Fire Behavior in Upland Jack Pine:

The Darwin Lake Project

by

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ABSTRACT

Fire behavior was studied in upland jack pine (*Pinus banksiana* Lamb.) stands in northeastern Alberta during the summer of 1974. Fire researchers from across Canada teamed up to establish experimental plots, sample vegetation and fuels, and monitor prescribed burns throughout a range of weather conditions. Extensive rains preceded the burning period, followed by the gradual development of a warm, stable air mass. This allowed a series of seven burns progessing from low hazard to extreme hazard as defined by the Canadian Fire Weather Index Tables. A relationship of fire spread in jack pine was established and is expressed in the form $RS=a(ISI)^b$.

Résumé

On a étudié le comportement du feu en peuplements de Pin gris (*Pinus banksiana* Lamb.) sur les hautes terres du nord de l'Alberta au cours de l'été 1974. Des chercheurs spécialisés dans l'étude des feux, venus de partout au Canada, ont uni leurs efforts pour établir des placettes expérimentales, des échantillons de végétation et de combustibles, et pour surveiller des brûlages dirigés à travers tout un éventail de conditions atmosphériques. Des pluies considérables ont précédé la période de brûlage, suivies du développement graduel d'une masse stable d'air chaud, ce qui a permis une série de sept brûlages, progressant d'un bas indice de danger de feu à un indice extrême tels que définis dans les Tables de l'indice canadien forêt-météo. Une corrélation de la propagation du feu fut établie relativement au Pin gris et elle s'exprime par la formule $RS = a\,(ISI)^b$.

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INTRODUCTION

Fire behavior study in natural coniferous stands is a continuing goal of the Canadian Forestry Service (CFS) national fire program. In January of 1974 fire researchers at the Great Lakes Forest Research Centre proposed a major cooperative fire behavior study in northern Ontario. This study and the support commitment from CFS Headquarters (Ottawa) were transferred to Alberta following Ontario's decision that it could not host a 1974 operation. The Alberta Forest Service (AFS) and the Northern Forest Research Centre (NFRC) approved the alternate Darwin Lake site in March 1974 and a proposal to study surface and crown fires in the upland jack pine (*Pinus banksiana* Lamb.) fuel type and relate fire spread to the Canadian Fire Weather Index (Anon. 1976; Van Wagner 1974). Interagency agreements and plot establishment were completed in June, and burning commenced in July. CFS personnel from five locations across Canada united at Darwin Lake with the AFS, Northwest Lands and Forest Service (NWLFS), Parks Canada, and the Atmospheric Environment Service (AES).

Generally the study was designed to document fire behavior response to natural variation in weather and fuels within a given area, and specifically to determine at what Fire Weather Index (FWI) levels crowning occurs in natural jack pine stands. The original idea was to observe behavior of a fire or fires that would be permitted to spread unimpeded to a natural end in a remote area. A site for such an operation was not found. The alternative chosen was to study fires contained within the boundaries of plots that represented a cross-section of the fuels in an area. Fuels and vegetation within the plots were measured, and burning was done at various levels of fire weather severity as indicated by on-site determination of the FWI.

Rate of fire spread, tendency of the fire to crown, and fire intensity (rate of energy release) were the main behavior phenomena studied.

THE RESEARCH SITE

The site chosen for the study lies on the north side of the western arm of Darwin Lake, a 5 km (3 mile)-long shallow body of water about 75 km (47 miles) north of Ft. Chipewyan, Alberta (Fig. 1). The area is on the Canadian Shield some 25 km (16 miles) from its western edge. Gently rolling terrain separates granitic outcrops. Study units were selected on the higher ground, exclusive of rock outcrops, where the soil consists of about a 30 cm (12 in.) layer of coarse, grayish sand at the surface above 15 cm (6 in.) of medium-sized gravel, all underlain by somewhat finer, yellowish sand up to several metres deep. The surface layer (A horizon) is thin, and a slightly leached Ae horizon indicates weak podzolization. The coarse mineral soil and thin organic layer contribute to an extremely permeable substrate. Consequently, the site is droughty, as indicated by rate of tree growth and sparsity of other vegetation.

Figure 1. Geographic location of the Darwin Lake study area

Jack pine of various ages, sizes, and stand densities occupies the study site. Past fires appear to have been mainly responsible for the variation, although some particularly open stands may result from unusually dry sites. (See Appendix I for a more complete description of vegetation and history.) Aspen (Populus tremuloides Michx.) occurs occasionally, mainly near rock outcrops and in moist areas. Infrequent sprout clumps of white birch (Betula papyrifera Marsh.) in the vicinity of rock outcrops and the lake margin never reach tree size. Black spruce (Picea mariana (Mill.) B.S.P.) is the sole tree species in the muskegs that border the pine uplands.

