABLES
        UV=1+UC+SLC
        FV=(PF*TR*(WMIX*T*H*SM)**2)/(PB*EMIX*581)
        EV=I/FV
        GMV=EV/UV

        CROWN FIRE CALCULATIONS
        CV1=FV/CI
        CI2=(CR*12700*WMIX)/3.34
        CV2=FV/CI2
        IF (I .LT. CI) THEN
                RVALUE=0
                PCF=0
                ACF=0
        ELSE IF (I .GE. CI) THEN
                RVALUE=R*3.34
                PCF=1
                IF (RVALUE .LT. CR) THEN ACF=0
                ELSE ACF=1
                END IF
        END IF
        GO TO 20
        END
```

A	CONSTANT IN T	BF	2° WT. FOLIAGE
A1	1° WEIGHT 1 HOUR	BL	2° WT. LITTER
A10	1° WT. 10 HOUR	BLIVE	2° WT. LIVE FUELS
A100	1° WT. 100 HOUR	BM	2° WT. MOSS
ADEAD	1° WT. DEAD FUELS	BOP	OPTIMUM PACK. RATIO
AF	1° WT. FOLIAGE	BS	2° WT. SHRUB
AL	1° WT. LITTER	C	CONSTANT IN UC
ALIVE	1° WT. LIVE FUELS	CI	CRITICAL INTENSITY
AM	1° WT. MOSS	CI2	ICRIT EQUIV. OF RCRIT
AS	1° WT. SHRUB	CR	CRIT. RATE OF SPREAD
AT	1° WT. TOTAL	CV1	1st CROWN FUEL VAR.
B	CONST. IN WIND COEF.	CV2	2ND CROWN FUEL VAR.
B1	2° WT. 1 HOUR	D	MEAN FUEL BED DEPTH
B10	2° WT. 10 HOUR	DDEAD	DEPTH OF DEAD FUELS
B100	2° WT. 100 HOUR	DDEAD	DEAD FUEL DEPTH
BB	BETA/BOP	DH	DEPTH OF HERBS
BDEAD	2° WT. DEAD FUELS	DL	DEPTH OF LITTER
BETA	PACKING RATIO	DLIVE	LIVE FUEL DEPTH

DR	DEAD:LIVE RATIO	TM	MAX. REACTION RATE
DS	DEPTH OF SHRUBS	TR	RESIDENCE TIME
E	CONSTANT IN UC	U	WINDSPEED
ED	HEATING NO. DEAD	UC	WIND COEFFICIENT
EL	HEATING NO. LIVE	UE	EFFECTIVE WINDSPEED
EMIX	HEATING NO. MIXED	UV	WIND VARIABLE
EV	WEATHER VARIABLE	V1	SA/VOL 1HOUR FUELS
FDD	H_2O DAMPING DEAD	V10	SA/VOL 10HOUR FUELS
FDEAD	DEAD FUEL H_2O	V100	SA/VOL 100HOUR FUELS
FDL	H_2O DAMPING LIVE	VDEAD	SA/VOL DEAD FUELS
FLIVE	LIVE FUEL H_2O	VF	SA/VOL FOLIAGE
FM1	1H FUEL H_2O	VL	SA/VOL LITTER
FM10	10H FUEL H_2O	VLIVE	SA/VOL LIVE FUELS
FM100	100H FUEL H_2O	VM	SA/VOL MOSS
FMF	FOLIAGE H_2O	VS	SA/VOL SHRUB WOOD
FML	LITTER H_2O	VT	MEAN FUEL BED SA/VOL
FMM	MOSS H_2O	W	TOTAL FUEL LOAD
FMS	SHRUB H_2O	W1	ADJUSTED 1 H LOAD
FMX	DEAD H_2O EXTINCT.	W10	ADJUSTED 10 H LOAD
FMXL	LIVE H_2O EXTINCT.	W100	ADJUSTED 100 H LOAD
FRD	MF/MX DEAD	WDEAD	ADJ. DEAD LOAD
FRL	MF/MX LIVE	WF	WIND ADJUSTMENT
FT	MEAN FUEL BED H_2O	WF	ADJ. FOLIAGE LOAD
FV	FUEL VARIABLE	WL	ADJUSTED LITTER LOAD
GMV	MOISTURE VARIABLE	WLIVE	ADJUSTED LIVE LOAD
HH	HEAT CONTENT HIGH	WM	ADJUSTED MOSS LOAD
HL	HEAT CONTENT LOW	WMIX	MEAN ADJ. FUEL LOAD
I	SURFACE INTENSITY	WS	ADJUSTED SHRUB LOAD
IPR	PREVIOUS DAYS INT.	Z1	1 HOUR FUEL LOAD
IR	REACTION INTENSITY	Z10	10 HOUR FUEL LOAD
JD	DATE OF SUMMER	Z100	100 HOUR FUEL LOAD
JY	YEAR	ZF	FOLIAGE LOAD
P	MASS DENSITY	ZL	LITTER LOAD
PB	BULK DENSITY	ZM	MOSS LOAD
PF	PROP.FLUX RATIO	ZN	TREE NEEDLE LOAD
Q1	HEAT SINK 1 HOUR	ZS	SHRUB WOOD LOAD
Q10	HEAT SINK 10 HOUR		
Q100	HEAT SINK 100 HOUR		
QD	HEAT SINK DEAD		
QF	HEAT SINK FOLIAGE		
QL	HEAT SINK LITTER		
QLIVE	HEAT SINK LIVE		
QM	HEAT SINK MOSS		
QS	HEAT SINK SHRUBS		
QT	MEAN HEAT SINK		
R	RATE OF SPREAD		
RVALUE	POT. CROWN R. OF SP.		
S	MINERAL CONTENT		
SL	SLOPE IN DEGREES		
SLC	SLOPE COEFFICIENT		
T	REACTION RATE		

APPENDIX 3.

Fuel Moisture Program and Symbols. This program was written in FORTRAN and compiled using WATFOR77 compiler. Moisture contents were all based on published equations: Litter moisture content was determined as the moisture equivalent of the Fine Fuel Moisture Code of the Fire Weather Index (Van Wagner 1987[3]). Moss/lichen moisture content was determined from equations by Pech (1989). All other moisture contents were determined using National Fire Danger Rating System equations (Bradshaw *et al.* 1984).

---

[3]Van Wagner, C.E. 1987. Development and Structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. Ottawa, Ontario. For. Tech. Rep. 35.

