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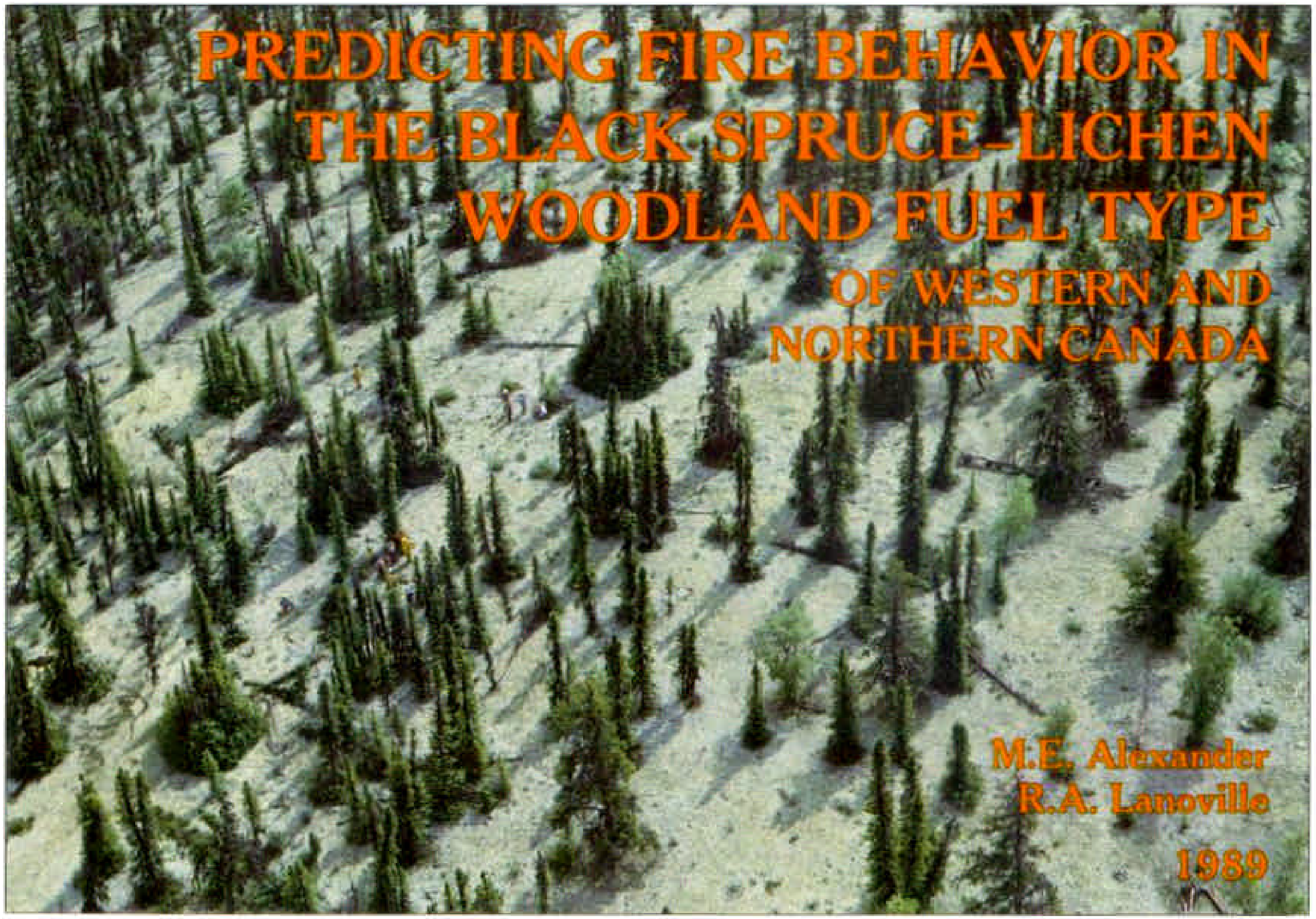
Northwest Territories Renewable Resources



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INTRODUCTION

The behavior of free-burning forest fires is controlled by the fire environment (i.e., the surrounding conditions, influences, and modifying forces of topography, fuels, and weather). Successful fire management depends very heavily upon, among other things, an intimate knowledge of fire behavior (Underwood 1985). Although there are fundamental mechanisms involved in fire behavior, each area has a unique fire environment. Fore example, under certain weather conditions the black spruce-lichen woodland forests of Canada's western and northern subarctic zones are prone to the occurrence of large, high-intensity crowning wildfires exhibiting very rapid spread rates that are beyond our ability to effect control.

This poster presents a guide for predicting fire behavior in the black spruce-lichen woodland fuel type for use by northern fire mangers. It is based largely on the results of an experimental burning project conducted at Porter Lake in the Caribou Range of the south-central Northwest Territories during the 1982 fire season by territorial fire management staff and Forestry Canada fire research personnel (Alexander et al. 1989). A representative photo of each experimental fire and information on the attendant environmental conditions and associated fire behavior characteristics are also presented (Plates 1 to 7). The guide provides assistance in determining the probable behavior of wildfires occurring in the black spruce-lichen woodland fuel type. Five basic characteristics of fire behavior are considered:

- ✓type of fire
- ✓head fire rate of spread
- ✓frontal fire intensity
- ✓fire area
- ✓fire perimeter length

Although the guide is specific to the black spruce-lichen woodland fuel type, it does nonetheless demonstrate many of the basic principles of predicting wildfire behavior.

The fire behavior guide actually consists of several easy-to-use decision aids, with an example provided to demonstrate the methods[1]. A working knowledge of the two major subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Canadian Forestry Service 1987; Stocks et al. 1989) is presumed, i.e., the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1984; Van Wagner and Pickett 1985; Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System[2] (Lawson et al. 1985).