Extensive mats of bearberry (Arctostaphylos uva-ursi (L.) Spreng.) and dry-ground cranberry (Vaccinium vitis-idaea L.) are the most conspicuous ground cover. "Caribou moss" and "British soldier" lichens (Cladonia spp.) occur frequently, with the former sometimes consisting of mats of considerable size (Fig.2). Herbs and erect low shrubs are sparse and generally inconspicuous. Tall shrubs likewise are mostly inconsequential; only green alder (Alnus crispa (Ait.) Pursh.) is sometimes dense and tall enough to impede foot travel.

Study units ranging in size from 1 to 3 ha (2.5 - 7.5 acres) were established as shown in Fig. 3. The main criteria for delineating a unit were: (1) dry enough site to burn throughout most of the probable FWI range, (2) essentially continuous surface fuels, (3) homogeneous

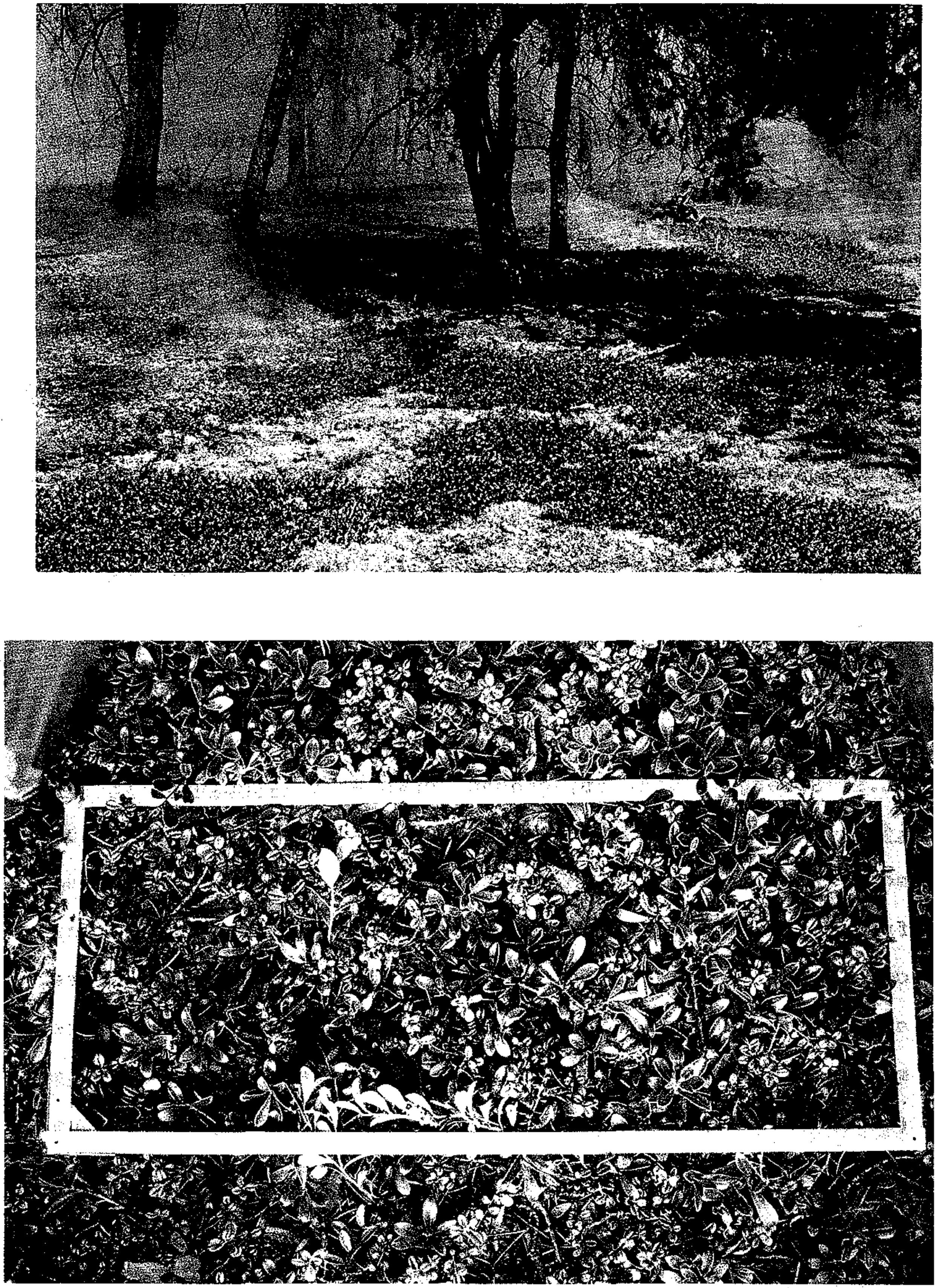

Figure 2. General view of interspersed lichen and dwarf shrub ground cover on Unit 1 (top) with a close-up illustrating a concentration of bearberry (bottom).