```
C       FUEL MOISTURE PROGRAM
        INTEGER DY
        CHARACTER*12 SITE

        OPEN(10,FILE='(T)C:\INPUT.DAT')
        OPEN(11,FILE='(T)C:\OUTPUT.DAT')

10      CONTINUE

C       INITIALIZATION OF VARIABLES
        AM100=20
        AM1000=25
        X1000=25
        DA=25
        DB=25
        DC=25
        DD=25
        DE=25
        DF=25
        AMA=25
        AMB=25
        AMC=25
        AMD=25
        AME=25
        AMF=25
        HM=0
        SM=0
        A=0
        AMY=150

C       INPUT SITE, LATITUDE AND YEAR
        READ(10,1000,END=30)SITE,PHI,YR
1000    FORMAT(A12,F7.2,F6.0)

        WRITE(11,*) 'MOISTURE VALUES AND WINDSPEED FOR ',SITE, YR
        WRITE(11,*) 'MONTH  DAY  MLITT  M1  M10   M100  M1000 MMOSS
        MHERB  MSHRUB WINDSP'
        WRITE(11,*) ' %  %  %  %  %  %  %  % (M/S) '

C       LEAP YEAR FACTOR
        IY=YR/4
        IY=IY*4
        IF (YR .EQ. IY) E=1
        IF (YR .NE. IY) E=0

C       BEGIN LOOP
20      CONTINUE
        READ(10,*) MO,DY,T,H,WS,PA,F
        IF (MO .EQ. 999) GO TO 10
```

```
C       CALCULATION OF MOSS AND LICHEN MOISTURE CONTENT
        IF (T .LE. 0) TX=0
        IF (T .GT. 0) TX=T
        IF (H .LE. 40) EX=0.136*H**1.07+13*EXP((H-100)/10)
        IF (H .GT. 40 .AND. H .LT. 75)
                EX=-4.013+0.2772*H+0.18*(21.1-T)*(1-1/EXP(0.1*(H-40)))
        IF (H .GE. 75)
                EX=0.618*H**0.753+10*EXP((H-100)/10)+0.18*(21.1-T)
                        *(1-1/EXP(0.1*(H-40)))
        IF (PA .GT. 0) THEN
                AMMOSS=AMY+(150*(400-AMY)/(150+AMY))
                        *(1-EXP(-0.00125*(400-AMY)*PA))
        ELSE IF (PA .EQ. 0) THEN
                IF (EX .LT. AMY) THEN
                        AKO=0.424*(1-(H/100)**1.7)+(0.069*WS**0.5)*(1-(H/100)**8)
                        AK=AKO*(1.378*EXP(0.0365*TX))
                        AMMOSS=EX+(AMY-EX)*10**(-AK)
                ELSE IF (EX .EQ. AMY) THEN
                        AMMOSS=AMY
                ELSE IF (EX .GT. AMY) THEN
                        AKO=0.424*(1-((100-H)/100)**1.7)+(0.0694*WS**0.5)
                                *(1-(100-H)/100)**8
                        AK=AKO*(1.378*EXP(0.0365**TX))
                        AMMOSS=EX-(EX-AMY)*10**(-AK)
                END IF
        END IF
        AMY=AMMOSS