FUEL TYPE DESCRIPTION

The black spruce-lichen woodland fuel type is characterized by open, park-like stands of black spruce occupying well-drained uplands in the south-central area of the Northwest Territories, northern Saskatchewan, northern Manitoba, and to a limited extent in northeastern Alberta. Jack pine and white birch may also occur as minor associates in the overstory. Forest cover occurs as widely spaced individuals and dense clumps. Three heights vary considerably but are generally less than 10 metres; both live and dead bole branches uniformly extend to the forest floor, and layering development is extensive. Downed-dead woody surface fuel accumulation is very light and scattered. Shrub and herbaceous cover is exceedingly sparse. The ground surface is fully exposed to the sun and is covered by a nearly continuous, but shallow, layer or mat of yellowish and whitish lichens averaging 3-4 centimetres in depth above mineral soil.

USER INPUT REQUIREMENTS

The principal input variable is the Initial Spread Index (ISI) component of the FWI System. The ISI is in turn dependent on the 10-m open wind speed (Turner and Lawson 1978) and the Fine Fuel Moisture Code (FFMC) component of the FWI System, as shown in Graph 1. The predictions for each of the fire behavior characteristics as determined by the actual or forecast FFMC are intended to apply to the daily period of maximum fire danger that normally occurs in late afternoon or early evening. The chart of ISI versus the FFMC and 10-m open wind speed (Graph 1) is simply a graphical representation of the standard ISI equations in the FWI System (Van Wagner 1987). Field users also have the option, of course, to use the FWI System tables (Canadian Forestry Service 1984) in lieu of computer-calculated ISI values (Van Wagner and Pickett 1985). The ISI values, including the maximum value, given in Graph 2 and Table 1 should be sufficient for most practical purposes. An ISI value of 35 represents just about the limit of the experimental fire data gathered during the Porter Lake project.

FIRE BEHAVIOR CHARACTERISTICS

Type of fire -- As shown in Graph 2 and table 1, three types of fires in the black spruce-lichen woodland fuel type have been identified on the basis of threshold values of the ISI:

ISI	Type of fire
= 7	Surface fire
8-17	Intermittent crown fire
=18	Crown fire

An intermittent crown fire is characterized by discontinuous torching (Merrill and Alexander 1987). Thus the range in ISI values associated with this type of fire should be regarded as representing the transition zone between an intense surface fire and full-fledged crowning in which a well-defined wall of flame extends from the ground surface to above the tree crowns.

Head fire rate of spread -- The relationship between the head fire rate of spread (ROS) and the ISI has

[1] The five color codes used in Graph 2, Table 1, and Table 2 are the standard colors used in various fire danger index classification schemes (Merrill and Alexander 1987).

[2] Alexander, M.E.; Lawson, B.D.; Stocks B.J.; Van Wagner, C.E. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim ed. Environ. Can., Can. For. Serv., Fire Danger Group, Ottawa, Ontario. [First printing July 1984; revision and second printing Sept. 1984.]

been prepared in both graphical and tabular formats, as illustrated in Graphs 2 and Table 1. The ROS is defined as the forward spread with wind, or radial spread with no wind, on level to gently undulating terrain after the fire has reached an equilibrium or steady-state condition. The influences of crowning and spotting are automatically accounted for in terms of their influences on the overall spread rate. The ROS is expressed in both metres per minute (m/min) and kilometres per hour (km/h). Descriptive terminology can also be attached to the ISI-ROS relationship for the black spruce-lichen woodland fuel type. Note that an approximation of a wildfire's forward or radial spread distance from the point of origin or source can be obtained by multiplying the ROS by the elapsed time since ignition (Figure1). Additional study is needed to determine the appropriate downward adjustment in the forward spread distance due to the time required for the fire to accelerate until an equilibrium or steady-state condition is reached (Cheney 1981).

Frontal fire intensity -- The frontal fire intensity (FFI) represents the rate of heat energy release per unit time per unit length of fire front (Alexander 1981; Merrill and Alexander 1987). The recommended unit of measure is kilowatts per metre (kW/m). The FFI is directly related to flame size. Numerically, it is equal to the product of the net low heat of combustion, quantity of fuel consumed in the flaming front, and the linear rate of spread (Byram 1959). Since the heat content of forest fuels is relatively constant, any change in the fire's forward rate of advance or fuel consumption will be reflected in its frontal intensity. For example, if the rate of fire spread were to double, then the FFI would also increase accordingly.

The amount of fuel available for combustion in this fuel type is relatively constant and, as a result, any variation in the FFI is primarily dependent on the head fire ROS and influenced by wind and the moisture content of fine fuels. This fact greatly simplifies the computation process and allows for the FFI to be determined directly from the ISI, as shown in Table 1. The FFI is a major determinant of the relative difficulty encountered in controlling a wildfire (Alexander and De Groot 1988) as indicated in Table 2. The FFIs listed in Tables 1 and 2 refer to the intensity at the head-fire section of the fire perimeter, that is, where the frontal intensity is generally the greatest (Catchpole et al. 1982). Fires with predicted FFI values less than 10 kW/m are not likely to sustain themselves (Byram 1959). Thus, an ISI of 1.0 would appear to be the absolute minimum condition for fire spread in this fuel type based on the criteria used in calculating the FFIs given in Tables 1 and 2.

