FIRE BEHAVIOR IN BLACK SPRUCE–LICHEN WOODLAND: THE PORTER LAKE PROJECT

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Black spruce–lichen woodland fuel type (courtesy of W.J. De Groot).

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ABSTRACT

The behavior of single point-ignition and line-ignition experimental fires was studied in upland black spruce (*Picea mariana* [Mill.] B.S.P.)–lichen (*Stereocaulon paschale* [L.] Hoffm.) woodland stands at Porter Lake in the Caribou Range of the Northwest Territories (N.W.T.) from June 26 to July 8, 1982. The experimental burning project objective was to relate the head fire rate of spread (ROS) in this fuel type to the Initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index System. The experimental fire plots varied from 0.02 to 0.65 ha in size. The live tree overstory averaged about 1200 stems/ha and 5.0 m in height. The lichen layer averaged about 3.5 cm in depth. Three point-ignition fires, seven line-ignition fires, and one wildfire (CR-6-82) were documented over a wide range of burning conditions. The ensuing fire behavior varied from creeping surface fires to full-fledged crown fires. Head fire spread rates from 0.6 to 51.4 m/min were observed and frontal fire intensities of nearly 33 000 kW/m were attained. A relationship for equilibrium fire spread in black spruce–lichen woodland stands was established. The experimental fire data gathered during the Porter Lake project presently forms the basis for the quantitative prediction of fire behavior in the spruce–lichen woodland fuel type as currently incorporated into the system of forest fire danger rating used in Canada.

RÉSUMÉ

Le comportement d'incendies expérimentaux allumés en un point unique et allumés sur une ligne a été étudié dans des peuplements de forêt claire de hautes terres à épinettes noires (*Picea mariana* [Mill.] B.S.P.) et à lichens (*Stereocaulon paschale* [L.] Hoffm.) au lac Porter, dans la chaine Caribou, dans les Territoires du Nord–Ouest, du 26 juin au 8 juillet 1982. L'objectif de l'étude était d'établir une relation entre la vitesse de propagation à la tête de l'incendie dans ce type de peuplement et l'indice de propagation initiale de la Méthode canadienne de l'Indice Forêt–Météo. La superficie des parcelles expérimentales variait de 0,02 à 0,65 ha. L'étage dominant d'arbres verts comptait en moyenne environ 1,200 tiges de 5,0 m de hauteur à l'hectare. L'épaisseur moyenne de la strate des lichens était d'environ 3,5 cm. Trois incendies allumés en un point, sept incendies allumés sur une ligne et un incendie naturel (CR-6-82) ont été étudiés. Les conditions de ces incendies variaient énormément. Leur comportement allait du feu de surface rampant au véritable feu de cimes. Des vitesses de propagation à la tête du feu de 0,6 à 51,4 m/min ont été observées, et l'intensité du front de flammes a atteint près de 33 000 kW/m. Une équation a pu être établie pour la progression du feu à l'équilibre dans les peuplements de forêt claire à épinettes noires et à lichens. Les données recueillies au cours de l'étude sont utilisées pour la prévision quantitative du comportement des incendies dans les peuplements de forêt claire à épinettes et à lichens dans la méthode d'évaluation du danger d'incendie de forêt employée au Canada.

FOREWORD

The Porter Lake project represents much more than a fire behavior field research experiment. It is also an integral part of a larger, on-going Forestry Canada national program directed at understanding fire behavior in a variety of Canadian vegetation types under a wide-range of weather conditions in order to develop predictive models. Along with other earlier, similar efforts it signifies a long-standing, productive association between research and operational agencies in Canada. That association is not easily won and demands a high-level of cooperation and commitment by individuals and organizations reaching for common goals and determined to solve urgent practical fire management problems for the ultimate benefit of all Canadians.

Experimental burning in a field setting involves some necessary risk, especially when the knowledge sought requires some burning under extreme weather conditions. The Porter Lake site, in the Caribou Range of the Northwest Territories, was carefully selected to meet not only research criteria, but also because of its relative remoteness, thus minimizing potential risk to life and property. During the course of the project, the final planned experimental fire escaped pre-established control lines, burning 1430 ha of spruce–lichen woodland and became known as wildfire CR-6. The escape caused some adverse publicity and overshadowed, to some extent, significant project achievements, not the least of which was the added invaluable knowledge gained from monitoring and documenting, a free-burning wildfire in a natural setting. It is not the first time that major research gains have been made when research experiments follow an unforseen or unplanned pathway.

Though this report is the official record of the Porter Lake project much of the information has already found its way into national user guides, and operational and training manuals.

The Porter Lake project is fundamental to Canadian forest fire research and the Canadian Forest Fire Danger Rating System. This system is a dynamic Canadian research effort, guided by Forestry Canada's Fire Danger Working Group with carefully considered input from fire management agencies across the country. Projects similar to Porter Lake must continue if we are to gather the vital information necessary to control and use fire in the effective management of Canada's forest resources. The information presented here will strengthen the resolve of researchers, managers and operational personnel to continue their cooperative pursuit of these worthwhile and essential endeavours.

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NOTE

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INTRODUCTION

The study of free-burning fire behavior in major forest and vegetation types found in Canada represents a continuing goal of the national fire research program of Forestry Canada. Forestry Canada has traditionally taken an empirical approach to fire behavior research (Kiil 1975b; Van Wagner 1984, 1987b), rather than relying on theoretical analyses and/or the conducting of fires in the indoor laboratory in order to develop physical-based models for predicting fire behavior (Catchpole and de Mestre 1986; Weber 1991). This has generally involved analysis of field data by correlation and regression techniques, supplemented with some simple physical principles (McAlpine et al. 1990). The outdoor experimental fires conducted and documented by Forestry Canada fire research personnel over the years have varied from two-minute test fires lit with a match during the 1930s, 40s, 50s, and early 60s (Paul 1969; Simard 1970) to line-ignition of plots 0.1–3.0 ha in size with drip torches or pressurized flame throwers since the mid- to late 1960s (Van Wagner 1973; Lawson 1973; Kiil 1975a; Quintilio et al. 1977; Newstead and Alexander 1983; Stocks 1987a, 1987b, 1989; Quintilio et al. 1991). Data gathered from these experimental fires has been supplemented with information obtained from investigations of some relatively well-documented wildfires (Alexander and Lanoville 1987; Stocks and Flannigan 1987; Stocks 1988; Alexander 1991). The result of Forestry Canada's fire behavior research activity is, in present day terms, the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989). The CFFDRS is the national system of fire danger rating in Canada (Canadian Forestry Service 1987) and includes all the guides to the evaluation of fire danger and the prediction of fire behavior such as the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1984; Van Wagner and Pickett 1985; Van Wagner 1987a), and the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985; Forestry Canada 1991). This report presents the results of an experimental burning project conducted in the Northwest Territories during the 1982 fire season.

BACKGROUND

In February 1982, the Northern Forestry Centre (NoFC) of Forestry Canada (formerly the Canadian Forestry Service) received an invitation from the Head of Fire Control for the Northern Affairs Program (NAP)—N.W.T. Region of Indian and Northern Affairs Canada, stationed at the Regional Fire Centre in Fort Smith, N.W.T., to participate in a short-term experimental burning project in the upland black spruce (*Picea mariana* [Mill.] B.S.P.)–lichen (*Stereocaulon paschale* [L.] Hoffm.) woodland in the Caribou Range area (Fig. 1). The NoFC fire research unit was specifically requested to undertake the scientific documentation of fire behavior associated with the experimental fires that were to be conducted. Prior to undertaking this investigation there had been no serious attempt to investigate fire behavior over a range of burning conditions in any fuel type in the Northwest Territories except for some small-scale test fires conducted in black spruce, jack pine (*Pinus banksiana* Lamb.) and boreal mixedwood within the vicinity of Fort Smith during the 1961 fire season (Kiil and Mactavish 1962; Mactavish 1963). Furthermore, much of the Forestry Canada fire research effort to date had been devoted to closed-forest stand types and clear-cut logging slash south of 60° (Quintilio 1972; Stocks and Walker 1972; Van Wagner 1973). Consequently, there was a general lack of quantitative data on fire behavior in the more open, northern boreal forest fuel types.

Fire research personnel from other Forestry Canada establishments were asked to assist with the fire behavior documentation. A suitable study area for the project was located following reconnaissance by NAP and Forestry Canada personnel in early June, 1982. A peninsula at the northeast end of Porter Lake (Fig. 2) was selected on the basis of the control possibilities it offered, including the availability of water. A base camp, initially established to support fire suppression operations in the early 1960s, situated 15 km south of the study area on the east shore of Porter Lake served as a logistics support center for the operational activities associated with the project. The study area lies within the observation zone according to the N.W.T. fire

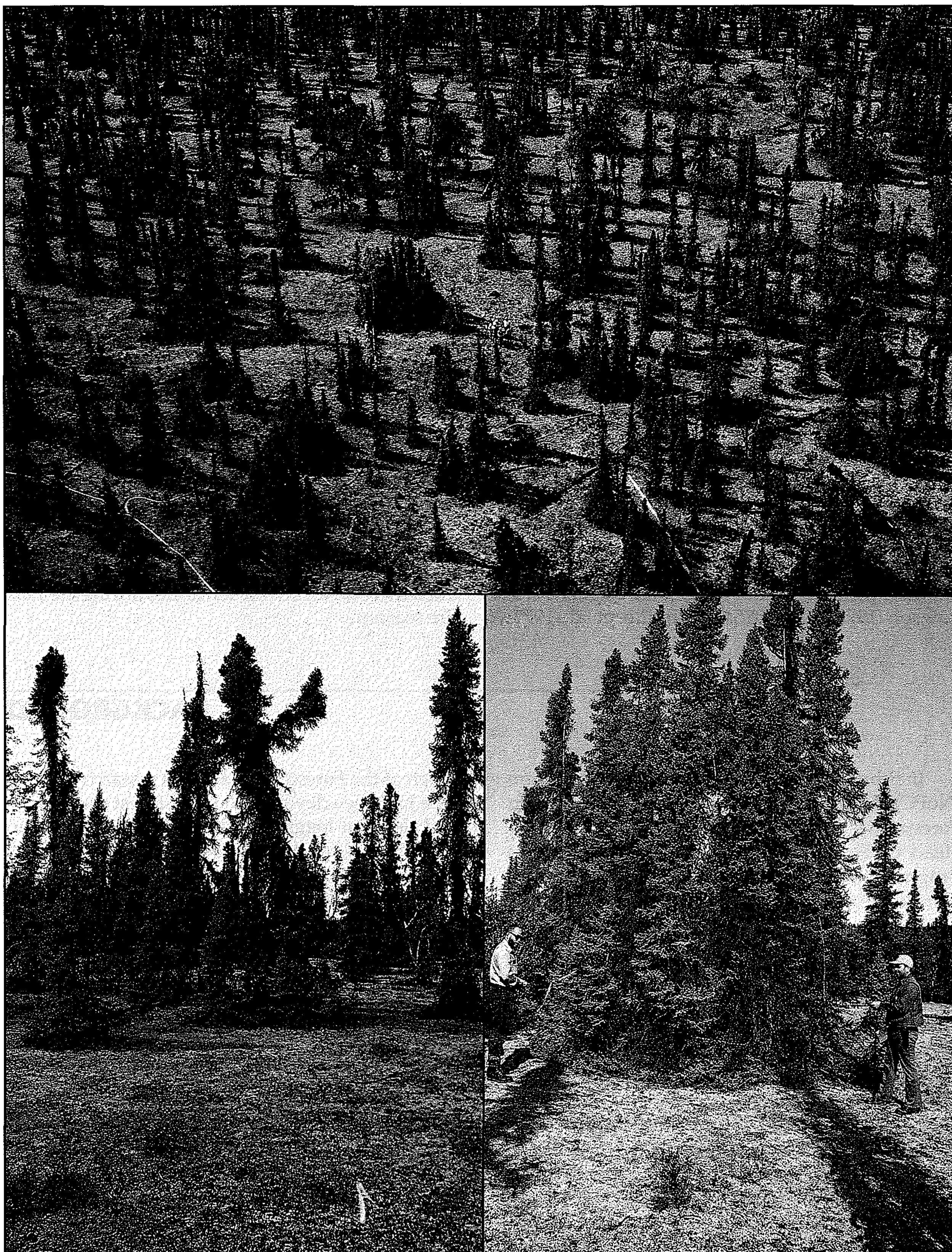

Figure 1. Aerial and ground views of the black spruce–lichen woodland fuel type at the Porter Lake study area.

management policy (Bailey 1985). Wildfires that occur in the observation zone are normally not "actioned" (i.e., no suppression action is initiated). Other than the Porter Lake base camp, there are no man-made structures of any significant value within 75 km of the study area. This degree of remoteness was considered desirable in the event of a fire escape from the immediate study area.

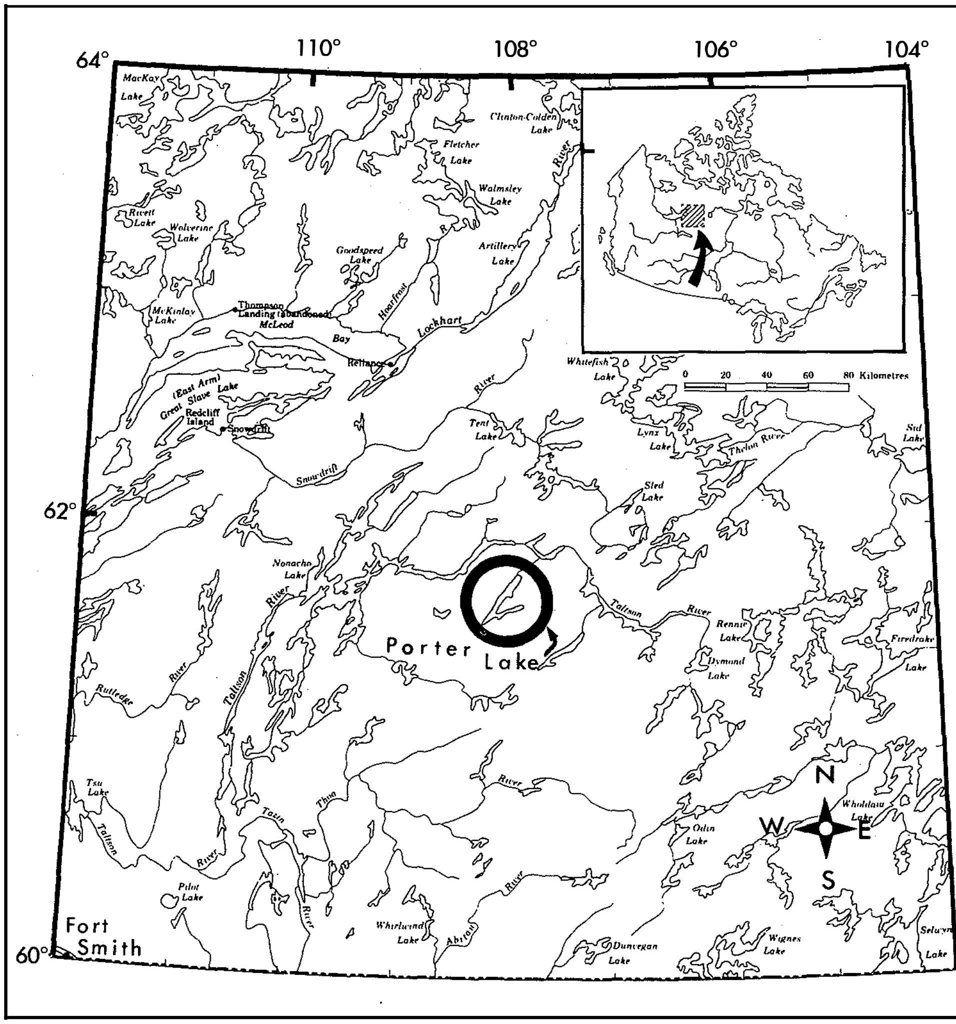

Figure 2. Location of the Porter Lake experimental burning project study area. (Source: Bradley et al. 1982.)

The northern variant of the black spruce forest found at Porter Lake is best described as forest cover type 12–subtype b (black spruce–lichen) as defined by the Society of American Foresters (Eyre 1980). The black spruce–lichen woodland fuel type is not only widespread in the N.W.T., but also in northern Saskatchewan and Manitoba (De Groot 1987, 1988; Hirsch 1988), and to a lesser extent in northeastern Alberta. The distribution map (Fig. 3), which is based on numerous sources (Ritchie 1960; Rowe 1972, 1984; Kershaw 1977; Larsen 1980, 1989; Bradley et al. 1982; Harris et al. 1983), represents an area of about 300 000 km^2.

STUDY AREA DESCRIPTION

Porter Lake is situated 290 km northeast of Fort Smith, N.W.T. at latitude 61°43'N, longitude 108°03'W (Fig. 2). The study area lies within the Northwest Transition Forest Section (B.27) of the Boreal Forest Region of Canada (Rowe 1972) and the Porter–Wignes Ecodistrict (LS2) of the Low Subartic Ecoregion as described by Bradley et al. (1982). The actual burning site was located on a well-drained flat at the northeast end of the lake (Fig. 4). The elevation above mean sea level (MSL) is approximately 365 m.