C       CONVERSION OF UNITS TO U.S.A. MEASURES
        T=1.8*T+32
        PA=PA/25.4

C       JULIAN DATE
        J=(31*(MO-1)+DY-0.4*MO-1.8+E)

C       WIND SPEED KM PER HOUR TO M PER S
        WS=WS/3.6

C       DRY FUEL MOISTURE CALCULATIONS
        IF (H .LT. 10) EMC=0.03299+0.281073*H-0.000578*H*T
        IF (H .GE. 10 .AND. H .LT. 50) EMC=2.22749+0.160107*H-0.01478*T
        IF (H .GE. 50) EMC=21.0606+0.005565*H**2-0.00035*H*T-0.483199*H
        D=0.41008*SIN(0.01721*(J-82))
        HL=24*(1-ACOS(TAN(PHI)*TAN(D))/3.1415926538)
        EMCAV=((24-HL)*23+HL*EMC)/24
        IPD=((PA+0.02)/0.05)
        IF (IPD .GT. 8) IPD=8
        D100=((24-IPD)*EMCAV+(0.5*IPD+41)*IPD)/24
        AM100B=AM100
        D1000=((24-IPD)*EMCAV+(2.7*IPD+76)*IPD)/24
        DAV=(DA+DB+DC+DD+DE+DF+D1000)/7
```

```
      DA=DB
      DB=DC
      DC=DD
      DD=DE
      DE=DF
      DF=D1000
      AM1000=AMA+(DAV-AMA)*0.3068
      DM1000=AM1000-AMF
      AMA=AMB
      AMB=AMC
      AMC=AMD
      AMD=AME
      AME=AMF
      AMF=AM1000
      IF (DM1000 .LT. 0) AK1=1
      IF (DM1000 .GE. 0) AK1=0.0333*DM1000+0.1675
      IF (T .GT. 65) AK2=1
      IF (T .LE. 65) AK2=0.6

C     CALCULATION OF DEAD FUEL MOISTURE CONTENTS
      IF (IPD .EQ. 8) THEN
            AM1=35
            AM10=35
      ELSE IF (IPD .NE. 8) THEN
            AM1=1.03*EMC
            AM10=1.28*EMC
      END IF
      AM100=AM100B+(D100-AM100B)*0.3165
      AMLITT=147.2*(101-F)/(59.5+F)

C     CALCULATIONS FOR LIVE HERB AND SHRUB MOISTURE CONTENTS
      X1000B=X1000
      AN=(J-135.)/21.
      X1000=X1000B+AK1*AK2*DM1000

C     PRE-GREEN-UP STAGE
      IF (AN .LT. 0) THEN
            AMHERB=AM1
            AMSHRB=70

C     GREEN-UP STAGE
      ELSE IF (AN .GE. 0 .AND. AN .LE. 1) THEN
            AMHERB=AM1+AN*(-42.7+9.8*X1000-AM1)
            AMSHRB=70+AN*(-22.5+8.9*AM1000-70)

C     POST-GREEN-UP STAGE
      ELSE IF (AN .GT. 1) THEN
            AMHERB=-137.5+15.5*X1000
            AMSHRB=-22.5+8.9*AM1000
            IF (AMHERB .LE. 30) HM=1
            IF (AMSHRB .LT. 70) SM=1
```

```
        IF (J .GE. 243 .AND. T .LE. 32) THEN
                IF (T .LE. 25) A=A+5
                IF (T .GT. 25) A=A+1
        END IF
END IF
IF (A .GE. 5) THEN
        HM=1
        SM=1
END IF
IF (HM .EQ. 1) AMHERB=AM1
IF (SM .EQ. 1) AMSHRB=70
WRITE(11,1001) MO,DY,AMLITT,AM1,AM10,AM100,AM1000,AMMOSS,AMHERB,
        AMSHRB,WS