Fire Area and Perimeter Length -- The growth pattern or general shape of forest fire originating from a single ignition source, such as a lightning strike or unattended campfire, is governed largely by surface wind velocity. Provided that the wind direction remains fairly constant, the general outline of a wind-driven fire resembles an ellipse, as depicted in Figure 1, with the actual shape depending on fuel and terrain conditions (Alexander 1985). Assuming a roughly elliptical or oval fire shape, it is possible to estimate potential fire sizes in the black spruce-lichen woodland fuel type on the basis of the ISI-ROS relationship, elapsed time since ignition, and the Area Shape Factor (K_{-A}). The K_A value depends on the ratio of the elliptical-shaped fire's total length to maximum width or breath, which in turn is a function of the 10-m open wind speed (Figure 1 and Table 3). The area computations presented in Table 4 are based on the concept of a simple elliptical fire growth model (Alexander 1985). It is assumed that the black spruce-lichen woodland fuel type is continuous, the terrain is level and unbroken, wind velocity is constant, and any suppression action would be ineffective in restricting fire growth, and the fire attains an equilibrium or steady-state condition fairly soon following ignition. Because of the lack of any commonly accepted theory at this time, no attempt was made to devise a procedure for reducing the computed fire area and perimeter length due to the acceleration in fire spread from a point ignition (Cheney 1981). Due to this uncertainty, it was felt that overestimates of forward spread distance, fire area, and fire perimeter length could be justified. A zero area burned would be assigned to ISI 0.5 based on the predicted FFI at that level.

The rate of area growth does not remain constant with time. Rather, it increases in direct proportion to the relative difference in elapsed time since ignition, that is, the total area burned will increase by a factor equal to the square of the time interval, provided, or course, the head fire ROS remains unchanged. For example, the fire area after 60 minutes will be four time the area 30 minutes after ignition.

The length of the perimeter about a smooth, elliptical-shaped fire can be calculated, as shown in Figure 1, by simply multiplying the forward spread distance by the Perimeter Shape Factor (K_p), which is also ultimately determined by the 10-m open wind speed (Table 3). This tends to result in the minimum possible fire perimeter length, because natural irregularities in the fire edge are not considered. In contrast to the rate of area growth, the rate of perimeter growth or increase does remain constant with time, provided the head fire spread rate does not change. The rate of perimeter growth can be obtained by multiplying the head fire ROS by the K_p value.

The elliptical pattern, corresponding to the fire size calculations, can be plotted on a map if the forward, back, and flank fire spread distances are available (Table 3). To convert the actual ground distances to equivalent map distances in centimeters, multiply the various spread distances by the appropriate map conversion factor as described in Table 3. To sketch in the outline of the Fire's perimeter, use the elliptical shapes illustrated in Figure 1 as a guide. Assess the most likely direction of fire spread on the basis of the measured or forecast wind direction and topographic features.

A PRACTICAL EXAMPLE

A fire management officer requires a quick estimate of the probable behavior for any newly reported wildfires during the first half-hour following ignition in an area dominated by the black spruce-lichen woodland fuel type. The FFMC calculated at 1300 local daylight saving time for the most representative fire weather station was 89, and the average 10-m open wind speed as measured over a 10-minute interval was 13 km/h. The fire weather forecast states that late afternoon winds are likely to be 20 km/h. An FFMC of 89 and 10-m open wind of 20 km/h would produce an ISI of 10 according to Graph 1. The associate fire behavior characteristics based on the guide for the black spruce-lichen woodland fuel type are as follows:

Type of fire: Intermittent crown fire

Head fire ROS: 4.5 m/min or 0.27 km/h

Head fire FFI: 2000 kW/m (FFI Class 2/3)

Forward spread distance:

4.5 m/min x 30 min = 135 m *or*

0.27 km/h x 0.5 h = 0.135 km

Fire area:

$[0.54 \times (135m)^2] \div 10\ 000$ *or*

$[0.54 \times (0.135\ km)^2] \times 100 = 1.0$ ha

Fire perimeter length:

135 m x 2.75 = 371 m *or*

0.135 km x 2.75 = 0.371 km

This constitutes a MODERATELY FAST spreading fire with a MODERATELY DIFFICULT to VERY DIFFICULT control rating. The backfire and total flank fire spread distances at the end of the first half hour would be 10 m (135 m ÷ 10.3) and 84 m (135 + 13 m ÷ 1.76), respectively. The fire would be 3.9 ha in size in another half hour. The rate of perimeter growth would be (4.5 m/min x 2.75 =) 12.4 m/min or (0.27 km/h x 2.75 =) 0.74 km/h. A CL=215 skimmer aircraft supported by helitack crews would probably be required to achieve containment during the first burning period.

POTENTIAL APPLICATIONS IN FIRE MANAGEMENT

The information presented in this guide permits an assessment of potential fire behavior for different fire weather conditions before a fire even occurs. For the reason, it will prove most useful in training (e.g., B.C. Ministry of Forests and Lands 1987) and in medium- to long-term planning for a wide variety of fire management problems and opportunities, including the development of a presuppression preparedness system for initial attack manning action, fire prevention guidelines, and fire detection standards. Because the guide is actually determined by four basic weather elements (dry-bulb temperature, relative humidity, wind, and rain), it is possible to establish a fire behavior climatology (e.g., Gill et al. 1987) to supplement the guide. For example, the following is a breakdown of the number of days certain types of fires could be expected (given an ignition) near the location of two fire weather stations in the black spruce-lichen woodland fuel type region of the Caribou Range during a 123-day fire season, from May 16 to September 15. It is based on a 10-year summary given in Alexander et al. (1989):

Type of fire	Fort Smith	Yellowknife
Nil fire spread	15	9
Surface fire	76	70
Intermittent crown fire	29	41
Crown fire	3	4

Use of the fire behavior guide in a near real-time sense for daily fire control purposes, beyond aiding in the dispatching of personnel and equipment during the incipient stage of wildfire growth, will vary from a consideration in escaped fire analyses to application in backfiring operations on campaign fires and in timing evacuation of people who may be in the path of an approaching wildfire.