The general region is located on the Precambrian Shield. Soils in the study area consist of eluviated dystric brunisols (Bradley et al. 1982) that have developed on moderately-deep, stony, noncalcareous glacial till derived mainly from granitic rocks. These upland soils are sandy loam to loamy

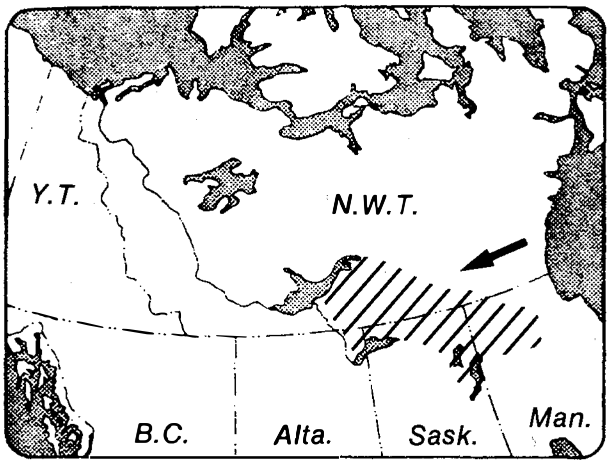

Figure 3. Approximate geographic extent of the black spruce–lichen woodland type in the northwest region of Canada.

sand in texture. Bedrock outcrops occur throughout the study area.

The region has a dry subhumid continental climate with short cool summers, long cold winters and slightly more precipitation during the summer than the winter (Atmospheric Environment Service 1982, 1984, 1986; Ecoregions Working Group 1989). The annual precipitation is variable and low (300–400 mm), of which about half falls as snow. Day length is reduced to four or five hours during mid-winter (December–January) when mean daily temperatures vary from -25 to -30°C. In contrast, summer days are 19–21 hours long (List 1951), giving high solar radiation and mean daily temperatures of 18–21°C for the short growing season.

The fire season generally lasts from mid- to late May, when the snow normally melts (Potter 1965), until the end of August or early September when cooler weather and reduced daylight hours prevail. Snow cover usually occurs by the first week of October. The fire climate of the Caribou Range can be roughly characterized by examining the fire danger climatologies for Fort Smith (elevation: 205 m MSL; 60°1′, 111°58′) and Yellowknife (elevation: 205 m MSL; 62°28′, 114°26′) presented in Figure 5 and Table 1. These summaries are for May 16 to September 15 (i.e., 123 days per fire season) based on the 10-year period from 1971 to 1980. The maximum values for the six standard components of the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1984; Van Wagner 1987a; Van Wagner and Pickett 1985) during this 10-year period are given in Table 2. The maximum Monthly Severity Rating (MSR) and Seasonal Severity Rating (SSR) for this same period were 9.39 MSR and 7.03 SSR at Fort Smith, while at Yellowknife they were 15.69 MSR and 6.56 SSR. The SSR exceeded a critical value of 2.0 (Harvey et al. 1986) in eight of the 10 fire seasons at Fort Smith and in all but one of the fire seasons at Yellowknife.

METHODS

Research Approach

The primary objective of the study was to develop a practical, quantitative scheme of fire behavior prediction in the open upland black spruce–lichen woodland fuel type for use by northern fire managers in the western subarctic region of Canada. A series of small-scale experimental fires were ignited over as broad a range of weather conditions as possible, and the resulting fire behavior characteristics were monitored (Alexander and Quintilio 1990).

Forward linear rate of fire spread (ROS), at equilibrium for any given combination of fire environmental factors, was the principal fire behavior characteristic of concern. Rate of spread data were collected from head fires ignited as lines across the upwind end of rectangular plots and allowed to spread with the wind down the length of the plot. Exploratory investigations of the incipient phase fire spread from single-source point-ignitions were also carried out in the same fuel type. Consumption of ground, surface, and crown fuel components was documented for each fire, and frontal intensity calculated from observed ROS and measured fuel consumption.

The ranges of fire weather conditions of most concern in this open-canopied fuel type were expressed through the range in Initial Spread Index (ISI), a component of the FWI System combining wind and fine fuel moisture. The ISI component is used in the FBP System as a predictor of ROS in a variety of fuel types. The plan was simply to conduct as many experimental fires over as broad a

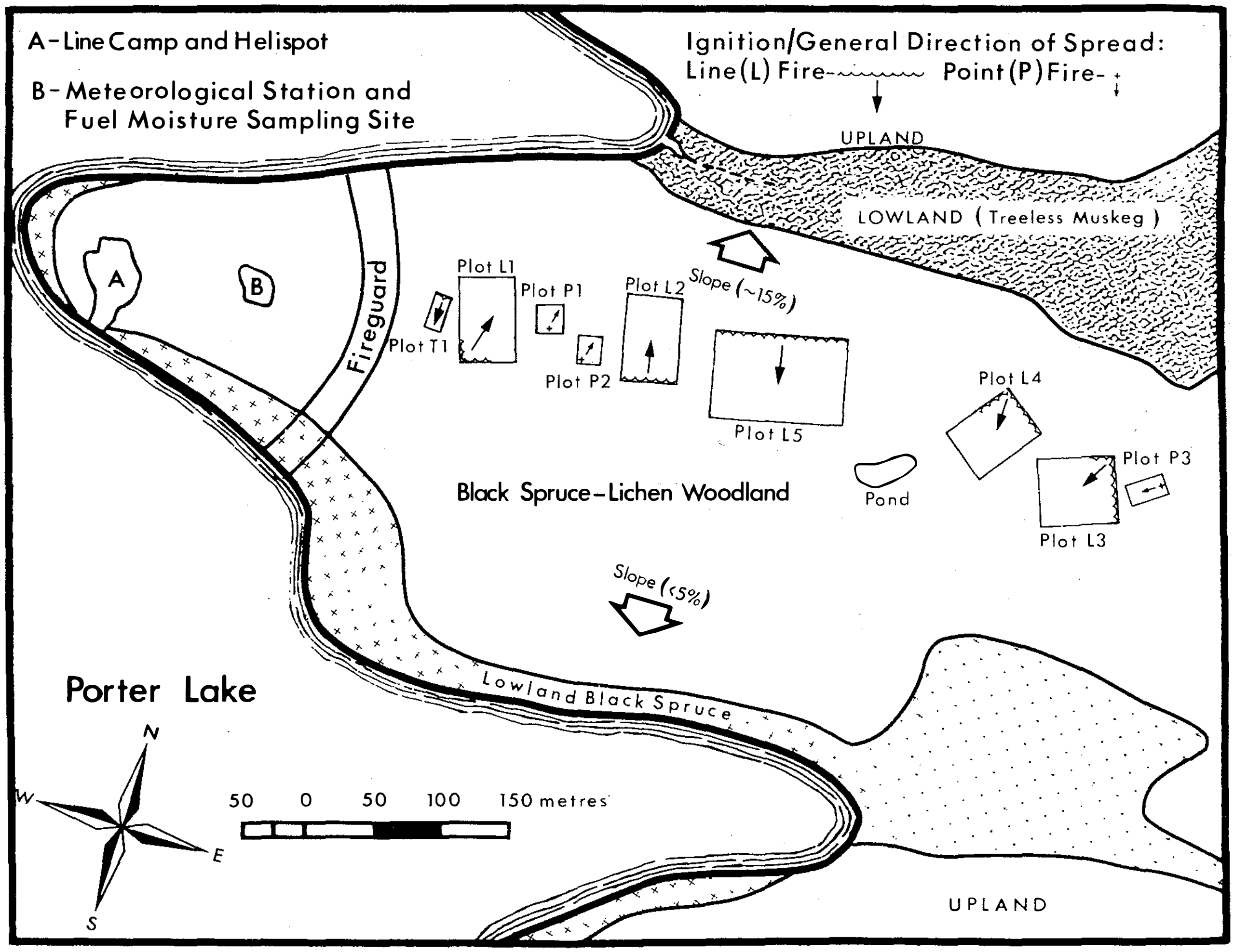

Figure 4. General layout of the Porter Lake experimental burning project study area.

range of weather conditions, as reflected by the ISI, as the length of the project would accommodate. The required number of fires to be documented was not as important as achieving the maximum possible breadth in burning conditions as reflected in the ISI component.

Obtaining experimental fire data over a wide range of Buildup Index (BUI) was not a high priority in this particular study, because a large range in observed fuel consumption, of which BUI is a suitable predictor in certain fuel types, was not anticipated due to the light ground/surface fuel loads present. Thus, any variation in the frontal intensity of the experimental fires would be chiefly a reflection of spread rates and type of fire (i.e., surface or crown), which determines the degree of crown fuel involvement. In fact, the short duration planned for the project (10 days) precluded designing it around a wide range of BUI; however, the rapid recovery of the principal fire-carrying fuels in this fuel type from rainfall effects ensured that a short-term study could result in a suitable range of weather conditions affecting ROS.

All fires originating from a single point undergo a period of acceleration in linear rate of advance and frontal intensity until fire behavior approaching an equilibrium or steady-state is reached (McArthur 1968; Cheney 1981; Luke and McArthur 1986; Weber 1989). The point-ignition fires were designed to allow for the investigation of the incipient phase of fire-growth whereas the line-ignition fires were intended to represent the behavior of an established fire front. Simultaneous ignition of line- and point-ignition fires was planned to ensure the acceleration of fire spread from a single ignition point to equilibrium ROS, as was expected to be achieved on the line fires, could be documented under nearly identical fuel and fire weather conditions (e.g., Johansen 1987).

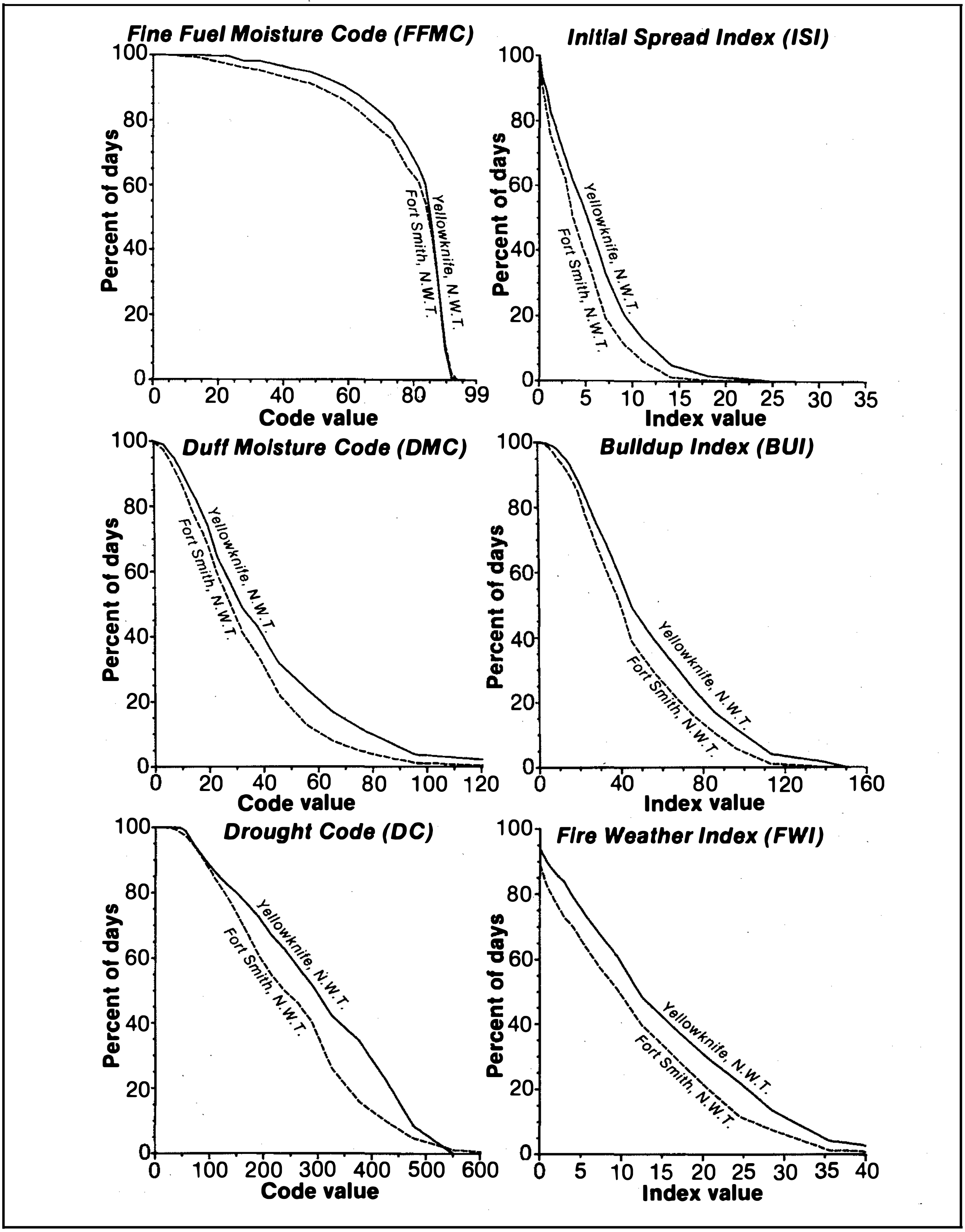

Figure 5. Cumulative frequency distribution curves of the Canadian Forest Fire Weather Index System components for two locations adjacent to the Caribou Range, Northwest Territories, based on the 10-year period from 1971 to 1980.

Table 1. **Average number of days per Initial Spread Index (ISI) value during the fire season for two locations adjacent to the Caribou Range Northwest Territories, based on the 10-year period from 1971 to 1980**

ISI	Fort Smith, N.W.T.	Yellowknife, N.W.T.
≤0.5	14.7	8.3
1.0	9.3	5.8
1.5	8.0	7.7
2.0	6.3	5.7
2.5	6.3	5.8
3	10.4	9.2
4	10.2	8.9
5	8.0	10.0
6	10.0	8.9
7	7.6	7.6
8	6.2	8.3
9	5.4	8.7
10	4.6	5.4
11	3.2	5.2
12	2.9	3.3
13	1.8	1.8
14	1.4	3.0
15	1.8	2.5
16	1.2	1.2
17	0.4	1.3
18-19	0.7	2.2
20-24	1.7	2.2
25-29	0.5	0.5
30-34	0.3	0.1
35	0	0

Table 2. **Maximum values of the Canadian Forest Fire Weather Index (FWI) System components recorded at two locations adjacent to the Caribou Range, Northwest Territories, during the 10-year period from 1971 to 1980**

FWI System component	Fort Smith, N.W.T.	Yellowknife, N.W.T.
Fine Fuel Moisture Code (FFMC)	96	94
Duff Moisture Code (DMC)	148	202
Drought Code (DC)	639	638
Initial Spread Index (ISI)	31	34
Buildup Index (BUI)	155	202
Fire Weather Index (FWI)	59	74

Tentative dates for the project were established early in the planning cycle. The actual starting date for the project was ultimately determined by the weather outlook and the territorial wildfire situation. The N.W.T. fire management and support staff initially reached the project site on June 26. The Forestry Canada fire research documentation team arrived at Porter Lake on June 29.

Plot Establishment

The general layout of the Porter Lake study area is shown in Figure 4. The project line camp and meteorological station for the study area were protected by a safety strip or zone created by a controlled burning operation during the afternoon of June 28. Plots for five line-ignition fires, three point-ignition fires, and two test fires were all located within the 28-ha study area. This study area was selected for three reasons: 1) the flat terrain would eliminate topography (i.e., slope steepness) as an influence on fire behavior; 2) the uniform and homogeneous nature of the black spruce tree cover would ensure all plots were relatively similar in terms of fuel composition; and 3) the lowland sites and water surrounding this point of land would increase control capabilities. With the influences of fuel and topographic variables being constant, differences in fire behavior monitored on-site would be attributable to weather measured on site and reflected through the components of the FWI System.

Specific plot locations were often influenced by minor local discontinuities in the fuel complex. Plots were oriented in a variety of directions in order to accommodate the most probable wind directions that would be experienced. Plot size was a compromise between what was manageable in terms of fire behavior monitoring and safety concerns, and what would also ensure an equilibrium forward rate of advance. A 5-m or 1-m buffer strip was established on the ignition end of each line-ignition fire plot to permit the establishment of a uniform fire front entering the area to be monitored. A 10 × 10 m grid pattern was laid out in each line-ignition fire plot to facilitate several observations and measurements. Table 3 gives individual plot dimensions and areas. The experimental fires were numbered in order of burning and designated as line-ignition (L), point-ignition (P), or test (T). The open, park-like nature of the stand and the shallow lichen layer eliminated the need for prepared fireguards (i.e., extensive cutting and clearing to mineral soil).