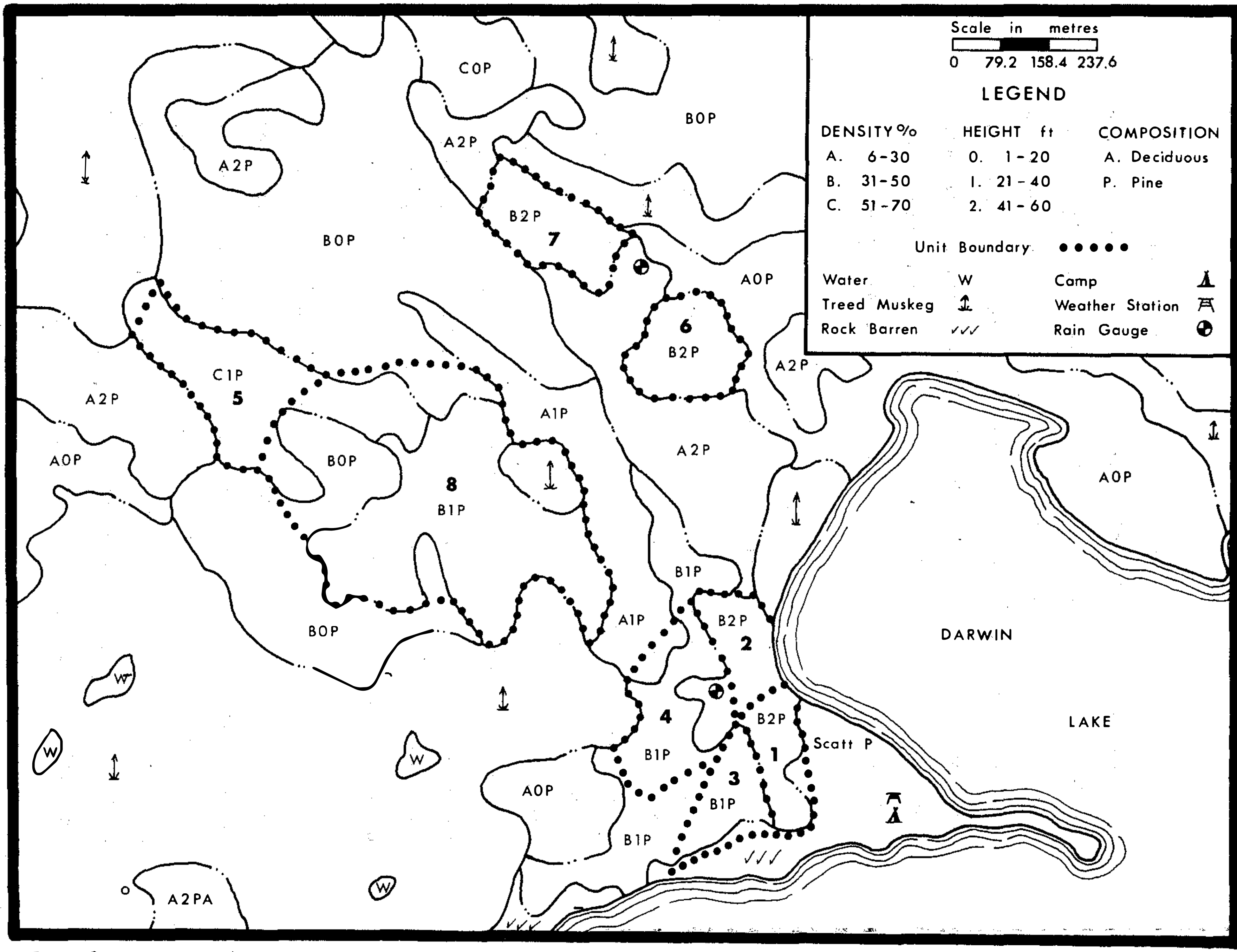

Figure 3. Location and cover type of Darwin Lake study units

surface fuel and tree cover, and (4) manageable size for measurement of fuel and observation of fire behavior. The boundaries of units 1-7 followed rather closely either mapped type changes or openings within a type that were too narrow to map. Unit 4 was bisected by a roughly east-west fireline and burned as two units. Unit 8, with its variable cover, was not intended to be part of the study but ultimately was used for some informal experimentation.