1001  FORMAT (I4,I6,F7.0,F4.0,F5.0,F7.0,F7.0,F6.0,F7.0,F8.0,F7.2)

GO TO 20

STOP
END
```

INPUT VARIABLES

DY	DAY	
F	FINE FUEL MOISTURE CODE	
H	RELATIVE HUMIDITY	%
MO	MONTH	
PA	PRECIPITATION AMOUNT	mm
PHI	LATITUDE OF WEATHER STATION	deg
SITE	WEATHER STATION	
T	TEMPERATURE	°C
WS	WIND SPEED	km h^{-1}
YR	YEAR	

OUTPUT VARIABLES

AM1	1 HOUR TIMELAG FUEL MOISTURE CONTENT	%
AM10	10 HOUR TIMELAG FUEL MOISTURE CONTENT	%
AM10	100 HOUR TIMELAG FUEL MOISTURE CONTENT	%
AM1000	1000 HOUR TIMELAG FUEL MOISTURE CONTENT	%
AMLITT	LITTER MOISTURE CONTENT	%
AMMOSS	MOSS MOISTURE CONTENT	%
AMHERB	HERBACEOUS FUEL MOISTURE CONTENT	%
AMSHRB	SHRUB FUEL MOISTURE CONTENT	%
WS	WIND SPEED	m s^{-1}

CALCULATION VARIABLES AND CONSTANTS

A	FREEZING SEVERITY VALUE
AK	SECONDARY FACTOR IN MOSS MOISTURE CALCULATION
AK1	DRYING/WETTING FACTOR FOR HERBACEOUS FUELS
AK2	TEMPERATURE FACTOR FOR HERBACEOUS FUELS
AKO	PRIMARY FACTOR IN MOSS MOISTURE CALCULATION
AM100B	PREVIOUS DAY MOISTURE 100 HOUR MOISTURE CONTENT
AMA	1000 HOUR MOISTURE CONTENT FROM 6 DAYS PREVIOUS
AMB	1000 HOUR MOISTURE CONTENT FROM 5 DAYS PREVIOUS
AMC	1000 HOUR MOISTURE CONTENT FROM 4 DAYS PREVIOUS
AMD	1000 HOUR MOISTURE CONTENT FROM 3 DAYS PREVIOUS
AME	1000 HOUR MOISTURE CONTENT FROM 2 DAYS PREVIOUS
AMF	1000 HOUR MOISTURE CONTENT FROM 1 DAY PREVIOUS
AMY	PREVIOUS DAY MOSS MOISTURE
AN	GREEN-UP STAGE INDICATOR
D	ANGLE OF SOLAR DECLINATION
D100	24 HOUR MEAN BOUNDARY CONDITION (100 H FUELS)
D1000	24 HOUR MEAN BOUNDARY CONDITION (1000 H FUELS)
DA	1000 HOUR BOUNDARY CONDITION 6 DAYS PREVIOUS
DAV	MEAN 7 DAY 1000 HOUR BOUNDARY CONDITION
DB	1000 HOUR BOUNDARY CONDITION 5 DAYS PREVIOUS
DC	1000 HOUR BOUNDARY CONDITION 4 DAYS PREVIOUS
DD	1000 HOUR BOUNDARY CONDITION 3 DAYS PREVIOUS
DE	1000 HOUR BOUNDARY CONDITION 2 DAYS PREVIOUS
DF	1000 HOUR BOUNDARY CONDITION 1 DAY PREVIOUS
DM1000	TODAYS MINUS YESTERDAYS 1000 HOUR MOISTURE
E	LEAP YEAR CATEGORY
EMC	EQUILIBRIUM MOISTURE CONTENT
EMCAV	WEIGHTED MEAN EQUILIBRIUM MOISTURE CONTENT
EX	EQUILIBR. MOISTURE IN MOSS MOISTURE CALCULATION
HL	DAY LENGTH
HM	HERBACEOUS FUELS CURING INDICATOR
IPD	PRECIPITATION DURATION
IY	LEAP YEAR DETERMINATION FACTOR
J	JULIAN DATE
SM	SHRUB FUELS CURING INDICATOR
TX	TEMPERATURE IN MOSS MOISTURE CALCULATION
X1000	LIVE FUEL MOISTURE RECOVERY VALUE
X1000B	PREVIOUS DAY LIVE FUEL MOISTURE RECOVERY VALUE