Vegetation Inventory

The following procedures were used to characterize the minor vegetation within the study area. A species list was compiled. The nomenclature for lichens used in this report is according to Egan (1987); for vascular plants, Porsild and Cody (1980) is the authority. Ten 50-m transects, oriented roughly in a northwest–southeast direction starting at the tip of the peninsula and proceeding inland away from the lake, were laid out with 20- to 50-m spacing between each transect. These transects were deliberately located in large openings of the forest canopy. Five 1.0-m^2 (1 × 1 m) quadrats, arranged at 10-m intervals, were located along each transect, yielding a total of 50 individual quadrats. Within each quadrat, the cover of each species was ocularly estimated to the nearest percent and the presence/absence noted within four equal subdivisions of the quadrat. The proportion of nonburnable ground cover was also visually estimated. The frequency (basis: n = 200) and mean cover of each individual species was computed for the study area as a whole. Prominence values (PV) were also calculated according to Beals' (1960) formula:

$$[1] \quad PV = C \times \sqrt{F}$$

where C = cover (%), and F = frequency (%). A maximum PV index of 1000 is possible.

At least a 40% cruise (by area) of all trees and snags exhibiting a diameter at breast height (dbh) was undertaken on each burning plot. The tree species, condition (live or dead), dbh, and height of each tallied stem was determined. The height to live crown base was assessed by measuring all live conifer trees that occurred along a 4-m wide strip around the exterior boundary of each plot. The distributions for dbh, height, stand basal area, and stem densities were computed for each plot. A generalized "stem map" was also prepared. Both of these tasks were completed *after* the burning in order to reduce compaction of the lichen layer. Basal fire scar cross-sections and increment cores were collected throughout the study area in order to determine the present stand age and previous fire occurrences.

Table 3. Plot sizes for the point-ignition (P), line-ignition (L), and test (T) fires conducted during the Porter Lake experimental burning project

Experimental fire no.	Plot dimensions Width (m)	Plot dimensions Length (m)	Plot area (ha)
P1	20	20	0.040
P2	20	20	0.040
P3	15	30	0.045
L1	40	65[a]	0.260
L2	40	65[a]	0.260
T1	10	21[b]	0.021
T2	10	21[b]	0.021
L3	50	65[a]	0.325
L4	40	65[a]	0.260
L5	65	100[a]	0.650

[a] Includes a 5 m buffer zone.

[b] Includes a 1 m buffer zone.

Preburn Fuel Assessments

The weight and bulk density of the forest floor was determined on the basis of 40 samples that were randomly collected throughout the study area but adjacent to the burning plots. Each sample measured 900 cm^2 in area. The forest floor depth was measured (to the nearest 0.1 cm) at the four corners of a 30 × 30-cm sampling frame. All of the lichen layer within the sampling frame was removed down to the mineral soil. The sample material was placed in paper bags, and returned to the laboratory at NoFC, and oven-dried to a constant weight. Every fifth sample was passed through a Wiley Mill and then ashed in a muffle furnace to determine the percentage of inorganic constituents.

Dead and down woody surface fuel loads were determined using the line intersect method (Van Wagner 1982a). The equilateral triangle (30-m sides) transect layout described by McRae et al. (1979) was followed. Theoretical quadratic mean diameters were used to calculate fuel loads (Van Wagner 1982b). Roundwood surface fuels were generally sparse but were sampled on each experimental line fire plot prior to ignition. Significant quantities of shrubs and herbaceous plants were virtually nonexistent and therefore no sampling was undertaken because these fuels would contribute very little to the energy released by the combustion process.

Preburn crown fuel loads were estimated by applying available applicable biomass regressions to each dbh size class distribution determined from the stem tally conducted on each burning plot. The following equations, developed for the the open black spruce–lichen (*Cladonia* spp.) woodlands of northern Quebec (after Rencz and Auclair 1980) and jack pine–lichen (*Cladonia* spp.) woodlands of northeastern Alberta were used in generating the component fuel weights:

$$[2] \quad W_1 = (e^{-0.89 + 1.774 \ln D})/1000$$

$$[3] \quad W_2 = (e^{5.53 + 1.594 \ln D})/1000$$

$$[4] \quad W_3 = (e^{2.32 + 2.293 \ln D})/1000$$

$$[5] \quad W_4 = -6.0128 + 0.90031D \qquad \text{where } D > 7$$

$$[6] \quad W_5 = -1.1759 + 0.21701D \qquad \text{where } D > 7$$

where W_1 = weight of tree lichen on black spruce (kg), W_2 = black spruce foliage (kg), W_3 = dead black spruce twigs and branchwood (kg), W_4 = jack pine foliage and small live twigs (kg), W_5 = small dead jack pine twigs (kg), and D = dbh (cm).

Just prior to ignition of each line source fire, a number of depth-of-burn (DOB) pins were systematically located throughout each plot. These pins were placed in the ground so that a horizontal "t-bar" on each DOB pin was flush with the top of the forest floor layer (McRae et al. 1979). The number of DOB pins used varied with plot size but averaged 1–2 pins per 100 m^2.

The only study of tree crown biomass for black spruce and jack pine in the Northwest Territories is that of Singh (1984). The predictive equations for the fine fuels less than 0.5 cm in diameter, which would typically be consumed in a crown fire, showed poor correlation with diameter-at-breast height (dbh); therefore, alternate sources were sought. The regressions of Rencz and Auclair (1980), which appear as Equations [2] to [4], appeared most appropriate for the tree form characteristic of black spruce in an open lichen woodland stand (Grigal and Kernik 1984). For jack pine, it was decided to use the tree crown weight work completed by B.J. Stocks during the Darwin Lake project (Quintilio et al. 1977) in northeastern Alberta because of the similarity in tree form to the jack pine at Porter Lake. The results of that work were utilized but never published *per se*. The methods used were similar to those described by Stocks (1980). In brief, ten living jack pines of various diameters and heights were selected, measured, felled, and their crowns dissected into six fuel components (Table 4). The total fresh or green weight of each crown fuel component was measured in the field with a hanging balance. Subsamples of each component were then taken for moisture content determination in order to calculate the ovendry weight. Although only ten trees were sampled, crown fuel component weights correlated highly with dbh. Regressions of ovendry weights on dbh were calculated using a variety of equation forms. Simple linear regressions appeared the most suitable. The coefficients of determination (R^2) for Equations [5] and [6] were 0.91 and 0.74, respectively. The following equation may prove useful in future non-forest fire related studies:

$$[7] \quad W_6 = -12.936 + 1.8176D \qquad \text{where } D > 7$$

Table 4. Sample tree and fuel component data for jack pine stems collected at Darwin Lake, northeastern Alberta

Sample tree no.	Stem			Live crown		Tree age (yr)	Fuel component weight (kg ODW)[c]					
							Live size classes (cm)			Dead size classes (cm)		Mature cones
	Dbh (cm)	Dgl[a] (cm)	Height (m)	Width (m)	Length (m)		0.64[b]	0.64–1.27	1.27–2.54	0.64	0.64–1.27	
1	7.1	8.1	7.9	0.9	4.0	60	0.87091	0.00454	0.0	0.36742	0.0	0.25402
2	13.0	15.0	11.8	1.5	6.9	58	6.74050	1.15214	0.21773	1.55131	0.34020	1.07503
3	10.2	11.9	9.7	1.2	5.8	58	3.56983	0.61236	0.0	0.64411	0.02722	0.0
4	11.4	13.7	10.7	1.4	6.8	58	4.27291	1.18843	0.56246	2.10017	0.53071	0.26762
5	8.1	9.9	10.5	0.8	4.4	58	0.86638	0.06804	0.0	0.69401	0.0	0.0
6	15.7	19.0	12.4	—[d]	—	—	8.12398	1.44698	1.19750	2.18635	0.87998	2.34058
7	9.9	13.2	10.8	1.4	5.9	62	3.38386	0.44906	0.0	0.77566	0.0	0.0
8	10.7	14.0	11.6	1.3	5.5	63	2.86222	0.23134	0.0	0.82102	0.0	0.0
9	14.5	17.8	12.2	—	—	—	7.37100	1.66925	0.79834	1.80533	0.75298	0.72122
10	12.2	16.0	10.1	1.8	5.6	61	3.36571	1.17029	0.80741	1.77358	1.36080	1.38802

[a] Dgl = diameter at ground level.

[b] Includes foliage.

[c] ODW = ovendry weight.

[d] Missing data.

where W_6 = total tree crown weight (kg) and D = dbh (cm). The R^2 for Equation [7] is 0.95.

Fire Weather Observations

A fully-instrumented fire weather station was established at the study site on the peninsula of Porter Lake, in close proximity to the experimental burning plots (Fig. 4), and according to the location and instrument exposure standards outlined by Turner and Lawson (1978). An opening roughly 30 m in diameter (approximately four times the tree height) was created and a Forest Technology Systems (FTS) Ltd. 6100-3/Model WR 61-24 electronic fire weather station (Ward 1983) was, after unforeseen problems, finally set up on June 26, 1982[3]. This station was used to obtain standard daily noon local standard time or 1300 Mountain Daylight Time (MDT) observations of dry-bulb temperature, relative humidity, 10-min average wind speed at 10 m above the ground in the open, and 24-h rainfall. These parameters were required for daily calculation of components of the FWI System. Additional instrumentation at the weather station included standard Atmospheric Environment Service (AES) maximum/minimum thermometers, a Weathermeasure Model H311-A-S-1/7 hygrothermograph and a Frederick Goertz fan ventilated psychrometer, all located in double-louvered screens at a height of 140 cm, a Taylor Clear-Vu plastic rain gauge and a Belfort bimetallic actinograph. The FTS station recorder was configured to enable the collection of hourly observations of temperature, relative humidity, 10-min average wind speed and wind direction, and hourly rainfall[4].

During each test fire, the FTS station was used to monitor 10-min average wind speed and direction at 10 m every 10 min, as well as screen temperature and relative humidity just prior to ignition. In addition, during each fire, a Casella sensitive 3-cup anemometer was used to monitor 10-min average wind speed at 1.4 m at the weather station. At two locations within the stand, upwind and approximately 25 m from the fire plot edge to minimize fire indraft influences (Sneeuwjagt and Frandsen 1977), Casella sensitive 3-cup anemometers at 1.4 m recorded 2 minute average wind speeds for the duration of each fire. Wind direction at these locations was estimated every 2 minutes, using compass bearings. Portable electric fan psychrometer (Bendix) readings of wet- and dry-bulb temperatures were taken at the fire site just prior to ignition and at the conclusion of each experimental fire.

Fire Danger Rating Computations

Starting Values

Calculation of FWI System components commenced June 27, 1982 using the following starting values: Fine Fuel Moisture Code (FFMC) 85; Duff Moisture Code (DMC) 47; and Drought Code (DC) 175. Starting values for DMC and DC were interpolated from surrounding stations, which had operated for the full fire season up to June 26, whereas FFMC starting value was set at 85, as suggested in Turner and Lawson (1978). Five stations surrounding Porter Lake were available as fire weather reference points for DMC and DC starting values[5].

The DMC values on June 26 for these stations were averaged, and since all stations including Porter Lake were within a 250-m elevation of each other, the weather data was treated as being applicable without modification to the Porter Lake area. The net increases in DMC between May 23, the third day after the snow melted at Porter Lake, and June 26 were determined for the five reference stations, calculating each station as if snow had melted

[3] The FTS station was equipped with a Phys-Chemical Research PCRC-11 relative humidity sensor and a Fenwall Electronics UUT51J1 thermistor combined in one probe, a Downeaster model WV II Type 2 anemometer, a Downeaster model WVI Type 1 vane, and a Sierra-Misco tipping bucket rain gauge.

[4] On the basis of 140 paired observations taken during the course of the study, the average difference in air temperature between the FTS sensor and the dry-bulb thermometer reading of the electric fan psychrometer (observed to the nearest 0.5°C) was –0.76 ± 0.64°C over a sample range of about 7.5 to 27.5°C. The average difference in the relative humidity between the FTS sensor and the value determined from dry- and wet-bulb thermometer readings (each observed to the nearest 0.5°C) of the electric fan psychrometer was 2.3 ± 4.9%.

[5] The five fire weather stations included: Fort Reliance, N.W.T. (elevation: 164 m MSL) (AES), Snowdrift, N.W.T. (elevation: 177 m MSL) (N.W.T. Fire Management weather station), Fort Smith, N.W.T. (elevation: 203 m MSL) (AES Weather Station used by N.W.T. Fire Management), Tsu Lake, N.W.T. (elevation: 213 m MSL) (N.W.T. Fire Management lookout), and Uranium City, Sask. (elevation: 318 m MSL) (AES weather station) located at latitude 59°34′, longitude 108°29′ (see Fig. 2 for locations).

by May 20, as it did at Porter Lake. The mean incremental increase in DMC by this procedure was within two points of the mean DMC of the five stations. Hence, a starting DMC of 47, midway between the two mean calculations, was used for Porter Lake on June 26.

A similar analysis of the five stations was done to determine a DC starting value. The June 26 DCs were averaged for the five stations, without adjustment for overwinter precipitation. DCs for the five stations were then recalculated starting from May 23, as if they had the same snow- free date as Porter Lake. The mean incremental increase in DC for the five stations over this period was within 30 points of the mean actual station DC for June 26. The most applicable starting value for DC at Porter Lake for June 26 was selected as 175, the mean of the five stations as calculated over the snow-free period common to Porter Lake, and nine points lower than the mean of the actual five station DCs for June 26.

Daily Calculations

Daily calculations of all FWI System components continued at the Porter Lake station until August 10, based on the noon FTS-6100 observations. Following a break in the continuous record between August 11 and 21, daily calculations resumed August 22 and continued through September 21 when the station was removed. In addition continuous hourly calculations of FFMC and ISI were made from the FTS hourly weather observations for the period of June 27 to July 18, except for a 22-h break in the record July 9–10. A modified computer program for hourly FFMC was based on a program developed by Van Wagner (1977a). Breaks in the continuous FTS station record were filled where possible from electric fan psychrometer readings, hygrothermograph readings and plastic rain gauge readings.

Fuel Moisture Sampling

The fuel moisture sampling conducted during the Porter Lake project served a two-fold purpose: 1) to document the attendant burning conditions associated with each experimental fire, and 2) to examine the unique drying and wetting characteristics of the ground lichen and forest floor material at a far northern latitude during mid-summer with the aim of eventually developing codes or models to predict the moisture content of these fuels from weather observations.

The trend of fuel moisture content (MC) with weather was followed: by destructive sampling and the tray method (Wright 1932). The trays measured 30 × 24 cm in area and 6 cm high (Fig. 6). They

Figure 6. A) Fuel moisture sampling tray containing a lichen mat.
B) Fuel moisture sampling tray containing the forest floor layer within a black spruce clump.

were shaped from galvanized wire screen, 14 mesh per 10 cm, and lined with nylon mesh cloth. Sections of the upper 6-cm portion of the forest floor were removed in one piece to fit the trays, which were then set into prepared openings with the fuel surfaces flush. The following trays were maintained throughout the project:

- Tray 1–4: Full lichen layer in the open (~3.4 cm thickness),
- Tray 5: Top half of lichen layer in the open (~1.7 cm thickness),
- Tray 6: Feather moss in a black spruce clump (well-sheltered),
- Tray 7: Forest floor layer in a black spruce clump (heavily-sheltered), and
- Tray 8: Forest floor layer under a jack pine tree (slightly-sheltered).

Trays 1–5 and 8 rested on mineral soil. All trays were weighed hourly or when judged appropriate to record rain effect, drying immediately after rain, and the diurnal range of moisture content in dry weather. Trays 1–5 were renewed once during the project. At the end of each run, the tray contents were removed and eventually oven-dried for 24 hours in the laboratory at NoFC in Edmonton, Alberta.

Destructive samples of the lichen layer were taken hourly (or when the trays were weighed), two tins each time, each a composite of several spots. Every day at 1400 MDT three tins each of jack pine foliage, black spruce foliage, and tree lichen were picked, each tin a composite of several spots. Fuel moisture tins were sealed with masking tape to prevent moisture loss (Fraser 1959), flown to a laboratory facility in Yellowknife, and oven-dried at 100°C for 24 hours.

Finally, four sets of standard B.C. Forest Service (BCFS) 100-g (oven-dry) fuel moisture sticks made out of four 1.3-cm diameter Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) dowels (Bell 1970) were exposed on June 26, in the open 30 cm above ground, and weighed hourly or when trays were weighed. At the completion of the project, the sticks were returned to the laboratory at NoFC and oven-dried for 24 hours.

All of the fuel moisture sampling was confined to an area within the immediate vicinity of the weather station (Fig. 7). Trays and BCFS fuel moisture sticks were weighed on a K-TRON model DS-10 precision electronic weighing balance operated using battery power or a portable generator.

Burning Procedures

The decision whether or not to burn depended on the current burning conditions and the afternoon fire weather forecast. Plot selection for burning was determined primarily on the basis of the expected wind direction at the time of ignition. Ideally, all experimental line-ignition fires were ignited along the windward edge of each plot (preferably the narrowest side), and allowed to spread with the wind down the length of the plot in order to simulate a free-burning wildfire. If the prevailing wind was blowing directly on a plot corner rather than a side, ignition took place along a portion of two adjacent boundaries, starting at the plot corner. A briefing of all on-site project personnel was conducted in advance of any experimental fires in order to review the planned ignition time and pattern, control measures, and safety precautions. Separate meetings were held by N.W.T. fire management and Forestry Canada fire research staff to outline individual assignments and instructions in more detail.