METHODS

Preburn Measurements

A grid of 20 m (66 ft.) squares was laid out on units 1 to 7. The line bisecting unit 4 roughly bisected the grid also, so that measurements for the entire plot were considered to represent both the south and the north half (4A and 4B). Woody fuels larger than 10 cm (4 in.) were measured by the line intercept method along the full length of each grid line (Van Wagner 1968). Smaller woody fuels were tallied by diameter classes on the last metre (3.3 ft) of each line (Brown 1971).

Depth of the forest floor (duff) was measured along the grid lines at 20 m (66 ft.) intervals. A metal pin marked at the duff surface was set in the ground at each measurement point for use in determining depth of burn. In addition, five randomly selected samples were removed from each unit to determine weight. The samples, measuring 929 cm^2 (1 ft^2), were weighed and oven-dried at a later date.

The diameters of count trees selected by a 10-factor wedge prism were measured at every second intersection of the grid, and a stand table was developed. Density and mean maximum height were estimated for shrubs, and tree reproduction was counted on a 1-m-wide (3.3 ft.) transect centered on the last 3 m (9.9 ft) of each grid line; herbs, including lichens and mosses, were counted on the last 1 m (3.3 ft) of this transect. Species were listed in descending order of apparent importance. In addition, frequency and cover (percentage) of shrubs and herbs and cover of bare litter were determined on a number of randomly located, .2 x .5-m (.66 x 1.64 ft) plots on each unit. Frequency was calculated for species occurring on both sizes of plots, and prominence value (Douglas and Ballard 1971) for those on the smaller plots. The general characteristics of vegetation are described in Appendix I; features that proved to affect fire behavior are noted at appropriate points in the text.

Ten living jack pines 7.1 - 15.7 cm (2.8-6.2 in.) dbh and 8.0 - 12.4 m (26.0-40.8 ft) tall were felled, and their crowns were separated into six fuel categories: living material ≤.64 cm (.25 in.) (including needles), .65-1.27 cm (.26-.5 in.), and 1.28-2.54 cm (.51-1 in.) in diameter; dead fuels in the two smallest size classes; and cones. The crown components were weighed separately in the field with a hanging balance. Samples of each fuel category were taken for moisture content determination and calculation of ovendry weights. Regression equations of ovendry weight on dbh were calculated and applied to stand tables for the burning units to calculate weight of aerial fuel.

Postburn Measurements

The grids of line transects for fuel and vegetation inventory were rerun, and duff samples were obtained immediately after units were burned (except on units 1 and 3). Woody fuels ≥3 cm (1.2 in.) were tallied for the full lengths of the transect line. Estimates of scorch height, mortality on each unit, extent of fire-scarring on trees, and regrowth of lower vegetation were made later in the year.

Weather

A base weather station on high ground at the north edge of camp contained a standard rain gauge, recording rain gauge, maximum/minimum thermometers, hygrothermograph at 1.4 m (4.5 ft.) and one at ground level (both in Stevenson screens), psychrometer for checking the hygrothermographs, recording anemometer at 10 m (33 ft), recording anemometer at 1.4 m (4.5 ft), and two sets of 1.27 cm (.5 in.) fuel moisture indicator sticks. Two additional standard rain gauges were located in the experimental area. Weather observations were made at 0800[1], 1300, and 1800 h; fuel moisture sticks were weighed daily at 1200 h and 1600 h, and

[1] Mountain Daylight Time

on one occasion hourly during the full 24-h period. The 1300-h readings of precipitation, temperature, relative humidity, and wind were used to calculate the FWI. Table 1 lists weather and FWI components for each actual and attempted burn. The project meteorologist used all relevant measurements to develop descriptions of the current synoptic situation (Appendix II) and prepare forecasts. He also monitored, by radio, weather reports and forecasts for Fort Smith, N.W.T.; Fort Chipewyan, Alberta; Uranium City, Saskatchewan; and Wood Buffalo National Park several times a day and discussed these with the meteorologist at NWLFS Fire Centre in Fort Smith.