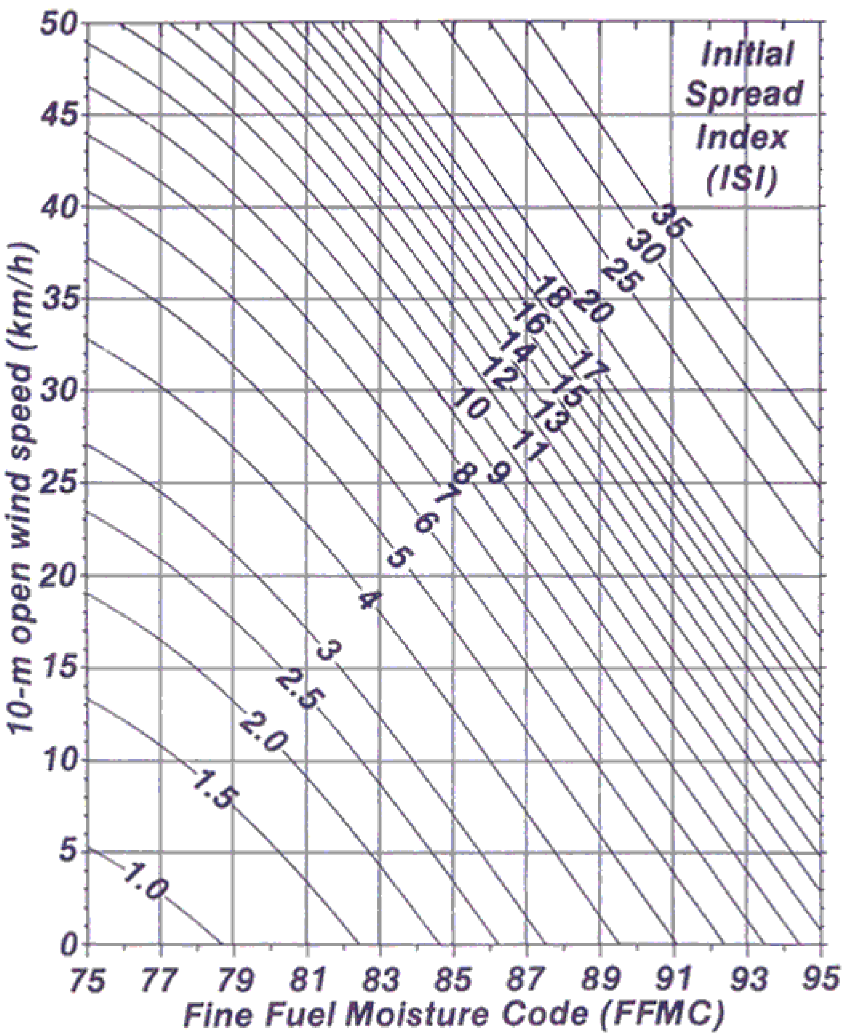
SOME CONCLUDING THOUGHTS

Predicting wildfire behavior is a difficult task. Even with this guide for estimating fire behavior characteristics, considerable judgment is required in applying the predicted values in development of fire suppression strategies and tactics. The fire manager who can relate the predictions to previously observed fire behavior should be able to make the necessary adjustments, to control and apply fire more safely and effectively.

One thing to keep in mind concerning the use of the guide is that on-site weather is necessary to obtain the most accurate estimates of potential fire behavior. As Burrows (1984) notes, “Weather forecasting provides an overall evaluation of fire weather conditions, but it is the personal responsibility of every fire fighter to continually observe weather conditions at the site of the fire.” The FFMC and ISI values calculated for the nearest or most representative fire weather station may be used to determine any of the fire behavior characteristics, with the understanding that they may be inaccurate if the weather recorded at the observing station is not reasonably indicative of the weather acting on the area being assessed. Predicting fire behavior certainly requires a representative wind speed, and wind can be highly variable. The main point is that wind-speed updates to the time(s) of interest for near real-time estimates of fire behavior will greatly improve prediction accuracy (i.e., in addition to the regular noon reading, there should be hourly or mid-afternoon observations). If on-site or representative measurements cannot be made nor current wind speeds obtained, then the corresponding losses in precision must be accepted. The reality of fire behavior forecasting is that overpredictions can be easily readjusted without serious consequences, but underpredictions of fire behavior can be potentially disastrous to both the operations of firefighters and the credibility of the person making the estimates of probably fire behavior (Cheney 1981).

Graph 1

Initial Spread Index (ISI) as a function of the Fine Fuel Moisture Code (FFMC) and 10-m open wind speed. For example, an FFMC of 89 and 10-m open wind of 20 km/h would give an ISI of 10.



Graph 2

Head fire rate of spread (ROS) on level to gently undulating ground as a function of the Initial Spread Index (ISI) for a black spruce-lichen woodland fuel type (note that the type of fire is determined on the basis of ISI). For example, the head fire ROS at ISI 10 is 4.5 m/min or 0.27 km/h and would result in an intermittent crown fire.