The ignition of the line fires and the control, mop-up and patrol of all experimental fires were the responsibility of N.W.T. fire management personnel which consisted of three permanent supervisory staff and a seasonal fire suppression crew. A sprinkler system (Quintilio et al. 1971; Maffey 1983) augmented with additional hose lengths and nozzles was used to wet down areas downwind of the plot boundaries in advance and during each experimental fire. Air support consisted of a 206-B Jet Ranger helicopter equipped with a bucket for containing any spot fires and "excursions" that might occur. All line-ignition fires were, except in one case, started with a Forester pneumatic flame thrower; fire L1 was started with fusees due to an equipment malfunction at the time of ignition. Point-ignition fires were started with a single wooden match by a member of the Forestry Canada fire research documentation team. During each experimental fire, fire research personnel documented the attendant fire weather conditions and various aspects of fire behavior.

Fire Behavior Monitoring

Line-ignition burning plots were gridded on a 10 × 10-m scale and a metal pin located at each grid point. As noted earlier, each experimental

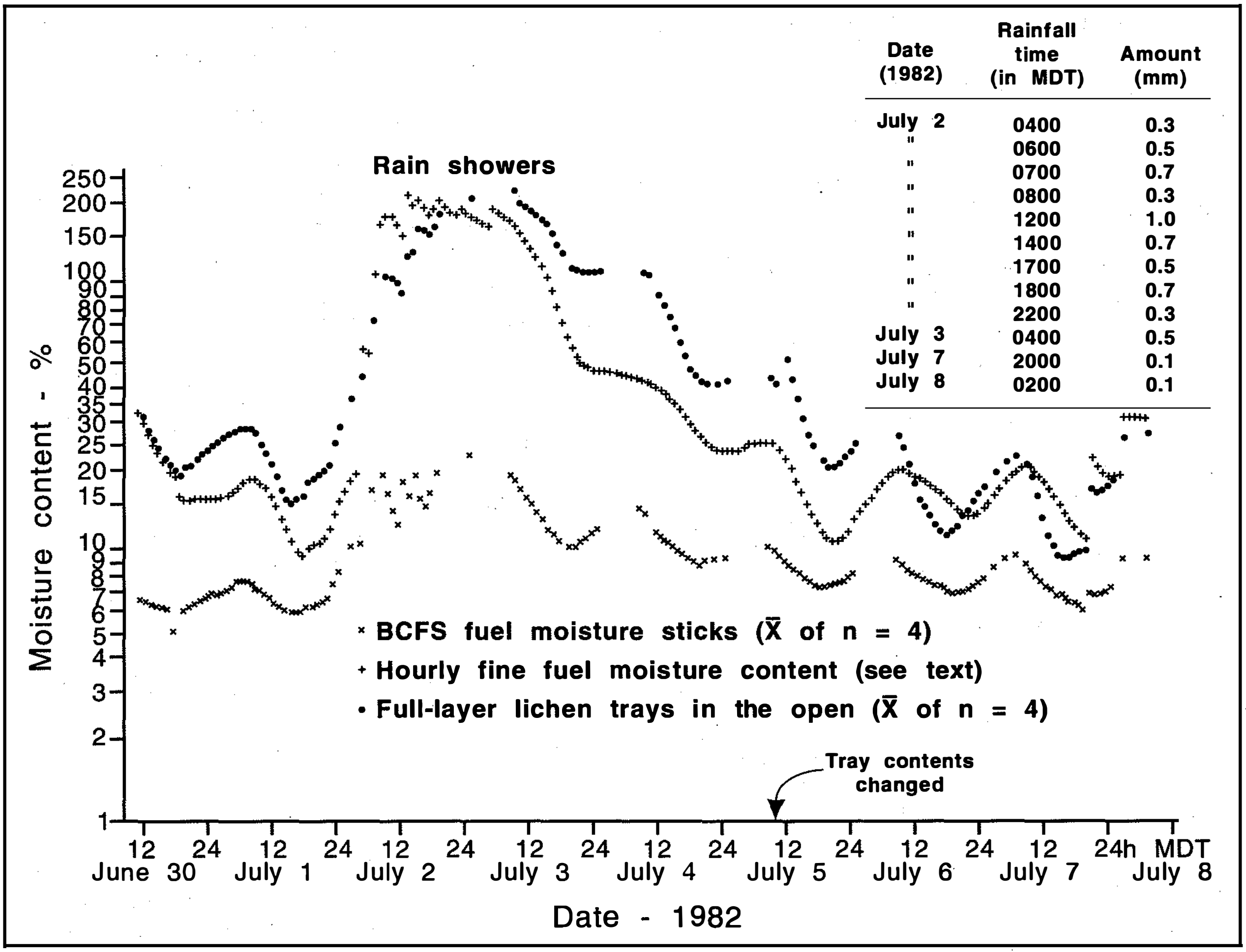

Figure 7. Diurnal changes in fine fuel moisture over time for nine days during the experimental burn.

line-ignition fire was ignited along the windward edge of the plot. Ground observers noted the time necessary to complete ignition, the time required for the fire front to pass from the plot edge through the buffer zone interface, and the times taken for the active flaming front to reach each grid point in the plot. Observers used stopwatches and pocket tape recorders to document this phase of fire behavior.

The location within the plot for the origin of a point-ignition fire was selected just prior to the time of ignition, according to the prevailing wind direction. An ignition point near the windward end or corner of the rectangular plot was chosen and marked with a metal pin. The point of ignition was chosen to ensure fuels were representative of the open portion of the stand, not those in close proximity to trees or tree clumps. Ignition was achieved using a single wooden match to light the surface lichen and litter. In the case of experimental fires P1 and P2, this took place once the front of the associated line-ignition fires had progressed through the buffer zone. The fire perimeter was monitored at timed intervals appropriate to the rate of perimeter advance, generally every two or four minutes. At these intervals, observers placed a sufficient quantity of numbered metal tags around the head, flanks and back of the fire to permit postburn mapping of the fire's perimeter at each marked interval (Peet 1967; Cheney 1971). The point-ignition fires were terminated when the head fire reached the downwind end or corner of the plot; flank and backing fire observations were not continued beyond this time. After the fire area had cooled, the metal tags were surveyed by bearing and distance from the point of ignition; a map of the fire growth pattern was then drawn up from the plot of points. From these sketched outlines, the area and perimeter length associated with the time intervals of each point-ignition fire were determined with the aid of an electronic planimeter; the same instrument was also used in the fire growth analysis of wildfire CR-6-82.

On both point- and line-ignition fires, observations of fire vigor, continuity, and type of advance (e.g., creeping, running), were recorded. An observer also noted times and locations of such fire behavior phenomena as torching, crowning tendency and spotting distances, and recorded estimated head fire flame lengths at intervals. These observations were supported by time-documented 35 mm color photography and color video coverage from both ground and helicopter vantage points. The videotape documentation may prove to be more valuable to the understanding and prediction of fire behavior in later years, as a supplement to the slide transparencies and this written record, than at present.

Postburn Fuel Evaluations

Immediately following each experimental line source fire, the degree of forest floor depletion was measured (to the nearest 0.1 cm) at each t-bar DOB pin. In addition, twelve 30 × 30 cm samples of the remaining lichen layer were collected and subsequently analyzed in the same manner as the preburn samples. Forest floor fuel consumption was determined on the basis of the preburn bulk density, DOB and postburn load. Dead and down woody materials were remeasured on each line intersect transect which had been established prior to burning in order to calculate postburn fuel loads. Roundwood fuel consumption was taken as the difference between the preburn and postburn loads.

An ocular estimate of the proportion of live crown consumed was made of every tallied tree during the postburn overstory cruise of each plot. The consumed crown fuels were assumed to be limited to tree foliage and roundwood material less than about 0.5 cm in diameter. Crown fuel consumption was calculated on the basis of the supposed available preburn load and percentage of live crown consumed.

RESULTS AND DISCUSSION

The basic data collected during the course of the Porter Lake project has been assembled into a file report[6] for future reference. The most pertinent information follows. Where appropriate, both the mean ($\bar{X}$) and standard deviation (SD) are quoted together (e.g., 3.4 ± 0.9 cm).

Stand Characteristics

The stand structure characteristics associated with each of the experimental burning plots is summarized in Table 5. The forest canopy in the Porter Lake study area is dominated by sparsely stocked, stunted black spruce stands; however, scattered jack pine trees and white birch clumps (*Betula papyrifera* Marsh.) can be found in the overstory. Individual black spruce stems seldom exceed 13 m in height or 20 cm dbh. Many older black spruce trees had tended to reproduce vegetatively by layering, forming dense clumps of up to 50–60 stems. Some of these clumps possessed a dead and decaying central bole, indicating extreme old age. A single black spruce clump sampled near the southwest corner of Plot L2 revealed that the parent tree originated around 1843 and first started layering about 35 years later. Since that time, 25 individual stems were produced at more or less regular intervals with the most recent originating around 1950. The physical appearance of jack pine stems in the area suggested very old age; many exhibited multiple basal fire scars. It was evident that the scattered white birch clumps had developed from basal sprouting after the parent tree died.

The available fire scar information obtained from jack pine indicated that the last fire in the study area occurred about 1840 in the eastern part of the study area and about 1823 in the western section around the weather station and camp. No jack pine regeneration was found that may have

[6] Alexander, M.E. (compiler). 1988. The Porter Lake Experimental Burning Project, Caribou Range, Northwest Territories: data compendium. Govt. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Study NOR-5-05 File Rep. 18.

Table 5. Stand structure characteristics for the plots associated with the Porter Lake experimental burning project

Experimental plot no.	Dbh (cm) Black spruce	Jack pine	White birch	Dead stems	Dbh size class (live stems/ha) ≤4.9 cm	5.0–9.9 cm	10.0–14.9 cm	≥15.0 cm	Height (m) Black spruce	Jack pine	White birch	Dead stems	Height class (live stems/ha) 1.3–3.0 m	3.1–8.0 m	≥8.1 m
L1	5.2 + 3.6[a]	—[b]	4.1 + 2.3[a]	6.4 + 4.0[a]	1270	700	200	60	4.1 + 1.8[a]	—	4.3 + 1.7[a]	2.7 +1.4[a]	820	1350	50
L2	5.7 + 4.6	7.0 + 0.0[a]	2.5 + 1.7	5.7 + 4.6	579	191	97	29	4.3 + 2.3	4.2 + 0.0[a]	2.7 + 1.2	3.4 + 1.8	432	432	32
L3	7.3 + 4.4	15.1 + 3.6	2.6 + 2.5	9.3 + 4.3	386	400	288	80	5.2 + 2.2	7.5 + 1.7	3.0 + 0.0	5.7 + 3.1	276	765	113
L4	5.7 + 3.6	13.0 + 7.1	—	8.5 + 1.7	570	270	150	40	4.1 + 1.9	5.6 + 0.2	—	5.0 + 1.6	340	640	50
L5	8.0 + 5.7	21.5 + 7.0	3.5 + 3.3	11.8 + 8.3	325	282	158	112	5.6 + 2.5	7.6 + 2.1	3.3 + 1.5	6.0 + 4.9	260	515	102
P1	7.6 + 4.6	—	—	16.5 + 0.0	294	176	294	59	5.2 + 1.9	—	—	3.5 + 0.0	59	705	59
P2	5.6 + 5.3	—	4.1 + 2.9	5.6 + 5.3	1110	613	111	111	4.2 + 2.2	—	4.4 + 1.8	—	556	1056	333
P3	8.7 + 5.5	—	—	—	228	86	257	86	4.9 + 2.3	—	—	—	228	400	29

[a] Mean and standard deviation.

[b] Not present.

Table 5 continued.

Experimental plot no.	Basal area (m^2/ha) Live stems	Dead stems	Basal area by species (%) Black spruce	Jack pine	White birch	Density (no./ha) Live stems	Dead stems	Density by species (%) Black spruce	Jack pine	White birch	Average spacing (m)[c] Live stems	Dead stems	All stems
L1	6.77	0.48	94.8	0.0	5.2	2220	110	90.5	0.0	9.5	2.1	9.5	2.1
L2	2.96	0.39	93.2	0.7	6.1	896	54	72.1	0.4	27.5	3.3	13.6	3.2
L3	6.78	0.97	92.2	7.4	0.4	1154	120	94.8	2.3	2.9	2.9	9.1	2.8
L4	3.85	0.29	92.2	7.8	0.0	1030	50	98.1	1.9	0.0	3.1	14.1	3.0
L5	7.41	0.15	69.6	26.9	3.5	877	10	78.1	5.7	16.2	3.4	31.6	3.4
P1	4.94	1.24	100.0	0.0	0.0	823	59	100.0	0.0	0.0	3.5	13.0	3.4
P2	7.39	0.00	90.3	0.0	9.7	1945	0	80.0	0.0	20.0	2.3	—[b]	2.3
P3	5.37	0.00	100.0	0.0	0.0	657	0	100.0	0.0	0.0	3.9	—	3.9

[b] Not present.

[c] Average between-stem spacing = $\sqrt{10\,000 \text{ (no. stems/ha)}}$.

originated after either of these fires, indicating a low intensity surface fire. Some black spruce regeneration was found to have originated after the 1823 fire, indicating that black spruce is more sensitive to fire (no live or dead black spruce stems could be found that exhibited a fire scar). Another fire occurred around 1803 in the northern section of the study area. One jack pine was found which could have originated after this fire. This fire was probably also a low-intensity surface fire. Most of the jack pine and black spruce in the study area originated after two different fires. The most recent fire was around 1759 and the older fire occurred around the 1680s or 90s (based on the oldest live jack pine found, which was 284 years old). The results of the limited fire history sampling indicated that the Porter Lake study area had a mean fire interval of around 58 years for all fires and 145 years for fires which caused significant jack pine and black spruce regeneration. The peninsula on which the study area is based is isolated from more continuous tracts of forest. Past wildfires may have moved into this area as flank or backing fires of larger conflagrations. The fire history did indicate that stand replacing fires have occurred on the study area in the past at infrequent intervals. The oldest jack pine aged in the study area was a snag that was 314 years old when it died. The fire scar information on this snag was not usable because the year of death could not be determined.

Lesser Vegetation Characteristics

The species composition and quantitative characteristics of the understory flora in the Porter Lake study area is summarized in Table 6. The forest floor in the large openings consists of a well-developed carpet of shade intolerant lichens, dominated by *Stereocaulon paschale*. Low-to-moderate ericaceous shrubs are found interspersed throughout the lichen covering. Mineral soil and rock account for 4.3% of the ground cover. The forest floor covering within the black spruce clumps consists chiefly of feather mosses such as *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) B.S.G.

Arboreal lichens were fairly abundant on both black spruce and jack pine in the Porter Lake study area. The principal lichen was *Bryoria trichodes* (Michaux), commonly called oldman's beard. Other common arboreal lichens included *Evernia mesomorpha* Nyl., *Hypogymnia physodes* (L.) Nyl., and *Usnea hirta* (L.) Weber *ex* Wigg.

Fuel Properties

The mean forest floor depth in the Porter Lake study area was 3.4 ± 0.9 cm. The corresponding weight and bulk density of the lichen layer, on an inorganic-free oven-dry weight basis (the amount of inorganic matter in the forest floor was ~5%) averaged 1.52 ± 0.32 kg/m^2 and 0.045 g/cm^3, respectively.

Total dead and down woody surface fuel loads were exceedingly low ($\bar{X}$ = 0.38 kg/m^2) in comparison to other coniferous forest types. Most of the material consisted of large diameter (>7.0 cm) roundwood ($\bar{X}$ = 0.30 kg/m^2), a significant proportion of which was in an advanced state of decay (78%). The preburn crown fuel properties for each of the experimental line source fire plots is given in Table 7. Height to live crown base averaged 0.8 m.

Fire Weather Conditions and Fire Danger Indexes

The ice in Porter Lake melted around mid-June. Pertinent meteorological extremes observed at Porter Lake study area weather station for the period June 27 to July 17 are given in Table 8. The 1300 MDT fire weather observations and computer-calculated components of the FWI System (1984 version) are listed in Table 9 for the June 27 to July 26 period of the experimental fires and associated wildfire. Experimental fires were ignited over the eight-day period of June 30 to July 7, which included two drying cycles interrupted by small rains on July 2 and 3; dew formation was, however, observed on the actinograph globe when the charts were changed every morning. The second drying cycle was interrupted by a moderate rainfall July 10, then drying continued until July 19 when heavy rains commenced, resulting in the wildfire associated with the last experimental fire being declared out on July 26.