On July 16 the FWI was 0 at Ft. Chipewyan. The three cumulative drying indicators, Duff Moisture Code (DMC), Drought Code (DC), and Buildup Index (BUI) stood at 8, 140, and 15, respectively. These were used as starting values for the Darwin Lake Project. More than 25 mm (1 in.) of rain in 5 days brought DMC and BUI to their lowest points on July 20, while FWI failed to reach 0 only because of high wind speed. All three values reached moderate peaks July 24-25, then declined because of rain and cool weather July 26-28, FWI reaching 0 again. Thereafter, FWI climbed steadily to a high of 28 on August 5, fell back to 5 on August 8 because of rain, and rose again to 12 the next day before cool, wet weather terminated the project. DMC and BUI increased rather steadily from July 27 to August 9. Figure 4 summarizes the progression of FWI components.

Table 1. Weather and FWI components at time of actual and attempted burns of Darwin Lake experimental units

	Unit 1	Unit 2		Unit 3	Unit 4A	Unit 4B	Unit 5		Unit 6	Unit 7	Unit 8
Date	23/7	31/7	2/8	24/7	3/8	4/8	6/8	7/8	5/8	6/8	9/8
Weather at 1300 h:											
Temperature °C	26.5	19.5	-27	24.5	29	31	23	22	30.5	23	22
Relative humidity %	48	66	39	45	40	26	46	56	33	46	57
Wind speed km/h	11	19	2	18	13	14	13	3	13	13	13
Wind direction	SW	E	S	SW	S	S	SW	E	S	SW	SW
Fuel stick m.c.%	-	13.2	10.8	-	9.4	9.4	9.2	10.0	9.2	9.2	12.2
FWI components:											
FFMC	88	84	90	89	91	92	92	90	93	92	84
DMC	13	22	30	16	34	39	47	48	44	47	49
BUI[1]	21	33	43	25	50	52	61	65	61	61	63
ISI	5	5	5	9	9	11	11	5	12	11	4
FWI	8	10	13	14	21	24	26	16	28	26	12
Time of fire											
Start	1530	1500	1335	1530	1450	1400	-[3]	1340	1330	1352	1340
End	1730	1530[2]	-	1700+	-	-	-	-[4]	1405	-	2000

[1] Formerly Adjusted Duff Moisture Code (ADMC)