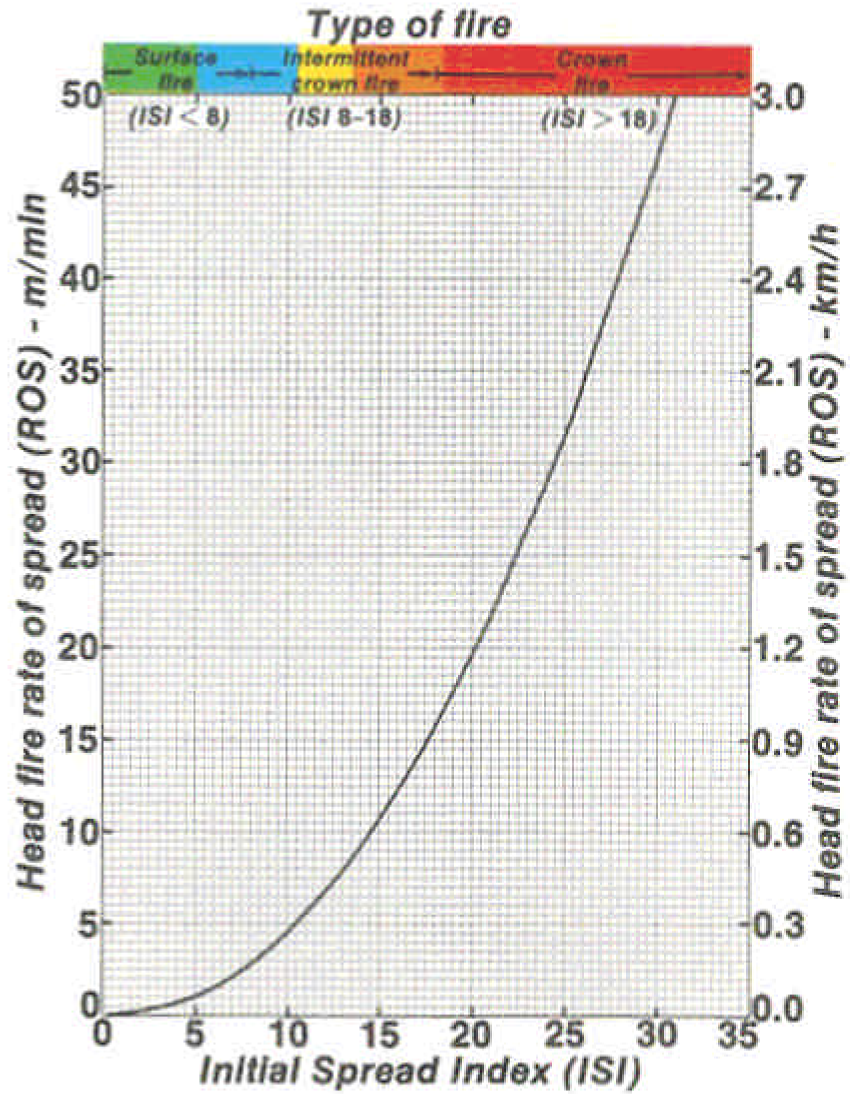


Table 1

Head fire rate of spread (ROS) and frontal fire intensity (FFI) on level to gently undulating ground as a function of the Initial Spread Index (ISI) for the black spruce-lichen woodland fuel type (note that the type of fire is determined on the basis of the ISI). For example, at an ISI of 10, one would expect a MODERATELY FAST spreading (4.5 m/min or 0.27 km/h) intermittent crown fire with an FFI of approximately 2000 kW/m.

	Head fire ROS			FFI
ISI	m/min	km/h	Descriptive term[a]	(kW/m)
			Surface fire	
0.5	0.01	<0.001	EXTREMELY SLOW	3
1.0	0.03	0.002	VERY SLOW	12
1.5	0.1	0.01	VERY SLOW	30
2.0	0.1	0.01	VERY SLOW	55
2.5	0.2	0.01	SLOW	88
3	0.3	0.02	SLOW	130
4	0.6	0.02	SLOW	240
5	1.0	0.06	MODERATELY SLOW	390
6	1.5	0.09	MODERATELY SLOW	580
7	2.1	0.12	MODERATELY SLOW	800
			Intermittent crown fire	
8	2.8		MODERATELY SLOW	1 100
9	3.6		MODERATELY SLOW	1 500
10	4.5		MODERATELY SLOW	2 000
11	5.5	0.33	MODERATELY FAST	2 600
12	6.6	0.40	MODERATELY FAST	3 200
13	7.8	0.47	MODERATELY FAST	4 000
14	9.2	0.55	MODERATELY FAST	4 800
15	11	0.64	FAST	5 800
16	12	0.73	FAST	7 000
17	14	0.84	FAST	8 200
			Crown fire	
18	16	0.94	FAST	9 600
20	20	1.2	VERY FAST	12 100
25	32	1.9	EXTREMELY FAST	19 500
30	47	2.8	EXTREMELY FAST	28 700
35	65	3.9	EXTREMELY FAST	40 000

[a] Adapted from Muraro (1975) and the B.C. Ministry of Forests (1983). The ROS criteria for FAST, VERY FAST, and EXTREMELY FAST is 10.0-18.0, 18.1-25.0, and >25 m/min, respectively.

Table 2

Frontal fire intensity (FFI) and associated fire control implications as a function of the Initial Spread Index (ISI) for the black spruce-lichen woodland fuel type.

FFI class	FFI (kW/m)	Control rating[a]	Fire suppression interpretations	ISI
1	<500	FAIRLY EASY	Direct attack at fire's head or flanks by firefighters with hand tools and back-pack pumps possible. "Light" helicopters with helibucket also effective. Constructed fireguard should hold.	=5
2	500-2000	MODERATELY DIFFICULT	Hand-constructed fireguards likely to be challenged. Ground suppression crews with water under pressure (i.e., fire pumps and hose-lays) can work along the fire's flanks and possibly "hot spot" the head. Heavy equipment (e.g. "medium" helicopter with helibucket, skimmer aircraft, or muskeg tanker) generally successful in controlling fire.	6-10
3	2000-4000	VERY DIFFICULT	Any attempt to contain the fire's head limited to the use of air tankers applying chemical fire retardants. Control efforts may fail.	10-13
4	4000-10000	EXTREMELY DIFFICULT	Suppression action must be restricted to back and flanks of the fire. All efforts at direct control of the fire likely to fail. Indirect attack with aerial ignition, if available, may be effective	13-18
5	>10000	VIRTUALLY IMPOSSIBLE	Extreme fire behavior. Fires present serious control problems. An escaped fire is a very distinct possibility. Suppression activities should be curtailed until burning conditions ameliorate.	=19

[a] Adapted from Muraro (1975) and the B.C. Ministry of Forests (1983).