Fire danger conditions ranged widely over the 11-day period of the study (Table 8). Fire Weather Index values for the days on which fires were attempted ranged from 9 to 37, which covered the low (FWI 0–4), moderate (FWI 5–10), high (FWI 11–18), very high (FWI 19–24), and extreme (FWI 25+) classes of fire danger (Stocks et al. 1989), as used operationally by N.W.T. fire management personnel. Most of the range in fire danger over the study period was attributable to variations in fine fuel moisture and wind speed; heavy fuel moisture

Table 6. Characteristics of the ground vegetation within the openings of the forest canopy at the Porter Lake experimental burning project study area

Species composition: Scientific name	Species composition: Common name	Frequency (%)	Cover (%)	Prominence value (PV)[a]
Betula glandulosa Michx.	Ground or dwarf birch	1.0	0.1	0.1
Cetraria nivalis (L.) Ach.	—[b]	98.5	12.6	125.1
Cladina stellaris (Opiz) Brodo	—	51.0	0.9	6.4
Cladina mitis Hale & W. Culb.	Reindeer lichen	100.0	13.1	131.0
Cladonia spp.	—	80.5	1.1	9.9
Dicranum spp.	—	63.0	2.8	22.2
Empetrum nigrum L. ssp. *hermaphroditicum* (Lange) Böcher	Crowberry	3.5	0.2	0.4
Geocaulon lividum (Richards.) Fern.	Bastard toad-flax	2.0	0.2	0.3
Ledum decumbens (Ait.) Lodd. ex Steud	Northern Labrador tea	5.5	0.8	1.9
Ledum groenlandicum Oeder	Common Labrador tea	8.0	0.5	1.4
Loiseleuria procumbens (L.) Desv.	Azalea	8.5	0.9	2.6
Stereocaulon paschale (L.) Hoffm.	—	100.0	62.1	621.0
Vaccinium uliginosum L.	Bog bilberry	20.0	2.2	9.8
Vaccinium vitis-idaea L. ssp. *minus* (Lodd.) Hult.	Mountain cranberry	86.0	2.0	18.5

[a] See equation [1].

[b] Common name not available.

Table 7. Preburn crown fuel properties for the plots associated with the Porter Lake experimental burning project

Experimental plot no.	Available fuel load[a] (kg/m²)	Vertical depth (m)	Bulk density (kg/m³)	Live crown base height (m)
L1	1.02	3.2	0.32	0.9
L2	0.41	3.5	0.12	0.8
L3	0.96	4.3	0.22	1.0
L4	0.58	3.3	0.18	0.8
L5	0.81	4.7	0.17	1.1
P1	0.74	4.5	0.16	0.7
P2	1.03	3.7	0.27	0.5
P3	0.77	4.0	0.19	0.9

[a] Includes foliage, tree lichen, and dead roundwood which averaged 81.8%, 18.0%, and 0.2%, respectively, of the total available crown fuel weight.

Table 8. Extremes in selected weather elements during the Porter Lake experimental burning project and wildfire CR-6-82 based on hourly observations recorded at the main study area meteorological station

Date (1982)	Air temperature Minimum (°C)	Air temperature Maximum (°C)	Relative humidity Minimum (%)	Relative humidity Maximum (%)	Maximum 10-m open wind (km/h)
June 27	3	19	34	80	13
28	7	23	29	78	12
29	10	24	21	63	14
30	12	27	29	58	21
July 1	8	27	23	82	22
2	12	18	65	100	15
3	11	23	37	100	13
4	7	22	46	89	21
5	5	21	25	76	18
6	2	22	34	80	17
7	6	28	29	81	35
8	12	26	32	78	—[a]
9	11	24	43	90	—
10	—	20	37	—	14
11	10	17	39	63	12
12	8	21	26	74	9
13	10	23	33	68	14
14	11	26	23	68	15
15	6	18	40	73	17
16	4	22	24	93	14
17[b]	10	24	28	66	15

[a] Not recorded.

[b] After July 17 weather observations were recorded once a day only at 1300 MDT; refer to Table 9.

indicators varied over a narrow range, as expressed by the 12-point range in DMC, 74-point range in DC, and 15-point range in BUI. Fine fuel moisture, on the other hand, as indicated by FFMC, covered most of the working range of this scale, from the lower threshold of ignition (FFMC 79–82) to 93. When FFMC values were coupled with a fairly wide range in wind speed, resulting standard daily ISI values ranged from 3 to 16 on burning days.

While the fire danger ratings given in Table 9 were calculated from 1300 MDT observations, more accurate calculations of FFMC and ISI were made for each experimental fire and the initial run of the associated wildfire. For each fire, the previous day's standard FFMC was used as a reference value to calculate the FFMC for the fire using an average of the closest hourly screen temperatures and relative humidities from the FTS station as well as the electric fan psychrometer, the temperature, and relative humidity (RH) readings from the fire site just prior to ignition. The resulting FFMC was combined with the average wind speed during the fire to calculate the ISI value assigned to each experimental fire in further regression analysis. This wind speed was based on the 2 minute average stand wind recorded at 1.4 m during the fire, adjusted to a 10-m open wind speed using the ratio between the 10-m open wind for the nearest 10-min time interval from the FTS station and the corresponding 10-min average stand wind at 1.4 m at the fire site. While individual ratios between wind speeds at 1.4 m in the stand and wind speeds at 10 m in the open were determined for each fire, an average ratio for this fuel type was calculated as 1:2.2 based on 99 paired observations in which the 10-m open winds varied from approximately 2–24 km/h. A standard ratio between wind speed at 1.4 m in the open and at 10 m in the open is given by Turner and Lawson (1978) as 1:1.5, indicating that

Table 9. Daily fire weather observations and fire danger indexes for 1300 MDT at the main study area meteorological station during the Porter Lake experimental burning project and wildfire CR-6-82

Calendar date (1982)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind Direction	10-m open wind Speed (km/h)	24-h rain (mm)	Canadian Forest Fire Weather Index (FWI) System components[a] FFMC	DMC	DC	ISI	BUI	FWI
June 27	17.8	36	NE	10.0	0.0	88	50	182	5	59	15
28	17.7	41	S	0.5	0.0	88	53	188	3	62	11
29	22.2	32	SE	7.1	0.0	90	57	196	6	66	18
30	25.9	36	S	13.0	0.0	91	62	204	9	70	24
July 1	26.3	26	SE	18.1	0.0	93	67	212	16	75	36
2	16.2	74	E	9.1	2.8	63	54	219	0.5	67	2
3	20.1	65	NE	3.2	2.7	60	46	226	0.5	61	1
4	19.0	61	NE	18.9	0.0	77	48	233	2.5	63	8
5	18.9	25	NE	18.2	0.0	89	51	240	9	67	23
6	19.4	42	NE	13.0	0.0	89	54	247	7	70	20
7	27.4	35	NW	18.1	0.0	91	59	256	12	75	30
8	25.1	35	SW	6.0	0.2	91	63	264	7	79	21
9	23.8	52	N	12.2	0.0	90	65	272	8	82	24
10	19.5	43	E	11.8	3.8	73	50	272	1.0	68	4
11	15.8	46	NE	6.4	0.0	82	52	279	2.0	71	8
12	18.7	37	SW	4.6	0.0	87	55	286	3	74	12
13	20.1	51	SW	12.3	0.0	87	57	293	5	77	17
14	23.2	33	N	12.3	0.0	90	61	301	8	81	24
15	14.7	46	NE	15.3	0.0	89	63	307	8	83	25
16	18.8	33	SW	4.0	0.0	90	66	314	5	87	18
17	22.7	39	SW	10.8	0.0	90	70	322	7	90	24
18	17.7	65	SW	17.4	0.0	88	71	329	8	92	25
19	10.1	79	NW	4.7	21.0	37	31	268	0	48	0
20	9.7	81	NW	8.0	12.0	34	14	241	0	25	0
21	10.1	79	NW	14.7	0.5	53	15	247	0.5	26	1
22	24.9	36	SW	11.8	0.0	83	19	255	3	32	7
23	19.5	60	NE	13.0	0.0	84	21	262	4	35	9
24	22.6	46	E	11.3	0.0	87	24	270	5	39	12
25	21.7	59	W	11.7	0.0	87	26	278	5	42	13
26	22.6	48	NW	9.4	0.0	88	29	286	5	46	13

[a] The three fuel moisture codes and three fire behavior indexes comprising the FWI System are defined below (from Canadian Forestry Service 1984):

Fine Fuel Moisture Code (FFMC) - A numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel.
Duff Moisture Code (DMC) - A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-sized woody material.
Drought Code (DC) - A numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and amount of smouldering in deep duff layers and large logs.
Initial Spread Index (ISI) - A numerical rating of the expected rate of fire spread. It combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel.
Buildup Index (BUI) - A numerical rating of the total amount of fuel available for combustion that combines DMC and DC.
Fire Weather Index (FWI) - A numerical rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested area of Canada.

Calculation of the six standard components of the FWI System is based on the FORTRAN program for the 1984 version of the system (Van Wagner and Pickett 1985). The fuel moisture code startings were: FFMC = 85, DMC = 47, and DC = 175. Refer to the text for further details regarding derivation.

the open black spruce stands do not greatly constrain wind speed within the flame zone.

On a synoptic scale, the weather patterns affecting the Porter Lake study have been described by Flannigan and Harrington (1987). Briefly, a surface ridge over the Porter Lake area moved slowly eastward between June 27 and July 1, resulting in a moderate southerly flow of warm dry air during the first half of the study period. The situation changed as a small low pressure system over northern Alberta spread cloud and rain over Porter Lake on July 2, before moving slowly northeastward on July 3. This was replaced by a second warming and drying trend associated with a high pressure system moving down from the north on July 5 and 6. By July 7, a weak ridge extended from southern Alberta and Saskatchewan north to Great Slave Lake, resulting in a weak surface pressure gradient over Porter Lake and light northerly winds prevailed, although locally, gusty surface winds up to 35 km/h were observed at the study site. These winds were the result of hot dry unstable air over the Porter Lake area forming a strong temperature gradient, both at the surface and aloft, between the high pressure area and the cold surface low over Churchill, Manitoba on Hudson Bay. The atmosphere was potentially unstable to 3 km MSL and exhibited a superadiabatic lapse rate to 1.7 km MSL, based on Fort Smith and The Pas upper air soundings on the afternoon of July 7. Flannigan and Harrington (1987), using available satellite imagery, upper air charts and tephigrams, reconstructed the vertical wind profile for July 7 as being dominated by a low level jet (i.e., wind speed maximum near the earth's surface), blowing from the north and with its core located only about 8 km east of Porter Lake. The combination of strong thermal instability and the strong vertical wind shear in the lower atmosphere provided the vertical mixing necessary to bring strong upper winds to the ground on the afternoon of July 7, which contributed to the loss of control of the final experimental fire.

Fuel Moisture Contents

The mid-afternoon moisture contents (MC) determined for selected fine fuels during the course of the Porter Lake project are summarized in Table 10. The top of the surface lichen layer MCs varied from 9 to 243%. The tree lichen MCs in turn ranged from 9 to 25%. On fair days, tree lichen MC was close to that of the sun-exposed ground lichens, but it absorbed much less moisture during the rainy weather that occurred on July 2 and 3. During match ignition tests (Russell and Pech 1968) on July 4, it became readily apparent that *Cladina stellaris* (Opiz) Brodo, *Cetraria nivalis* (L.) Ach. and *Cladina mitis* dried out much more rapidly after rain than *Stereocaulon paschale*.

Moisture content of the tree foliage varied little, averaging about 79% for black spruce and 86% for jack pine. It is not clear just where the sample period (i.e., June 30–July 7) fits into the whole seasonal cycle of foliar moisture content in this region compared to other sections of the boreal forest (Chrosciewicz 1986b). In any case, these values are certainly low enough to readily permit crowning on days when surface fire intensity was favorable.

The BCFS fuel moisture sticks only varied from about 6 to 10% on burning days. The diurnal changes in stick MC during the duration of the project are very evident in Figure 7.

Following the escape of the last experimental fire on July 7, 12 samples of the forest floor layer (to a depth of about 6.5 cm) from within several black spruce clumps were taken. The resultant MCs averaged 51% (range: 32–75%).

Fuel Moisture Analyses

The purpose of the fuel moisture sampling undertaken in conjunction with the experimental burning phase of the Porter Lake project was to explore possible links between current fuel MC and past and present weather for specific fuels in the study area[7]. The fuel component of main interest was the surface lichen layer, which averaged 2.2 kg/m^2 as exposed in trays 1–4. Tray 5 was intended to represent the top half of the layer and actually averaged 57% of the whole layer during the two parts of its run. Figure 7 shows the whole moisture content trends for only the full-layer tray contents over the period of hourly measurement (with a few observations missing). The MC trend of the BCFS fuel moisture sticks is also shown.

[7] Van Wagner, C.E. 1983. Analysis of fuel moisture data and development of fuel moisture codes as practiced in the Canadian Forest Fire Danger Rating System. Environ. Can., Can. For. Serv., Petawawa Natl. For. Instit., Chalk River, Ontario. Unpublished Report.

Table 10. Daily mid-afternoon moisture contents (% oven-dry weight basis) for selected fuels during the Porter Lake experimental burning project

Date (1982)	Sun-exposed ground lichens[a]		Crown fuels[b]			BCFS fuel moisture sticks[c]	
			Needle foliage		Arboreal		
	1500 MDT	1600 MDT	Black spruce	Jack pine	lichens	1500 MDT	1600 MDT
June 30	9.1	9.1	91.4	75.2	10.8	6.1	6.0
July 1	8.7	9.2	108.3	84.8	9.0	5.9	5.9
July 2	242.8	188.0	92.0	91.4	24.9	15.6	14.8
July 3	158.2	148.5	78.6	88.2	15.2	12.3	11.7
July 4	65.1	46.9	77.0	84.7	14.8	10.2	9.9
July 5[d]	21.8	9.4	80.8	83.3	11.4	8.1	7.9
July 6	10.3	11.1	75.3	85.7	14.2	7.7	7.7
July 7[e]	12.9	9.2	78.2	84.9	10.7	7.1	6.7

[a] Mean of two destructive samples taken of the top 1–2 cm of the lichen layer.

[b] Mean of three destructive samples taken daily at 1400 MDT. The black spruce foliage samples on June 30 and July 1 included all of last year's twig. Only needles were taken on July 2–7 (i.e., a composite of all ages except for the current year's flush); jack pine foliage was treated in the same manner for the period June 30 to July 7.

[c] Mean of four individual stick measurements.

[d] The 1400 MDT ground lichen and BCFS fuel moisture stick values were 19.7% and 8.5%, respectively.

[e] The 1700 MDT ground lichen and BCFS fuel moisture stick values were 8.5% and 6.7%, respectively.

Based on the hourly weather readings, a few runs of the hourly version of the FFMC (Van Wagner 1977a) were carried out using the current (January, 1987) Program F-33 of the Petawawa National Forestry Institute[8]. This program allows operational choice of a Drying Rate Factor (DRF) and a Rain Factor (RF). A special version in which DRF was left at 0.0579 (the standard FFMC value), but RF was increased from the standard 42.5 to 200 is shown in Figure 7. In addition, the equations for equilibrium moisture content (EMC) were replaced with the following:

[8] $E_d = 0.070H^{1.45}$

[9] $E_w = 0.065H^{1.43}$

where H = relative humidity (%), E_d = EMC for drying, and E_w = EMC for wetting.

These equations allow a greater amplitude for variation between night and day than the standard equations. This special version of the hourly FFMC is also shown in Figure 7. Several points are apparent:

(1) The lichen absorbs far more moisture from rain and dries somewhat faster (judging by the slope of the MC trend) than the BCFS fuel moisture sticks.

(2) The lichen layer also absorbs rain much more readily than is reflected in the standard FFMC.

(3) The whole lichen layer appears to dry a little more slowly than is reflected in the standard FFMC. The half-layer, represented by tray 5 (not shown) dried somewhat faster than the standard FFMC.

(4) In terms of equivalent layer weight, the lichen is much faster drying than the standard FFMC fuel of 0.25 kg/m^2.

The hourly FFMC could, on the basis of this test, be used to represent reasonably well the lichen

[8] Enquiries concerning availability of the FORTRAN program should be directed to Forestry Canada, Petawawa National Forestry Institute, P.O. Box 2000, Chalk River, Ontario K0J 1J0.

layer at Porter Lake. One eight-day run with a single substantial rain is, however, too small a sample for a conclusive proposal.

The trend of MC from the hourly destructive samples of the lichen layer lay several points below the tray trend for the first two days; after that the two trends followed each other closely.

The forest floor tray moisture contents are not presented in their entirety. Instead, some analysis was carried out both on rain effect and on drying rate in comparison with the Duff Moisture Code (DMC). These results are shown in Table 11. The DMC rain effect portrayed the single rain event reasonably well. Log drying rates were calculated by plotting the 1600 MDT tray MCs on semi-logarithmic paper (first subtracting 12% for EMC) for the five days following the rain. These curves were all reasonably straight, and their slopes constitute a measure of drying rate. Even though the trays were shaded, these values were several times higher than the standard DMC rates (after normalizing for dry weight as shown in Table 11), indicating faster drying rates for the forest floor layer at Porter Lake. Two apparent reasons for much faster daily duff drying rates in the lichen–woodland forest are as follows:

(1) In the summer at high latitudes, good drying conditions prevail around the clock by comparison with the latitudes in which the DMC mainly applies.