[2] Terminated because fire did not spread

[3] Aborted because of wildfire report

[4] Terminated by shower

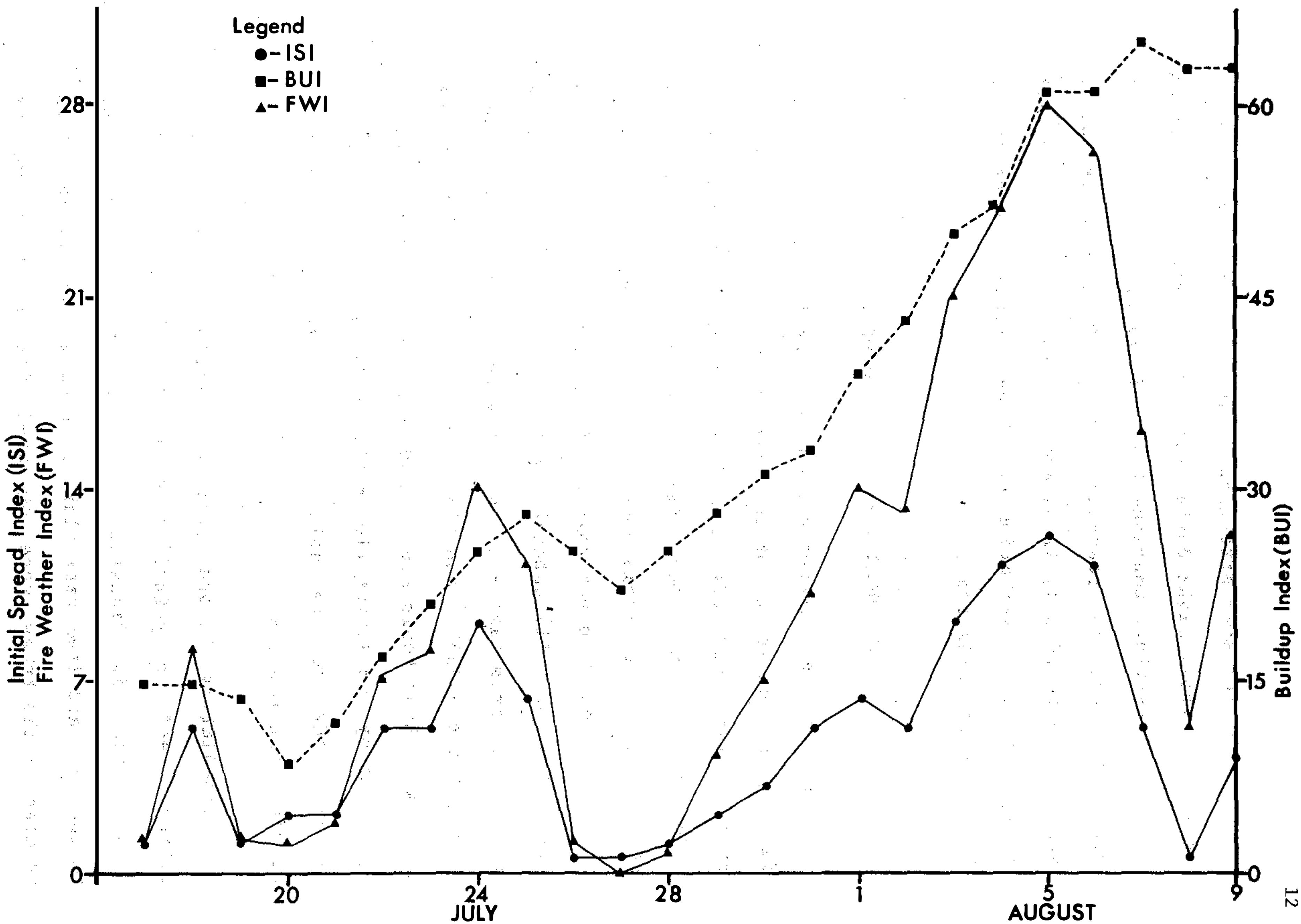

Figure 4. Fire Weather Index (FWI), Buildup Index (BUI), Initial Spread Index (ISI), during the Darwin Lake Project

Except for some strong gusts incident to showers, winds were relatively light during the project, especially during the driest weather. Consequently, Initial Spread Index (ISI) remained rather low, reaching 9 on July 24 with a wind of 18 km/h (11 mph) and only 12 on August 5 with a wind of 13 km/h (8 mph). Thus the variation in FWI was mainly a function of fuel moisture relations.

Experimental Burning Procedure

The project leader currently in residence (either the first or second author of this report) scheduled units for burning with the advice and concurrence of the other scientists present. The limiting criterion was weather; other important criteria were safety of the camp, likelihood of fire spread to other units, and expected fire behavior in the fuels of still-unburned units. The general progression was outward from camp and to windward. Burning was done mainly between 1330 h and 1730 h. The fire crew built a fire line with hand tools around each unit before burning, and a sprinkler system (Quintilio et al. 1971) was used on the leeward side of the units. Fires were ignited by hand-carried drip torches.

Immediately before ignition samples from surface litter, dead woody fuels <.64 cm (.25 in.) and .65-1.27 cm (.26-.5 in.) in diameter, Cladonia (caribou moss) and bearberry, and from bark flakes, hanging lichens, and green needles on the trees were obtained for moisture content determinations. The meteorologist moved a hygrothermograph to an adjacent unit and took periodic wind readings with a hand-held anemometer. The project leader noted the starting and approximate ending times of each burn. Scientists observed flame heights and flame-front depths, timed fire runs, took photographs, and made miscellaneous notes on fire behavior. Gridpoints located for fuel inventory were used to record fire spread. Two observers followed the flame front on respective sides of each plot, timing the advance between grid points. These recordings were then averaged for the total plot.

Seven units were burned from July 23 to August 6, with 4A and 4B considered as separate units within the same fuel and vegetation complex. An early attempt to burn unit 2 on July 31 was terminated after about 30 minutes because the fire obviously was not going to spread far beyond the ignition line. The scheduled August 6 burn of unit 5 was aborted because of a wildfire report just before ignition time. Next day a shower terminated the second attempt with too little of the unit burned for the results to be analyzed. Two spots and line of fire were lit the afternoon of August 9 on unit 8 and their progress was followed until evening. The intent was to learn a little about the behavior of point ignitions, simulating lightning strikes, and of a fire running into a muskeg. (See Appendix III for an operational description of each fire).

RESULTS

Fuel Loading

Surface Wood

Dead woody fuels -- fallen trees, branches, twigs -- aggregated from 6 to 38 t/ha (2.7-17 tons/acre) (Table 2). Three of the four old-growth units (2,6,7) had distinctly heavier loading of both fallen wood and duff (Fig.5, Top). The quantity of fuel and the generally better developed lesser vegetation suggested that the 1944 fire, and perhaps the 1906 fire, had burned lightly if at all in these units. (See Appendix I for fire history.) The fourth old-growth unit (1) obviously had burned in 1944, and it had relatively light fuel loading (Fig. 5, Bottom). Material >10 cm (4 in.) in diameter contributed 60-70% of total wood loading on the old-growth units but only 33-40% on the three younger units (3, 4, 5). Of material ≤10 cm (4 in.) in diameter, the 3 to 10 cm class made up 61-73% on all units except number 5; this unit apparently had not burned in the 1944 fire, so sustained no mortality in the 30 yr since.