Figure 1

Upper: The elliptical shapes of free-burning, wind-driven forest fires originating from a single ignition source (+ denotes the point of ignition). **Please note that it is the fire shapes and not the sizes shown that are relevant in this case.** The backfire spread distance becomes less pronounced, relative to the total spread distance, as wind speed increases. It is assumed that in the absence of wind and slope, a circular-shaped fire would result, with the point of ignition located at the center.
Lower: Schematic diagram illustrating the area and perimeter length calculations associated with elliptical-shaped forest fires (ROS = rate of spread).

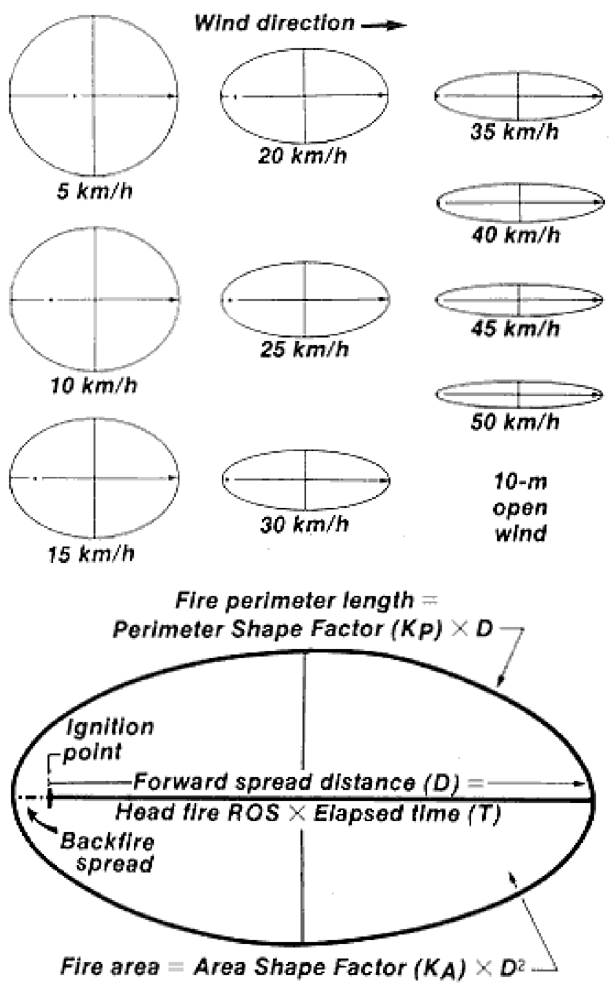


Table 3

Quantities used in determining the size and shape of free-burning, elliptical-shaped forest fires as a function of wind speed.[a]

10-m open wind speed (km/h)	Length-to-breadth ratio[b] (L/B)	Area Shape Factor (K_A)	Perimeter Shape Factor[c] (K_P)	Head/ backfire spread ratio (H/B)
0	1	3.14	6.28	1
5	1.04	1.88	4.86	1.57
10	1.17	1.16	3.84	3.16
15	1.41	0.77	3.17	5.78
20	1.76	0.54	2.75	10.3
25	2.23	0.39	2.49	17.8
30	2.82	0.3	2.32	29.8
35	3.54	0.23	2.22	48.1
40	4.39	0.18	2.15	75.1
45	5.37	0.05	2.1	114
50	6.48	0.12	2.07	166

[a] The formulas used to calculate fire area (A) in hectares (ha) and fire perimeter length (P) in metres (m) or kilometres (km) based on the head fire rate of spread (ROS) in metres per minute (m/min) or kilometres per hour (km/h) and elapsed time since ignition (T) in minutes (min) or hours (h) are as follows:

$$A \text{ (ha)} = [K_a \times \text{ROS (m/min)} \times \text{T (min)}]^2 \div 10000 \text{ or } [K_A \times \text{ROS (km/h)} \times \text{T (h)}]^2 \times 100$$
$$P \text{ (m)} = K_p \times \text{ROS (m/min)} \times \text{T (min) or } P \text{ (km)} = K_p \times \text{ROS (km/h)} \times \text{T (h)}$$

[b] The formulas required to plot the dimensions of an elliptical-shaped fire are as follows:

Forward spread distance = Head fire ROX x elapsed time since ignition
Backfire spread distance = Forward spread distance ÷ H/B
Total flank fire spread distance = (Forward + backfire spread distances) ÷ L/B

The formulas used to determine a map conversion factor (MCF) in order to convert the above distances to actual map distances are as follows:

MCF (cm/m) = 100 ÷ Map scale ratio or MCF (cm/km) = 100 000 ÷ Map scale ratio

[c] For example, the MCF for a 1:50000 scale National Topographic System (NTS) map sheet are 0.002 cm/m or 2.0 cm/km

The two elliptical shape factors (K_A and K_p) are passed on the “focus approach,” which indirectly accounts for the backfire spread as determined by the H/B, which is in turn ultimately determined by the L/B, which is a function of the 10-m open wind. For further details, see Alexander (1985).

Table 4

Fire area estimates in hectares (ha) of free-burning, elliptical-shaped fires in the black spruce-lichen woodland fuel type as a function of the Initial Spread Index (ISI), the 10-m open wind speed, and elapsed time since ignition. An * indicates that the fire area is less than 0.05 ha[a]. For example, a fire spreading under the influence of a 10-m open wind of 20 km/h and an ISI of 10 would be approximately 1.0 ha in size 30 minutes after ignition and 3.9 ha in 60 minutes.