(2) The open nature of the forest at Porter Lake allows the ground surface to warm in the sun; the resulting warmed air would flow freely into the shaded duff areas under the trees. By contrast, air near the ground in a closed forest may well be cooler and damper than at the standard weather station exposure.

Fire Behavior Characteristics

Fire behavior characteristics were monitored and documented on a total of 11 fires during the Porter Lake study. These included three point-ignition fires, seven line-ignition fires, and one wildfire, which resulted from the escape of the final experimental line-ignition fire. The fire weather observations and fire danger indexes associated with each fire are listed in Table 12.

Point-ignition Experimental Fires

Circumstances permitted simultaneous point- and line-ignition fires to be conducted on two

Table 11. Analysis of forest floor tray moisture results for rain effect and drying rate, day-to-day at 1600 MDT during the Porter Lake experimental burning project in 1982

Item	Tray			Mean
	No. 6	No. 7	No. 8	
Type of material	Black spruce feather mosses	Black spruce forest floor	Jack pine forest floor	—[a]
Dry weight (kg/m^2)	3.15	4.87	5.32	4.44
MC before rain, July 1	30	41	22	31
MC after 5.5 mm rain, July 3				
Actual	120	54	95	90
Predicted by DMC	75	85	70	77
Log drying rate, July 3–7				
Actual	0.245	0.211	0.163	—
Actual adjusted[b]	0.154	0.206	0.173	0.178
Predicted by DMC				
- at 1200 MDT	—	—	—	0.0253
- at 1600 MDT	—	—	—	0.0351

[a] Not applicable.

[b] Normalized as for 5 kg/m^2, which is the standard Duff Moisture Code (DMC) fuel load (Van Wagner 1987a).

Table 12. Fire weather observations and fire danger indexes associated with the various fires documented during the Porter Lake experimental burning project

Experimental fire no.	Time of burning: Date (1982)	(Hour MDT) Start	(Hour MDT) End	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind: Direction	Speed (km/h)	Days since rain[a]	Global solar radiation (W/m^2)	Sky[b]	Canadian Forest Fire Weather Index (FWI) System components[c]: FFMC	DMC	DC	ISI	BUI	FWI
						Point-ignition fires										
P1	June 30	1545	1601	26.5	30	SW	18.0	8	517	clear	92.1	62	204	14.3	71	34
P2	July 1	1531	1545	24.5	25	S-SW	21.0	9	293	p.c.[b]	92.8	66	212	18.3	74	41
P3	July 5	1530	1558	21.0	30	NE	15.0	2	628	clear	89.2	52	241	8.2	67	22
						Line-ignition fires										
L1	June 30	1540	1554	26.5	30	SW	20.4	8	517	clear	92.1	62	204	16.1	71	37
L2	July 1	1529	1537	24.5	25	S	24.0	9	293	p.c.	92.8	66	212	21.3	74	45
T1	July 4	1540	1612	20.5	50	NE	18.8	1	628	clear	82.0	49	233	3.7	64	12
T2[d]	July 4	1912	1925	21.0	48	E	17.0	1	175	p.c.	82.4	49	233	3.7	64	12
L3	July 5	1403	1428	20.0	28	NE	17.0	2	719	clear	89.4	51	240	9.3	67	24
L4	July 6	1519	1542	21.5	36	N	14.5	3	635	clear	90.1	55	247	9.1	71	25
L5	July 7	1517	1524	27.5	31	NW	28.0	4	544	p.c.	92.0	59	256	23.5	75	48
L5A	July 7	1524	1531	27.5	31	NW	34.6	4	565	p.c.	92.0	59	256	32.9	75	59
						Wildfire										
CR-6	July 7	1531	1735	27.0	32	NW-N	26.0	4	544	p.c.	92.0	59	256	20.4	75	44

[a] Greater than 0.6 mm.

[b] Cloudiness estimated as average conditions of sky during the afternoon; p.c. = partly cloudy.

[c] FFMC = Fine Fuel Moisture Code; DMC = Duff Moisture Code; DC = Drought Code; ISI = Initial Spread Index; BUI = Buildup Index; and FWI = Fire Weather Index. Refer to Table 8 for definitions of the six standard components of the FWI System.

[d] The fire front failed to spread from the line of ignition. Two attempts were made. The latest of the day (i.e., increasing length of shadows and rising relative humidity) and greater stand density than plot T1 hindered fire spread.

separate occasions. Thus, while the weather conditions were identical, the fuel distribution obviously could not be duplicated due to the small-scale heterogeneous nature of the fuel complex. Experimental fires L1/P1 and L2/P2 were carried out under fairly extreme burning conditions. As it turned out, the point-ignition plots for the first two fires were not large enough to allow for either fire to reach a spread rate comparable to the adjacent line source fire (i.e., the fire front reached the prepared fireguard before it had attained an equilibrium or steady-state condition). A significant amount of torching was achieved, however, within 10–15 min after ignition due to favorable fuel arrangement and changes in wind direction, which increased the width of the head fire and thus the radiant heat transfer. The third point-ignition fire (P3) was conducted under moderate burning conditions about an hour after the line-ignition fire was completed. Experimental fire P3 appeared to have reached an equilibrium or steady-state condition after about 20 min.

Fire behavior characteristics monitored on the three point-ignition fires are summarized in Table 13, with respect to wind speed, forward rate of spread, fire area and perimeter growth for each mapping interval and for each fire as a whole. The wind speeds listed in Table 13 are for the anemometer location and not necessarily exactly applicable to the plot area. As illustrated by experimental fire P2 in Figures 8 and 9, the point-ignition fires tended to spread slowly through the surface lichen layer from the point of ignition, accelerating in forward spread rate as individual trees or clumps of trees were encountered, resulting in torching and short-range spotting ahead within the plot. Spread rates and spread directions were very sensitive to small changes in wind speed and direction as well. Ignition of experimental fire P2 took place in open lichen at 1531 MDT. For the first eight minutes following ignition, the initiating fire exhibited weak spread with low vigor flames (~10 cm) leaning into the center; the compact lichen layer obviously hampered fire behavior during the early stages. The first black spruce clump torched at 8 min elapsed time since ignition and the fire immediately accelerated. By the 9-min interval, the fire had spotted ahead to the next clump; flame lengths in the open lichen were ~15–20 cm. The fire reached

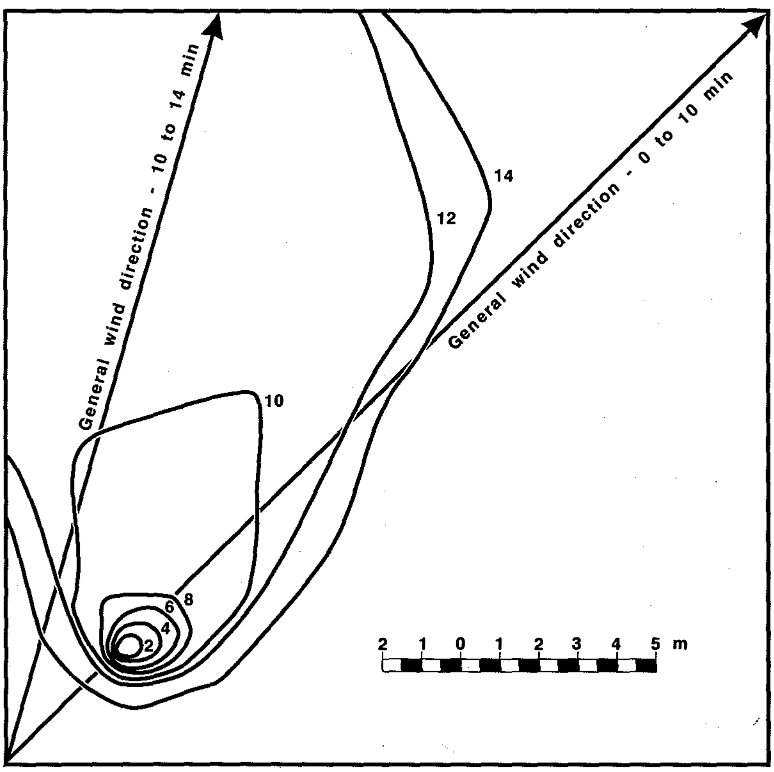

Figure 8. The documented perimeter at selected time intervals following ignition of experimental fire P2 conducted at Porter Lake on July 1, 1982.

Table 13. Fire growth characteristics and prevailing wind associated with the point-ignition (P) fires documented during the Porter Lake experimental burning project

Time interval (min)	10-m open wind speed (km/h)						Forward rate of fire spread[a] (m/min)						Backfire rate of spread[a] (m/min)					
	P1		P2		P3		P1		P2		P3		P1		P2		P3	
	Avg[b]	Inc.[c]	Avg	Inc.	Avg	Inc.	Avg	Inc.	Avg	Inc.	Avg	Inc.	Avg	Inc.	Avg	Inc.	Avg	Inc.
0–2	14.2	14.2	17.2	17.2	11.4	11.4	0.39	0.39	0.30	0.30	0.25[d]	0.25[d]	0.05	0.05	0.13	0.13	0.19[d]	0.19[d]
0–4	13.8	13.3	16.7	16.1	10.6	9.7	0.25	0.13	0.25	0.20	0.25	0.25	0.08	0.10	0.08	0.03	0.19	0.19
0–6	13.6	13.3	16.6	16.5	11.1	12.2	0.60	1.25	0.23	0.20	0.29[d]	0.38[d]	0.08	0.10	0.07	0.05	0.20[d]	0.21[d]
0–8	14.3	16.2	16.6	16.4	10.8	9.7	0.57	0.47	0.25	0.30	0.31	0.38	0.12	0.23	0.06	0.05	0.20	0.21
0–10	15.3	19.7	17.8	22.8	10.1	7.5	0.95	2.50	0.78	2.90	0.31[d]	0.28[d]	0.14	0.22	0.06	0.07	0.24[d]	0.39[d]
0–12	15.1	13.6	—[e]	—	9.7	7.8	1.34[f]	3.29[f]	1.45[f]	4.78[f]	0.31	0.33	0.13	0.06	0.07	0.10	0.26	0.39
0–14	14.5	11.0	—	—	10.2	13.2	1.33[f]	1.22[f]	—	—	0.34[d]	0.47[d]	0.12	0.07	0.10	0.30	0.28[d]	0.37[d]
0–16	14.3	12.6	—	—	10.3	11.1	1.30[f]	1.13[f]	—	—	0.36	0.47	0.11	0.06	—	—	0.28	0.35
0–20	—	—	—	—	10.2	9.6	—	—	—	—	0.62	1.78	—	—	—	—	—	—
0–24	—	—	—	—	10.0	8.0	—	—	—	—	0.71	1.08	—	—	—	—	—	—
0–28	—	—	—	—	10.1	10.6	—	—	—	—	0.79	1.27	—	—	—	—	—	—

[a] To calculate the cumulative forward or backfire spread distance at the end of any given time interval, multiply the average rate of spread value by the elapsed time since ignition. To determine the maximum forward or backfire spread distance for any given fire, multiply the highest incremental rate of spread value by 2.0 or 4.0 minutes as appropriate.

[b] Avg = Average value.

[c] Inc. = Incremental value (this refers to the value that occurred during the last two or four minutes of each time interval).

[d] Interpolated value.

[e] Not applicable.

[f] Estimated value.

Table 13 continued.

Time interval (min)	Cumulative area burned (m^2)			Cumulative perimeter length			Length-to-breadth ratio			Head/backfire spread ratio		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
0–2	0.48	0.29	1.01[d]	2.8	2.5	2.5[d]	1.20	1.50	—[e]	7.8	2.4	1.32[d]
0–4	1.26	0.97	2.03	4.1	3.8	5.0	1.06	1.76	1.06	3.3	3.3	1.33
0–6	7.36	1.94	5.23[d]	10.9	5.6	7.8[d]	1.89	1.41	—	7.2	3.5	1.45[d]
0–8	16.0	3.68	8.43	15.0	7.5	10.6	1.36	1.14	1.45	4.8	4.0	1.57
0–10	40.6	28.8	18.4	26.2	21.5	15.0[d]	1.94	1.42	—	6.9	12	1.31[d]
0–12	119[f]	203[f]	28.3	43.4[f]	56.2[f]	19.4	1.83[f]	1.67[f]	1.27	11[f]	21[f]	1.19
0–14	181[f]	259[f]	39.9	52.8[f]	63.8[f]	23.4[d]	1.65[f]	—	—	11[f]	—	1.23[d]
0–16	237[f]	—	51.5	59.4[f]	—	27.5	1.58[f]	—	1.52	12[f]	—	1.27
0–20	—	—	—	—	—	—	—	—	—	—	—	—
0–24	—	—	—	—	—	—	—	—	—	—	—	—
0–28	—	—	—	—	—	—	—	—	—	—	—	—

[d] Interpolated value.

[e] Not applicable.

[f] Estimated value.

Figure 9. Photographic record of experimental fire P2 conducted at Porter Lake on July 1, 1982 (photos B.D. Lawson).

another larger clump by the 10-min interval; flame lengths at the base of the clump and in the open lichen were ~1 m and ~20–25 cm, respectively. At the 12 min interval, torching was experienced in the larger clump and as a result the fire reached the prepared guard on the west side and northwest corner of the plot. A single spot fire was later documented as having occurred 70 m downwind of the plot.

Line-ignition Experimental Fires

The behavioral characteristics and associated impacts for the experimental line-ignition fires conducted during the Porter Lake project such as fuel consumption, rate of spread, frontal fire intensity, and depth of burn are summarized in Tables 14 and 15. The frontal fire intensities (I), in kilowatts per meter (kW/m), were calculated by Byram's (1959) formula (see also Alexander 1982):

[10] $I = Hwr$

where H is the fuel low heat of combustion, in kilojoules per kilogram (kJ/kg), w is the weight of fuel consumed (in the active flaming zone) in kilograms per square meter (kg/m^2), and r is the rate of spread in meters per second (m/s).

The experimental line-ignition fires at Porter Lake, after an initial establishment period following ignition, exhibited typically wind-driven fire behavior, accelerating quickly through the plot and moving most quickly through areas in each plot where black spruce stems or clumps were clustered closely together. This pattern is illustrated in Figure 10 using both ground-based and aerial photographs of experimental fire L5. Figure 11 shows the spread pattern of experimental fire L5 superimposed on a stem map of the plot, and illustrates a typically wedge-shaped fire perimeter which accelerated through the central portion of the burning plot.

Although the size of the experimental burning plots established for the line-ignition fires at Porter Lake were relatively small, the range of line fire behavior exhibited was quite significant—from creeping surface fires spreading at less than 1 m/min to full-scale crown fires with spread rates in excess of 50 m/min (Fig. 12). The objective of burning under a wide range of weather conditions necessary to attain vastly different fire behavior obviously was achieved at Porter Lake. A very strong correlation between ROS and the ISI calculated on-site was obtained over an ISI range of 3.7–32.9 measured during the Porter Lake line fires, as illustrated in Figure 12. Head fire ROS was correlated at the 1% level with ISI (the simple linear correlation coefficient (r) = 0.95). The relationship between rate of fire spread and the ISI can be expressed by the following power curve equation:

[11] $R = 0.032254(ISI)^{2.1416}$ where $ISI \leq 33$

where R = head fire rate of spread on level to gently undulating ground (m/min).

The coefficient of determination (r^2) between the actual versus calculated ROS values by Equation [11] for the line sources fires is 0.91.

The ISI/ROS relationship given above is based on a limited number of fires. Obviously it would be very desirable to gather additional wildfire spread data (e.g., Hirsch 1989a, 1989b) to verify the experimental relation and/or extend it above the existing ISI and ROS range (Rothermel and Rinehart 1983). It is, however, expected that the ROS would begin to gradually level off at very high ISI values (Lawson et al. 1985). The fire behavior data collected during the Porter Lake project was the sole basis for the Spruce–Lichen Woodland fuel type (C-1) in the 1984 interim edition of the FBP System (Lawson et al. 1985) and all the related products

Table 14. Percent reduction in preburn fuel loads associated with the line-ignition fires documented during the Porter Lake experimental burning project

Fuel component	Mean	S.D.[a]	Range
Forest floor	68	7	59–74
Roundwood surface fuels			
<7.0 cm[b]	73	33	33–100
≥7.0 cm[b]	78	26	49–100
total	81	26	45–100
Tree crowns	64	11	50–76

[a] Standard deviation.

[b] Diameter size class(es).