Forest Floor

Duff averaged 1.5-1.8 cm thick on units 1-5, 2.6 cm on unit 6, and 2.4 cm on unit 7 (Table 2). Weights were 19.9-21.1 t/ha (8.9-9.5 ton/acre) on the sampled old-growth units (2, 6, 7) and 13.3-15.0 t/ha (5.9-6.7 tons/acre) on the sampled younger units (4, 5). The relation between mean weight and mean thickness of duff for the units was not consistent; thickness on units 2 and 4 were notably lower than would be expected for the corresponding weights. However, mean weight of individual samples, regardless of unit, did bear a definite, curvilinear relation to thickness.

Aerial Fuels

Weights of crown components correlated highly with dbh, and the relations could be expressed by regressions similar to those developed for jack pine in Ontario (Walker and Stocks 1975). Total crown weight (Table 3) ranged from 8.7 to 13.6 t/ha (3.9-6.1 tons/acre), with no apparent relation to stand age. More than 60% of this was material ≤0.64 cm (.25 in.) in diameter (including foliage), the main size class that burns in crown fires. About one-fourth of the fine material was dead. Less than 20% of crown weight was in material larger than 1.27 cm (.5 in.) in diameter. Many trees, especially in the younger age class (units 3, 4, 5) had persistent dead branches to within a metre of the ground, often bearing a considerable growth of fruticose lichens. Beard lichens draped trunks and branches; their weight was not determined but might be expected to approximate the .3 t/ha (.14 ton/acre) found for 60-yr-old lodgepole pine in British Columbia (Muraro 1971) on units 3-5 and to be somewhat greater on units 1, 2, 6, and 7, but

Table 2. Dead surface fuels on the Darwin Lake Units before burning

	Weight of woody fuel, by diameter class (cm)								Duff[1]	
Unit	0-.2	.21-.5	.51-1.0	1.1-3	3.1-10	All ≤10	>10	Total	Weight[2]	Depth
					t/ha[3]					cm
1	.23	.79	.23	.24	2.37	3.86	6.90	10.76	-	1.8
2	.33	.96	.28	.73	3.76	6.06	13.70	19.76	21.1	1.8
3	.31	.52	.19	1.37	6.59	8.98	6.00	14.98	-	1.6
4a	.36	1.10	.37	1.14	2.76	5.73	4.50	10.23	15.0	1.5
4b	.37	0.88	.32	0.96	5.98	8.51	5.53	14.04	15.0	1.5
5	.25	1.11	.52	1.89	.39	4.16	2.11	6.27	13.3	1.8
6	.20	1.80	.84	2.82	10.73	16.39	21.47	37.86	21.1	2.6
7	.22	1.53	.44	1.38	8.44	12.01	15.28	27.29	19.9	2.4

[1] Includes some living mosses, lichens, and creeping vascular plants.
[2] Net weight of organic fraction.
[3] 1 metric t/ha = .45 short ton/acre.