	Elapsed time (min)				Elapsed time (min)				Elapsed time (min)				Elapsed time (min)				Elapsed time (min)			
ISI	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**
	10-m open wind: 5km/h				**10-m open wind: 10km/h**				**10-m open wind: 15km/h**				**10-m open wind: 20km/h**				**10-m open wind: 25 km/h**			
=3	*	*	=0.1	=0.2	*	*	*	=0.1	*	*	*	=0.1	*	*	*	=0.1	*	*	*	*
4	*	0.1	0.3	0.6	*	*	0.2	0.4	*	*	0.1	0.2	*	*	0.1	0.2	*	*	0.1	0.1
5	*	0.2	0.7	1.6	*	0.1	0.4	1	*	0.1	0.3	0.6	*	*	0.2	0.4	*	*	0.1	0.3
6	*	0.4	1.5	3.4	*	0.2	0.9	2.1	*	0.2	0.6	1.4	*	0.1	0.4	1	*	0.1	0.3	0.7
7	0.1	0.7	2.9	6.6	0.1	0.5	1.8	4.1	*	0.3	1.2	2.7	*	0.5	0.8	1	*	0.2	0.6	1.4
8	0.1	1.3	5.2	12	0.1	0.8	3.2	7.2	0.1	0.5	2.1	4.8	*	0.4	1.5	3.4	*	0.3	1	2.4
9	0.2	2.2	8.6	19	0.1	1.3	5.3	12	0.1	0.9	3.5	7.9	0.1	0.6	2.5	5.6	*	0.4	1.8	4
10	0.4	3.4	14	30	0.2	2.1	8.3	19	0.2	1.4	5.5	12	0.1	1	3.9	8.7	0.1	0.7	2.8	6.3
12	0.8	7.4	30	66	0.5	4.6	18	41	0.3	3	12	27	0.2	2.1	8.5	19	0.2	1.5	6.1	14
14	1.6	14	57	129	1	8.8	35	79	0.6	5.8	23	53	0.5	4.1	16	37	0.3	3	12	27
16	2.8	25	101	228	1.7	16	62	140	1.2	10	41	93	0.8	7.3	29	65	0.6	5.2	21	47
18	4.7	42	168	377	2.9	26	103	233	1.9	17	69	154	1.3	12	48	108	1	8.7	35	78
20					4.5	41	162	365	3	27	108	243	2.1	19	76	170	1.5	14	55	123
25	These combinations of ISI and 10-m open wind speed are impossible to achieve.								7.8	70	280	631	5.5	49	197	442	3.9	35	142	319
30									17	153	612	1377	12	107	429	966	8.6	77	310	697
35													23	208	831	1869	17	150	600	1350

	Elapsed time (min)				Elapsed time (min)				Elapsed time (min)				Elapsed time (min)				Elapsed time (min)			
ISI	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**	**10**	**30**	**60**	**90**
	10-m open wind: 30/h				**10-m open wind: 35km/h**				**10-m open wind: 40km/h**				**10-m open wind: 45km/h**				**10-m open wind: 50 km/h**			
=3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4	*	*	*	0.1	*	*	*	0.1	*	*	*	0.1	*	*	*	*	*	*	*	*
5	*	*	0.1	0.2	*	*	0.1	0.2	*	*	0.1	0.1	*	*	0.1	0.1	*	*	*	0.1
6	*	0.1	0.2	0.5	*	*	0.2	0.4	*	*	0.1	0.3	*	*	0.1	0.3	*	*	0.1	0.2
7	*	0.1	0.5	1.1	*	0.1	0.4	0.8	*	0.1	0.3	0.6	*	0.1	0.2	0.5	*	*	0.2	0.4
8	*	0.2	0.8	1.9	*	0.2	0.6	1.4	*	0.1	0.5	101	*	0.1	0.4	0.9	*	0.1	0.3	0.7
9	*	0.3	1.4	3.1	*	0.3	1.1	2.4	*	0.2	0.8	1.9	*	0.2	0.7	1.5	*	0.1	0.5	1.2
10	0.1	0.5	2.2	4.9	*	0.4	1.7	3.7	*	0.3	1.3	2.9	*	0.3	1.1	2.4	*	0.2	0.9	1.9
12	0.1	1.2	4.7	11	0.1	0.9	3.6	8.1	0.1	0.7	2.8	6.4	0.1	0.6	2.4	5.3	0.1	0.5	1.9	4.2
14	0.3	2.3	9.1	21	0.2	1.7	7	16	0.2	1.4	5.5	12	0.1	1.1	4.6	10	0.1	0.9	3.6	8.2
16	0.4	4	16	36	0.3	3.1	12	28	0.3	2.4	9.7	22	0.2	2	8.1	18	0.2	1.6	6.5	15
18	0.7	6.7	27	60	0.6	5.1	21	46	0.4	4	16	36	0.4	3.3	13	31	0.3	2.7	11	24
20	1.2	10	42	94	0.9	8	32	72	0.7	6.3	25	57	0.6	5.2	21	47	0.5	4.2	17	38
25	3	27	109	246	2.3	21	84	188	1.8	16	66	147	1.5	14	55	123	1.2	11	44	98
30	6.6	60	238	537	5.1	46	183	411	4	36	143	322	3.3	30	119	268	2.6	24	95	215
35	13	115	461	1038	9.8	88	354	796	7.7	69	277	623	6.4	58	231	519	5.1	46	185	412

Plate 1

Experimental Fire: T1 Date: July 4 Photo: B.D. Lawson

Fire Weather Observations

Dry-bulb temperature	20.5ºC
Relative humidity	50%
10-m open wind	18.8 km/h
Days since rain	1

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	3.7
Buildup Index (BUI)	64
Fire Weather Index (FWI)	12

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	82.0
Duff Moisture Code (DMC)	49
Drought Code (DC)	233

Fire Behavior Characteristics

Head fire rate of spread	0.6 m/min
Fuel consumption	0.23 kg/m^2
Frontal fire intensity	47 kW/m

Description of Fire Behavior:

Erratic, discontinuous fire spread, dependent almost entirely on the arrangement of black spruce or white birch clumps and downed-dead woody fuel concentrations. Lichen on downwind side of clumps in sunshine noticeably warmer and drier than that in open, so fire backs into clumps.