Table 15. Fire behavior characteristics and fire impact on forest fuels associated with the line-ignition fires and wildfire documented during the Porter Lake experimental burning project

Experimental fire no.	Depth of burn (cm)	Live crown consumed[a] (%)	Fuel consumption: Ground[b] (kg/m^2)	Surface[c] (kg/m^2)	Crown[d] (kg/m^2)	Total (kg/m^2)	Energy per unit area[e] (kJ/m^2)	Head fire rate of spread (m/min)	Frontal fire intensity (kW/m)	Type of fire
L1	2.0 + 0.9 (41)[f]	63	0.89	0.23	0.62	1.74	31 164	6.1	3 168	Intermittent crown[g]
L2	2.5 + 0.7 (52)	83	1.12	0.30	0.31	1.73	30 867	26.3	13 530	Crown
T1	0.5[h]	—[i]	0.23	0.05[h]	—[i]	0.23	4 747	0.6	47	Surface
L3	2.4 + 1.0 (39)	53	1.07	0.48	0.48	2.03	36 195	3.5	2 111	Intermittent crown
L4	2.1 + 1.1 (49)	58	0.94	0.24	0.35	1.53	27 320	3.7	1 685	Intermittent crown
L5	2.5 + 0.9 (94)	72	1.12	0.09	0.60	1.81	32 030	33.3	17 777	Crown
L5A	—[j]	100[h]	1.12[h]	0.27[h]	0.76[h]	2.15[h]	38 367	51.4	32 367	Crown
CR-6	—	85[h]	—	—	—	2.04[h]	36 361	31.9	19 332	Crown

[a] Synonymous with crown fraction burned (Van Wagner 1989; Forestry Canada 1991).

[b] Consists of the ground lichen layer.

[c] Consists of downed–dead roundwood material.

[d] Consists of coniferous needle foliage, dead branchwood, and arboreal lichens.

[e] Numerically equal to the product of the low heat of combustion, reduced for fuel moisture content (24 kJ/kg per moisture content percentage point as per Alexander 1982) and fuel consumed (Van Wagner 1978); computed for individual fuel components and then summed. The following low heat of combustion values were used: ground lichens—17 765 kJ/kg (Rowe et al. 1975; Miller 1976); woody fuels 18 700 kJ/kg (Alexander 1982); black spruce needles—19 890 kJ/kg (Hough 1969; Chrosciewicz 1986a); jack pine needles—20 385 kJ/kg (Hough 1969; Chrosciewicz 1986a); and arboreal lichens—15 715 kJ/kg (Parker 1975).

[f] Mean, standard deviation, and sample size.

[g] See Merrill and Alexander (1987).

[h] Estimate.

[i] A small amount (<10%) of crown fuel was consumed near the ground surface of a few isolated trees but was considered inconsequential on a per unit area basis.

[j] Not recorded.

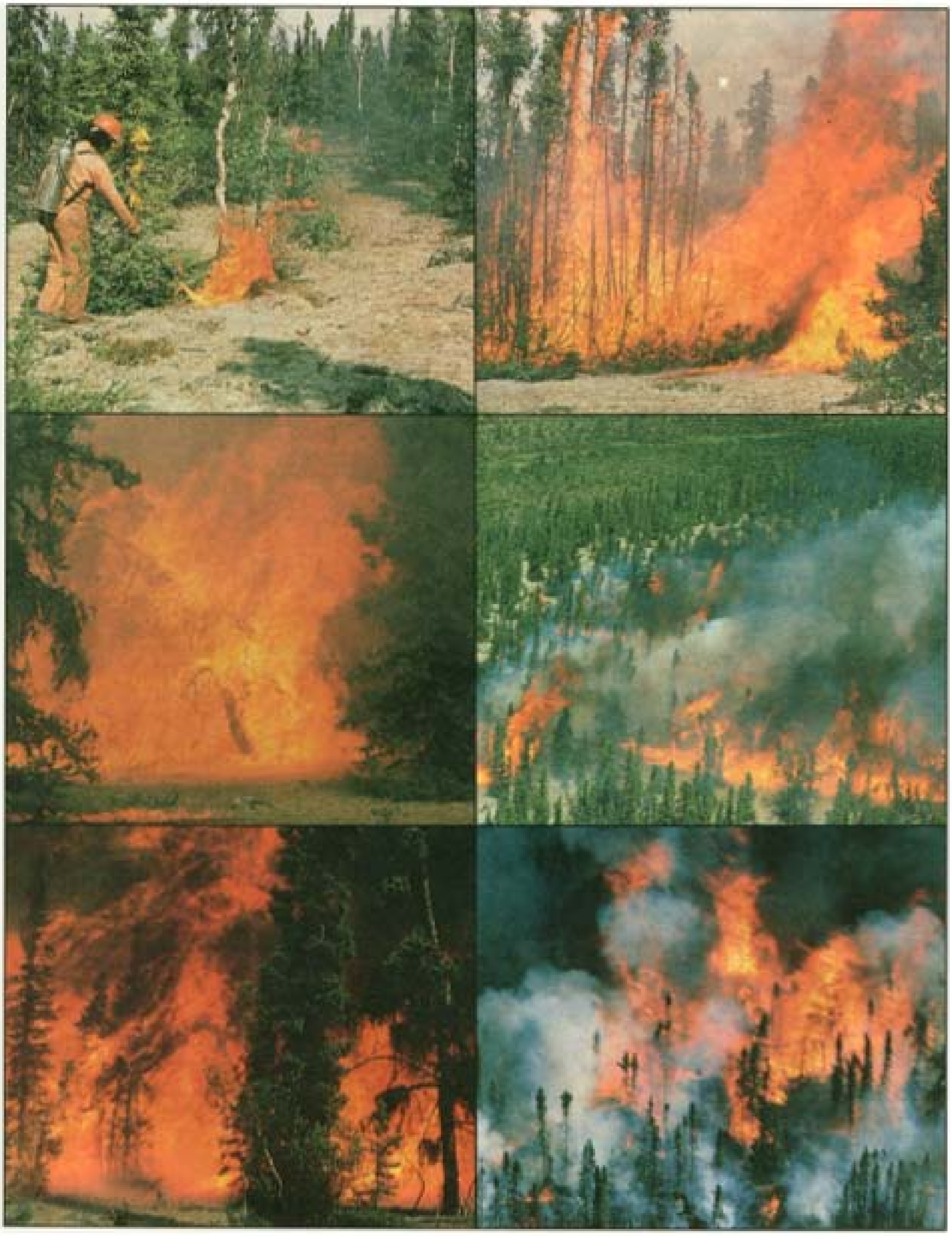

Figure 10. **Photographic record of experimental fire L5 conducted at Porter Lake on July 7, 1982 (photos B.D. Lawson and C.P. Delisle).**

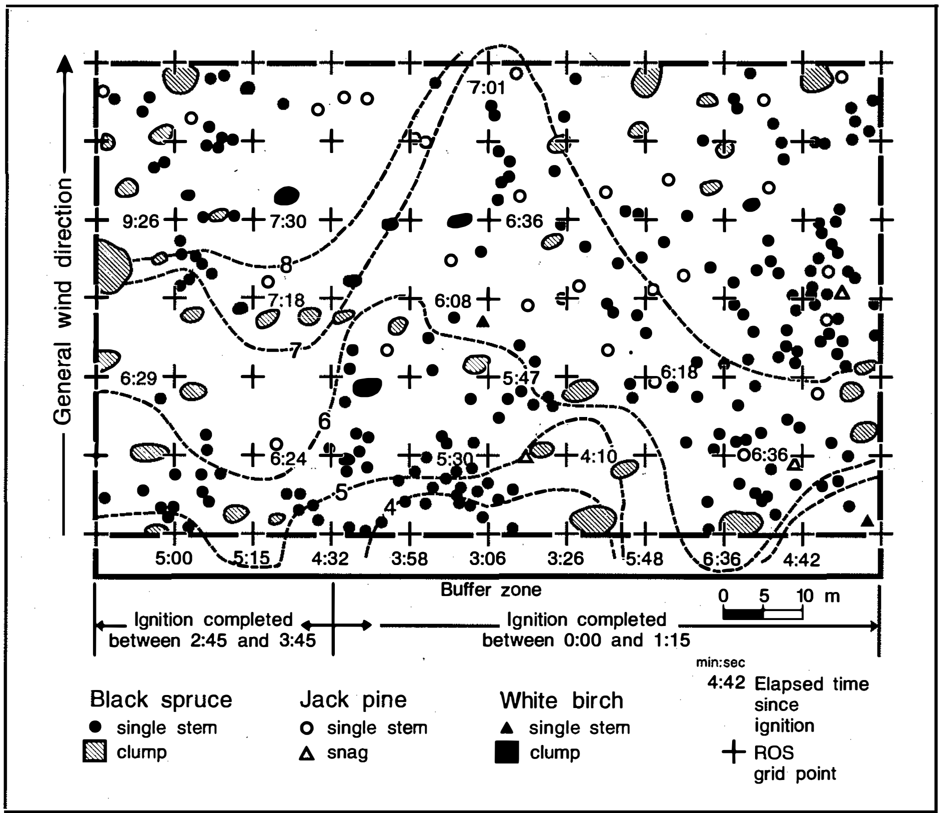

Figure 11. Composite overstory stem plot map and documented rate of spread (ROS) observations for experimental fire L5 conducted at Porter Lake on July 7, 1982.

ensuing from the user guide[9] (e.g., McAlpine 1986, 1987; Feunekes and Methven 1988)[10]. The equation used for predicting head fire ROS in fuel type C-1 from the interim edition of the FBP System was originally derived from computer calculated values of the ISI based on the equations in Van Wagner and Pickett (1975) rather than the 1984 edition of the FWI System (Van Wagner and Pickett 1985; Van Wagner 1987a). Although the differences are slight, there are differences none the less. An equation which forces the ROS to gradually level off at very high ISI values was also formulated. The results of the Porter Lake project remain the sole basis for fuel type C-1 in the first complete edition of the FBP System (Forestry Canada 1991).

Depth of burn, and resultant consumption of the lichen layer, is quite consistent between the eight formally documented line-ignition fires. Surface fuel consumption levels are also relatively consistent and would appear to be more dependent on preburn loads than on fuel moisture conditions. Crown fuel consumption appears to depend primarily on spread rate and the degree of crowning. The overall impression is that total fuel consumption is relatively consistent on fires in this fuel type—the general lack of surface fuel and the shallow forest floor result in very little change in fuel consumption with increasing dryness as reflected in the fuel moisture codes of the FWI System. Changes in frontal fire intensity are therefore most significantly related to changes in forward rate of spread, as influenced by wind velocity and the moisture content of fine fuels.

The type of fire thresholds could be set by informal experience on the basis of the observational evidence presented by the fires themselves. For example, crowning was fully developed on fires L2 and L5 when the ISI values were 21.3 and 23.5, respectively, and discontinuous torching of black spruce clumps occurred on fire L1 when the ISI was 16.1. With this in mind, the threshold condition for full-fledged crown fire development would probably occur at an ISI level of about 18, which, according to Equation [11], corresponds to a

[9] 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].

[10] Alexander, M.E.; McAlpine, R.S. 1987. Canadian Forest Fire Behavior Prediction (FBP) System field reference. Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Study NOR-5-05 File Rep. 17.

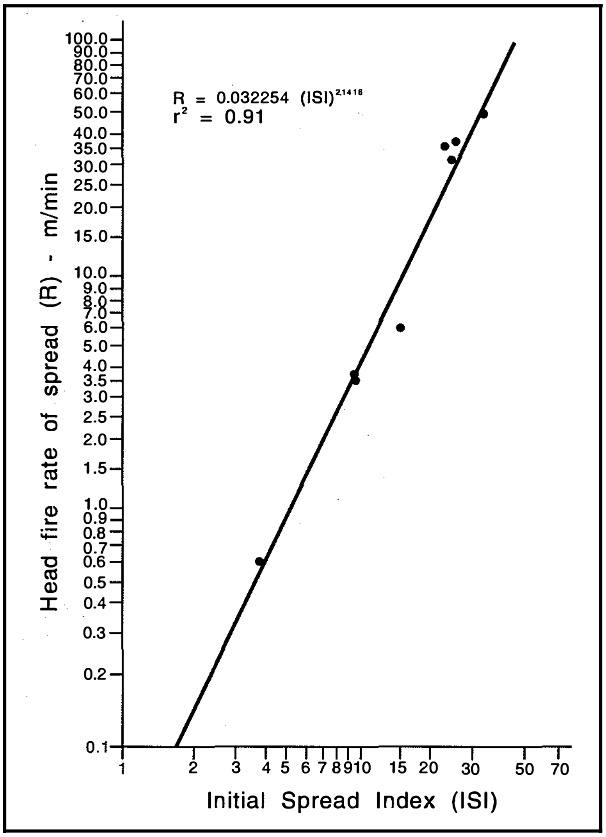

Figure 12. Line-ignition fires documented during the Porter Lake experimental burning project plotted as head fire rate of spread versus Initial Spread Index.

head fire ROS of 16 m/min. In actual fact, the threshold ISI value no doubt varies according to stand densities. The concept of an active crown fire (Van Wagner 1977b) in this particular type of conifer forest is somewhat inappropriate because of the open nature of the fuel complex and the fact that the crowns extend to the ground (i.e., a distinct crown fuel layer separated vertically from the surface fuels does not exist in the black spruce–lichen woodland). The crown bulk density for the Porter Lake study area is on the whole comparable to that of moderately well-stocked forest stands. The problem is that the present crown fire theory (Van Wagner 1977b) does not accommodate a situation in which the available crown fuel is concentrated in separate clumps, even though the average bulk density of the crown layer is similar. It is of interest to note, however, that theoretically the critical minimum spread rate for active crowning (Van Wagner 1977b) is 15 m/min based on an average of crown bulk density of 0.20 kg/m^3 for the Porter Lake study area as a whole (Alexander 1988).

It was pointed out earlier that in the black spruce–lichen woodland fuel type, most of the variation in frontal fire intensity can be attributed to the fire spread rate rather than the amount of fuel consumed. For very general operational planning purposes, frontal fire intensities could be computed by Equation [10] using the following assumed low heat of combustion (H) values, fuel consumption figures (w), and moisture content (MC):

The heat contents would be reduced for fuel moisture content (24 kJ/kg per moisture content percentage point) according to the typical values given above. The quantity of crown fuels consumed can be determined by the following semi-empirical equation:

Fuel component	H (kJ/kg)	w (kg/m^2)	MC (%)
Ground	17 765	1.03	10
Surface	17 700	0.27	10
Crown	19 890	0–0.76	80

[12a] $CFC = -0.48364 + 0.069091(ISI)$ where $7 < ISI < 18$

[12b] $CFC = 0.76$ where $ISI \geq 18$

where CFC = crown fuel consumption (kg/m^2).

This relation is similar in form to that of Stocks (1987b, 1989) and allows for the gradual increase in crown fuel consumption as the ISI rises from the surface fire-intermittent crown fire threshold (i.e., CFC = 0.0 kg/m^2 at ISI 7) to full crown fuel involvement (i.e., CFC = 0.76 kg/m^2 at ISI 18). The spread rate (r) in Equation [10] would of course be determined from the ISI using Equation [11].

The fire behavior characteristics chart or nomogram (Rothermel and Anderson 1966; Andrews and Rothermel 1982; Burrows 1984; Alexander and De Groot 1988) is a useful way of interpreting the behavior of free-burning forest fires having different spread rates and varying degrees of fuel consumption but similar frontal fire intensities (Fig. 13). The five levels of frontal fire intensity were delineated on the basis of distinctive differences in fire suppression effectiveness from the standpoint of fire behavior, determined, in part, from an extensive review of the literature (e.g., Byram 1959; Andrews and Rothermel 1982; Stechishen et al. 1982; Burrows 1984; Loane and Gould 1986; Alexander and De Groot 1988).

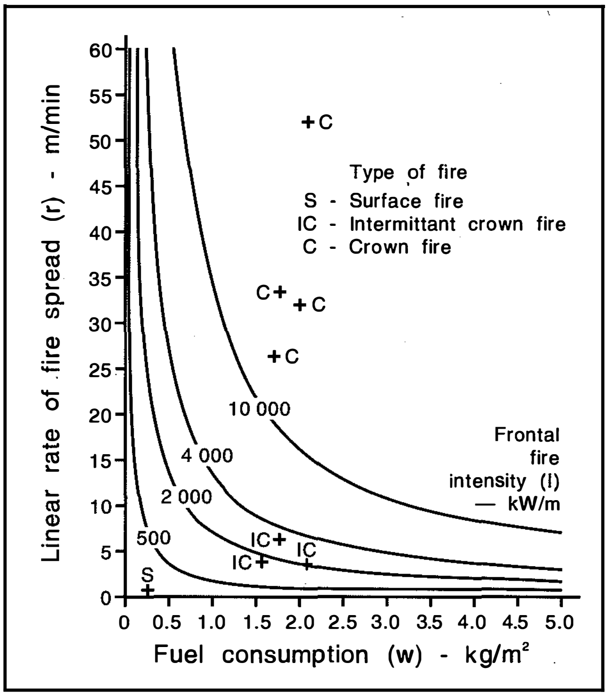

Figure 13. Porter Lake experimental line-ignition fires plotted as a function of head fire spread rate and fuel consumed in relation to frontal fire intensity levels.