Type of Fire: Low-intensity surface fire

Plate 2

Experimental Fire: L4 Date: July 6 Photo: G.P. Delisle

Fire Weather Observations

Dry-bulb temperature	21.5ºC
Relative humidity	36%
10-m open wind	14.5 km/h
Days since rain	3

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	9.1
Buildup Index (BUI)	71
Fire Weather Index (FWI)	22

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	90.1
Duff Moisture Code (DMC)	55
Drought Code (DC)	247

Fire Behavior Characteristics

Head fire rate of spread	3.7 m/min
Fuel consumption	1.53 kg/m^2
Frontal fire intensity	1685 kW/m

Description of Fire Behavior:

Fire spread more or less continuous across the plot area. Sporadic torching experienced at favorable locations. Smouldering black spruce needles and bark flakes were carried up to 15 m ahead of the flaming trees.Downed-dead woody fuels served to reinforce the spread rate.

Type of Fire: Intermittent crown fire

Plate 3

Experimental Fire: L3 Date: July 5 Photo: B.J. Stocks

Fire Weather Observations

Dry-bulb temperature	20.0°C
Relative humidity	28%
10-m open wind	17.0 km/h
Days since rain	2

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	9.3
Buildup Index (BUI)	67
Fire Weather Index (FWI)	24

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	89.4
Duff Moisture Code (DMC)	51
Drought Code (DC)	240

Fire Behavior Characteristics

Head fire rate of spread	3.5 m/min
Fuel consumption	2.03 kg/m^2
Frontal fire intensity	2111 kW/m

Description of Fire Behavior:

Continuous fire spread in the open lichen, but spread process across the plot as a whole was very erratic due to irregular fuel distribution. Spotting downwind for up to 20 m from torching trees. Coalescence of spots contributed to fire spread rate and frontal intensity.

Type of Fire: Intermittent crown fire

Plate 4

Experimental Fire: L1 | Date: June 30 | Photo: B.J. Stocks

Fire Weather Observations

Dry-bulb temperature	26.5°C
Relative humidity	30%
10-m open wind	20.4 km/h
Days since rain	8

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	16.1
Buildup Index (BUI)	71
Fire Weather Index (FWI)	37

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	92.1
Duff Moisture Code (DMC)	62
Drought Code (DC)	204

Fire Behavior Characteristics

Head fire rate of spread	6.1 m/min
Fuel consumption	1.74 kg/m^2
Frontal fire intensity	3168 kW/m

Description of Fire Behavior:

Torching occurred with ease at the base of the black spruce clumps. Continuous torching of clumps observed over sections of the plot at the active flaming front progressed across the area. Fire whirls about 2 m in height occurred.

Type of Fire: Intermittent crown fire

Plate 5

Experimental Fire: L2 | Date: July 1 | Photo: B.J. Stocks

Fire Weather Observations

Dry-bulb temperature	24.5^{o}C
Relative humidity	25%
10-m open wind	24.0 km/h
Days since rain	9

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	21.3
Buildup Index (BUI)	74
Fire Weather Index (FWI)	45

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	92.8
Duff Moisture Code (DMC)	66
Drought Code (DC)	212

Fire Behavior Characteristics

Head fire rate of spread	26.3 m/min
Fuel consumption	1.73 kg/m^2
Frontal fire intensity	13 530 kW/m

Description of Fire Behavior:

Intense radiation experienced downwind from torching black spruce clumps, which tended to reinforce the spread rate and intensity of the flaming front as the fire moved across the length of the plot. Flame lengths about 2 m in the open lichen. Fire whirls up to 5 m in height.

Type of Fire: Fully developed crown fire

Plate 6

Experimental Fire: L5 Date: July 7 Photo: B.D. Lawson

Fire Weather Observations

Dry-bulb temperature	27.5ºC
Relative humidity	31%
10-m open wind	28.0 km/h
Days since rain	4

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	23.5
Buildup Index (BUI)	75
Fire Weather Index (FWI)	48

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	92.0
Duff Moisture Code (DMC)	59
Drought Code (DC)	256

Fire Behavior Characteristics

Head fire rate of spread	33.3 m/min
Fuel consumption	1.81 kg/m^2
Frontal fire intensity	17 777 kW/m

Description of Fire Behavior:

Initially, intense radiant head experienced up to 30 m downwind of torching black spruce clumps. Spot fires developed a further 20 m away. As a result, fire accelerated very quickly. Involving many trees together, with flames about 15-20 m high.

Type of Fire: Fully developed crown fire

Plate 7

Experimental Fire: L5A   Date: July 7   Photo: B.J. Stocks

Fire Weather Observations

Dry-bulb temperature	27.5ºC
Relative humidity	31%
10-m open wind	34.6 km/h
Days since rain	4

FWI System Fire Behavior Indexes

Initial Spread Index (ISI)	32.9
Buildup Index (BUI)	75
Fire Weather Index (FWI)	59

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	92.0
Duff Moisture Code (DMC)	59
Drought Code (DC)	256

Fire Behavior Characteristics

Head fire rate of spread	51.4 m/min
Fuel consumption	2.15 kg/m^2
Frontal fire intensity	32 367 kW/m

Description of Fire Behavior:

Fire advanced as a very high intensity, continuous crown fire with flames extending well above the tree crowns. Openings in the forest canopy did not affect the general level of flame involvement. Spot fires up to 200 m downwind of the advancing front were observed.

Type of Fire: Fully developed crown fire

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