Caribou Range-06-1982 Wildfire

The final experimental fire (L5) of the project was ignited at 1517 MDT on July 7 and accelerated very rapidly following completion of the sequence (50 m in 1.5 min). Short-range spotting and an increase in flame size certainly contributed to the very vigorous fire behavior that ensued. The fire attained such an intensity by the time it reached the downwind edge of the plot that it completely overwhelmed the sprinkler line and control forces positioned near the boundary (Figs. 10 and 11). Upon leaving the confines of the plot, the fire advanced 360 m in 7 minutes in a southeasterly direction towards an inlet of Porter Lake (this run was designated as experimental fire L5A since the "excursion" was still within the project study area). The highest wind speeds recorded during the project occurred during this time (Table 12). By the time the flame front reached the water, the fire was probably about 5–8 ha in size. Spot fires were observed across the inlet and the fire also skirted the inlet (Figs. 14 and 15). At this stage, the excursion resulting from the experimental fire had now become an uncontrolled wildfire, designated as Caribou Range-06-1982 (or simply CR-6-82) by N.W.T. fire management staff, and control action began almost immediately using the available suppression resources including the Forestry Canada fire research and Canadian Wildlife Service personnel on site. The immediate concern was the safety of the camp and weather station near the tip of the peninsula (Fig. 4). A fireguard was constructed along the western flank from the plot to the lake. Work on the lower portion of the eastern flank continued late in the evening. Wildfire CR-6-82 was observed from a helicopter by N.W.T. fire management and Forestry Canada fire research personnel during its initial run. The fire exhibited a wind-driven convection column. Sketch maps made of the fire's progress revealed that it advanced approximately 4.21 km by 1735 MDT. This represents an averaged spread rate of 1.91 km/h or 31.9 m/min (Table 15). Further expansion of the fire's perimeter occurred along its western flank during a northwest to northeast wind shift between 1800 and 2100 MDT (Table 16). More than half of the final area burned (≅1430 ha) was attained during the first burning period on July 7 (Tables 17 and 18). The remainder of the active burning took place on July 8, 9, 12, and 17 (Fig. 14 and Table 14). The major suppression activity commenced during the evening of July 8 with the arrival of additional fire suppression crews and support equipment, and continued until July 12. This consisted mainly of hose-lays and hand-constructed fireguards along the south and southwest portions of the fire's perimeter. Mop-up operations continued until July 26 when CR-6-82 was declared out by N.W.T. fire management staff following three days of heavy rainfall (Table 9).

The CR-6-82 wildfire did exhibit the narrow elliptical shape characteristic of a wind-driven crown fire (Fig. 14). The wind flow affecting the fire spread was no doubt influenced by the terrain (i.e., the mixture of warm land surfaces and cold water bodies). The actual length-to-breadth ratios (L/B) for the three available time intervals on July 7 are summarized in Table 18. The L/B model for natural forest stands found in the FBP System (Alexander 1985) consistently underpredicted the L/B ratios (2.23, 2.34, and 1.54) for assumed 10-m open wind speeds of 25, 26, and 17 km/h based on the data given in Table 16. This underprediction of fire shape, however, would have resulted in an overestimate of fire area and perimeter length. Anderson's (1983) elliptical fire shape model on the other hand overpredicted the L/B ratios (5.72, 6.12, and 3.37).

"Tree-crown streets" were formed in an area of flat ground just southeast of the inlet on Porter Lake

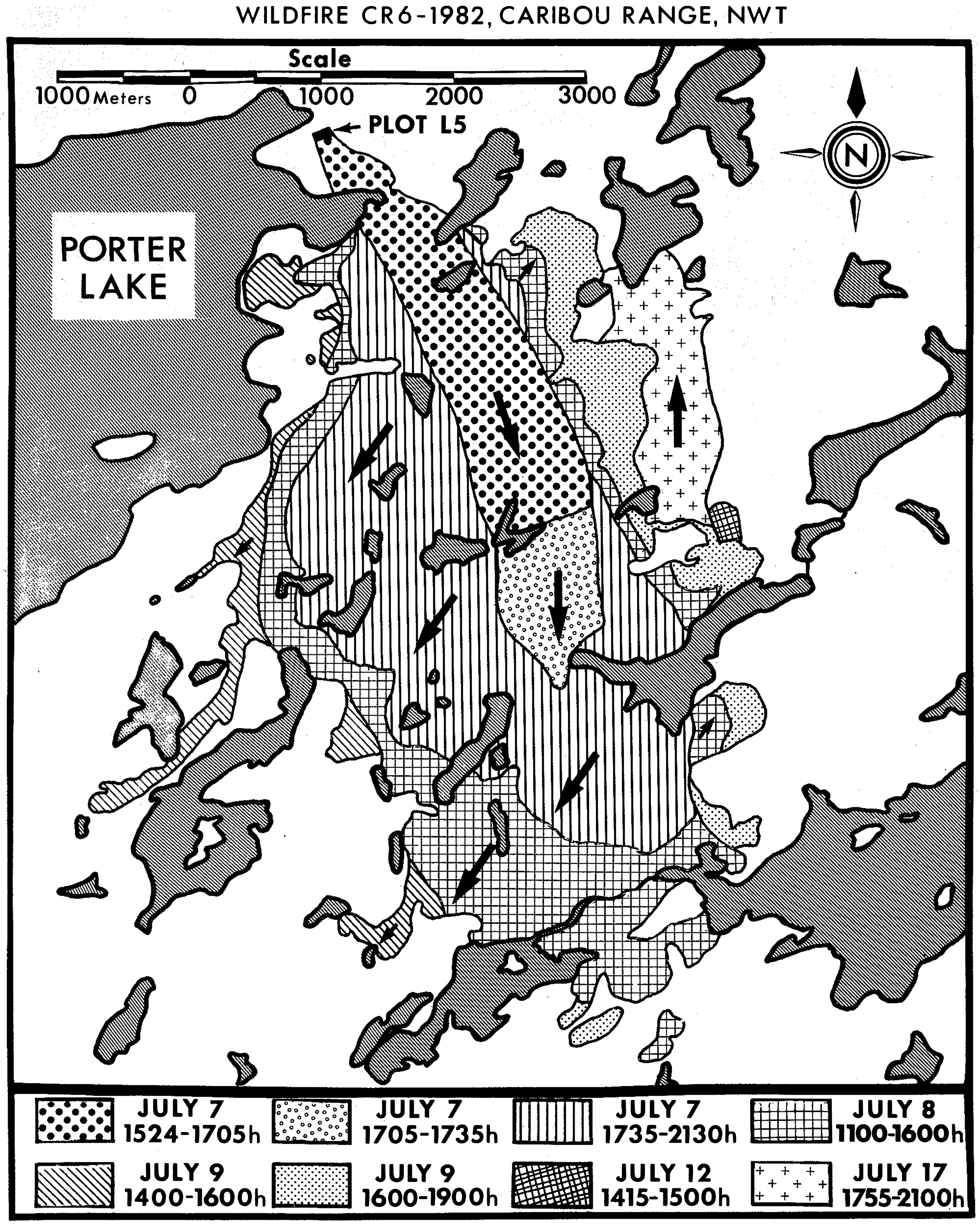

Figure 14. Fire progress map of wildfire CR-6-82.

Figure 15. Aerial view of the "tree-crown street" pattern near the origin of wildfire CR-6-82.

Table 16. Hourly fire weather observations recorded prior to and during the first burning period of wildfire CR-6-82 at the main study area meteorological station of the Porter Lake experimental burning project on July 7, 1982

Local time (MDT)	Dry-bulb temperature (C)	Relative humidity (%)	10-m open wind Direction (from)	10-m open wind Speed[a] (km/h)	Cloud type and sky condition[b]
1500	27.5	32	NW	21.0	CU 1 TCU4
1600	27.0	33	N	24.6	TCU 5
1700	27.5	32	NW	27.3	TCU 5
1800	27.5	30	NW	21.8	TCU 5
1900	27.0	33	N	13.8	TCU 5
2000	24.5	41	NE	6.8	TCU 5
2100	23.5	40	N	7.7	CB 1 TCU 2
2300	21.0	45	NW	9.2	—[c]
2300	19.5	47	NW	8.6	—
2400	17.0	55	W	3.6	—

[a] Averaged over a 10-min interval prior to the hourly reading.

[b] Cloud types: CU = cumulus; TCU = towering cumulus; and CB = cumulonimbus. Sky condition is reported in tenths (e.g., 3/10's of CU is reported as CU 3). For further information see Mullock (1982).

[c] Not recorded.

Table 17. The burned area and length of perimeter associated with wildfire CR-6-82 at selected time intervals

Period		Interval area burned				Cumulative area burned				Total perimeter length	
Date (1982)	Time of day (MDT)	Gross total[a] (ha)	Gross total[a] (%)	Land surface (ha)	Land surface (%)	Gross total[a] (ha)	Gross total[a] (%)	Land surface (ha)	Land surface (%)	(km)	(% inc.)
July 7	1524–1705	194	13.1	188	13.1	194	13.1	188	13.1	9.0	—[b]
	1705–1735	66	4.4	64	4.5	260	17.5	252	17.6	11.4	26.7
	1735–2130	545	36.7	507	35.5	805	54.2	759	53.1	16.9	48.2
July 8	1100–1600	347	23.4	339	23.7	1152	77.6	1098	76.8	22.9	35.5
July 9	1400–1600	108	7.3	108	7.6	1260	84.9	1206	84.4	30.2	31.9
	1600–1900	129	8.7	129	9.0	1389	93.6	1335	93.4	33.9	12.3
July 12	1415–1500	5	0.3	5	0.3	1394	93.9	1340	93.7	34.1	0.6
July 17	1755–2100	90	6.1	90	6.3	1484[c]	100.0	1430[c]	100.0	34.3	0.6

[a] Includes lakes.

[b] Not applicable.

[c] Not included in these totals is the area occupied by unburned islands located within the fire's perimeter, which amounted to 19 ha.

Table 18. Fire growth characteristics associated with the main run of wild fire CR-6-82 during its first burning period on July 7, 1982

Time interval (MDT)	Interval duration (hr:min)	Elapsed time (hr:min)	Forward spread distance Interval (km)	Forward spread distance Cumulative (km)	Head fire spread rate Interval (km/h)	Head fire spread rate Cumulative (ha/h)	Rate of area growth[a] (ha/h)	Rate of perimeter growth[a] (km/h)	Length-to-breadth ratio[a] (L/B)
1524–1705	1:41	1:41	3.06	3.06	1.82	1.82	115	5.35	3.9
1705–1735	0:30	2:11	1.15	4.21	2.30	1.93	119	5.24	5.2
1735–2130	3:55	6:06	1.35	5.56	0.34	0.91	132	2.76	2.4

[a] Computed for the end of each period.

(Fig. 17) suggesting the presence of horizontal roll vortexes as discussed by Haines (1982), and Haines and Smith (1987) or short-term variations in wind velocity (Fendell 1986; Windisch 1987). The characteristic char pattern on the tree boles along the outside of the tree-crown street as described by Haines (1982) was verified by a field check (Fig. 17). The irregular terrain and vegetative cover prevented the identification of other similar areas within the fire perimeter.

The wildfire escape did provide a unique, unplanned opportunity to study actual as opposed to simulated wildfire behavior in the black spruce–lichen woodland fuel type. In fact, interestingly enough, the spread rate for CR-6-82 between 1531 and 1735 MDT was very similar to that observed on the experimental plot (Table 15) under nearly identical burning conditions (Table 12). The ROS value computed for the excursion run between the plot and the lake represents the third highest sustained spread rate ever recorded for an experimental fire in Canada (Forestry Canada 1991); only two experimental fires in spruce-budworm-killed balsam fir stands have higher values (Stocks 1987a).

Analysis of Fire Behavior in the Black Spruce-Lichen Woodland Fuel Type

Potential fire behavior in the black spruce–lichen woodland fuel complex such as that found at Porter Lake can be quite deceiving. The continuous layer of lichen in this particular forest-type, exposed to the sun and drying very quickly after rain, is indeed a very flammable surface. Nevertheless, by itself, it does not produce a very high frontal fire intensity even under favorable burning conditions. There are two reasons for this—each related to its bulk density. The first reason is that the lichen's bulk density is too low to transmit enough heat downward to ignite the full layer before the flaming front has passed. The weight of material engaged in combustion may, therefore, be only about 1.0 kg/m^2, and after-smouldering is limited as well. Conversely, the second reason is that the bulk density of the lichen is considerably higher than optimum for fast spread in a fuel layer of such limited weight. The overall effect is to severely limit the spread rate and flame size of any fire burning in the lichen layer by itself. Wind tilts the flame easily but a high-intensity flame-radiation surface fire does not develop. Residence times are typically less than 30 seconds.

The combination of the lichen layer and scattered black spruce tree clumps produce high-intensity fires in the Porter Lake forest. This is because the lichen layer is only present when the canopy cover is low, and each spruce is open-growing with foliage extending to ground level. In older stands, successive circles of layered spruce surround the parent tree, and the unit then becomes a clump with a mantle of foliage overall. At the foliar moisture contents prevalent in high summer (about 80% in black spruce), flame climbs quickly into each crown the moment a substantial surface fire reaches it. A combination of lichen dryness and wind is required to initiate torching and the reinforcement in fire behavior that accompanies it. Wind is important because the lichen will support only a gentle surface fire under calm conditions. Wind also promotes short-distance spotting by carrying showers of burning spruce needles or cones a few meters past the main fire front. As each spruce tree or clump crowns, a body of flame is quickly produced that casts intense radiation in all directions. The unburned lichen ahead of this flame is then pre-heated much more intensely than it would have been by the surface lichen flame alone. Fire then spreads quickly into this irradiated zone, reinforcing both spread rate and flame size while it does so. A similar mechanism of fire spread has been observed in the piñon–juniper woodlands of the western United States (Bruner and Klebenow 1979). Spread through the open lichen area then resumes at the lower rate. Under any given set of burning conditions the effective spread rate will be a weighted average of these two processes. The greater the stocking of spruce, the faster the spread rate and intensity. As long as the fire spends some portion of its time burning on the surface lichen only, it can be classed as an intermittent crown fire (Merrill and Alexander 1987) or passive crown fire (Van Wagner 1977b), its behavior reinforced but not controlled by the spruce-torching phase. When the trees or clumps are close enough that the zone of intense radiation from one reaches the edge of the next, more-or-less continuous crowning results in what would normally be referred to as an active crown fire (Van Wagner 1977b; Merrill and Alexander 1987). Because the crowns are generally well separated, any appreciable wind will blow the torching flame downwind, usually leaving the tips unconsumed. Both short- and long-distance spotting may then further complicate and reinforce fire behavior.

Extreme fire behavior in the black spruce–lichen forest at Porter Lake occurred when lichen moisture content fell below 10%, the 10-m open wind speed approached 20 km/h, and ISI approached 20 (Tables 10, 12, 15). In contrast with the black spruce–lichen woodland, the pure jack pine-lichen forest was much less prone to high-intensity fire. This is because jack pine, as it ages, carries its crowns well above the surface, and there is no new circle of layers formed at intervals with foliage near the ground. The lichen layer by itself can hardly produce a surface intensity high enough to crown a mature jack pine stand under any burning conditions. Even a surface fire with an intensity lethal to mature trees would be rare in the pure jack pine–lichen forest.

FIRE MANAGEMENT APPLICATIONS

The Porter Lake project provided the opportunity to add another benchmark fuel type to the quantitative scheme of fire behavior prediction in the CFFDRS as represented by the FBP System. New and valuable information was obtained on rate of spread and fuel consumption in a unique fuel complex under low to extreme burning conditions. The experimental fires and wildfire also contributed to our general knowledge and understanding about fire behavior in Canadian forests.

The most convenient and accurate way to use the results of the Porter Lake project and other similar experimental fire behavior field studies conducted elsewhere in Canada, would be to program all the equations and related facts into a computer-based model of forest fire behavior which could perhaps be integrated with a geographic information system and other fire management-related information systems such as a library of historical fire weather data. Then, not only could all the input variables be entered on a continuous scale, but additional aspects of fire behavior could be considered such as the acceleration in fire spread to an equilibrium state (Cheney 1981; McAlpine 1988), mechanical effects of slope on fire spread rate (Van Wagner 1977c, 1988), elliptical fire growth rates (Alexander 1985), frontal fire intensity (Byram 1959; Alexander 1982) including the variation about an elliptical fire perimeter (Catchpole et al. 1982), and theoretical maximum spot fire distances (Morris 1987). The control capability of individual kinds of fire fighting resources and various mixes based on fireguard production rates and general level of suppression effectiveness (Murphy and Quintilio 1978; Newstead and Lieskovsky 1985) in relation to elapsed time since ignition, initial fire size, rate of perimeter growth, and frontal fire intensity for full or only partial containment of the fire perimeter could also be simulated (Mees 1985, Loane and Gould 1986; Smith 1986; Thiemann 1989). In fact, the results of the project were applied almost immediately in determining suppression strategy and tactics in containing wildfire CR-6-82. The main findings of the Porter Lake project have been presented in the form of a few tables and graphs, which will permit reasonably accurate predictions of potential fire behavior in the black spruce–lichen woodland fuel type (Alexander and Lanoville 1989).

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