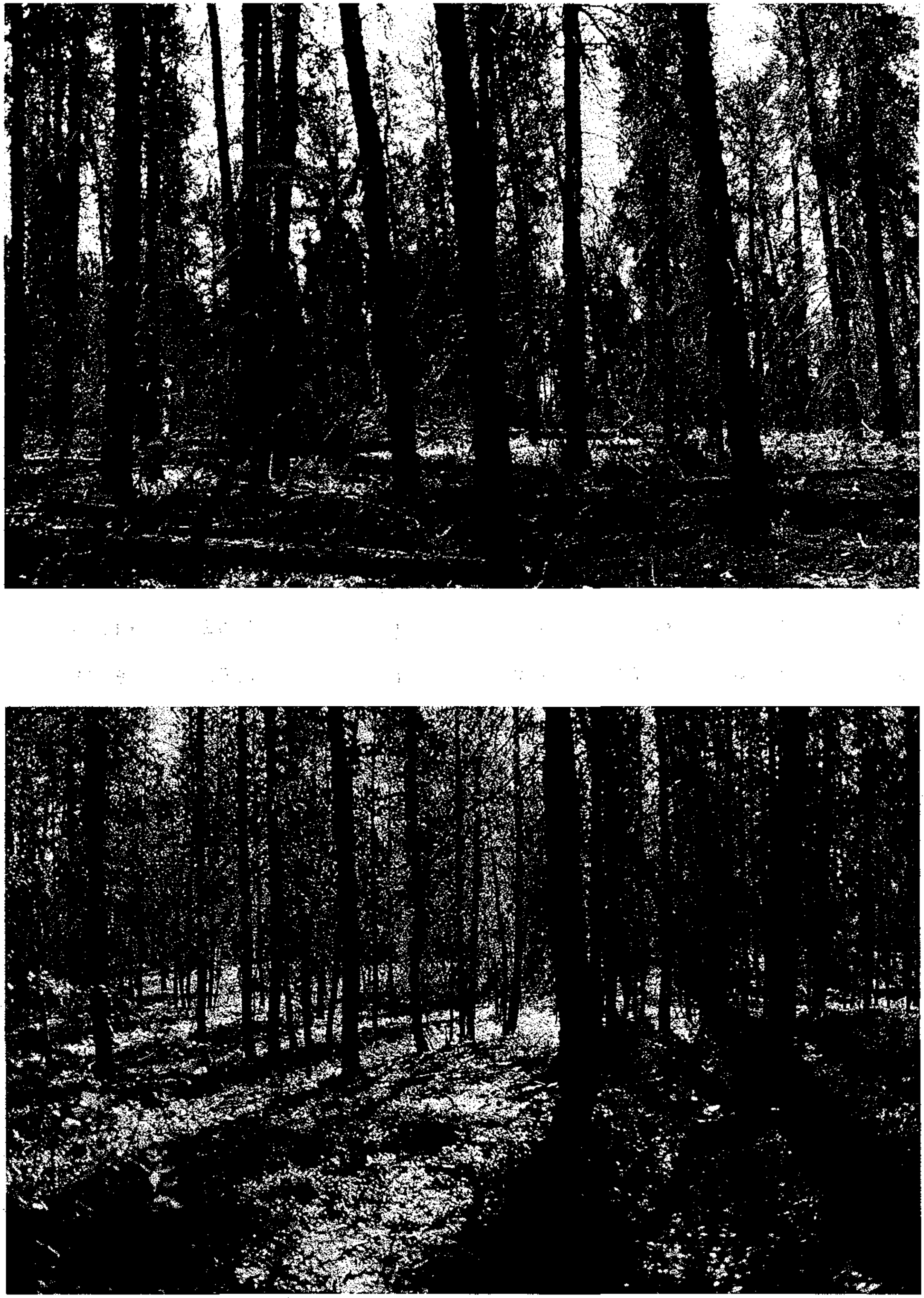

Figure 5. Woody surface fuel on Unit 6 (top) and Unit 1 (bottom).

Table 3. Crown weights on Darwin Lake units before burning

Unit	Weights by diameter classes (cm)					Total
	0-.64			.65-1.27	>1.27	
	Dead	Living	All			
			t/ha			
1	1.57	5.68	7.25	1.85	1.90	11.00
2	1.86	6.95	8.81	2.32	2.47	13.60
3	2.21	6.77	8.98	1.89	1.66	12.53
4	1.98	6.34	8.32	1.87	1.62	11.81
5	1.65	4.77	6.42	1.29	1.08	8.79
6	1.44	5.43	6.87	1.81	1.92	10.60
7	1.70	6.44	8.14	2.69	2.30	13.13

perhaps not so heavy as the .8 t/ha (.36 ton/acre) found for 80- to 130-yr-old Douglas-fir (Edwards et al. 1960).

Fire Spread

Observed spread rates averaged 0.6-6.1 m/min (2-20 ft/min) on the seven documented units. The early fires exhibited slow, steady surface spread that was quite sensitive to ground vegetation (Fig. 6), and was generally continuous on bare litter but interrupted to some degree by mats of bearberry, etc. The later, more vigorous fires spread faster and more erratically, with more dependence on the quantity and continuity of woody surface fuel (Figs. 7, 8). All fires were sensitive to short-term fluctuations of wind speed and direction.

Rate of spread was correlated significantly at the 5% level with 1300-h FFMC (r=.84) and ISI (r=.77) measured at the base station (Fig. 9) and at the 1% level with loading of woody fuel ≤3 cm in diameter (r=.88). However, because of the sequence of burning[1], there was also a highly significant correlation (1% level) between FFMC and fine-fuel loading (r=.97). The number of observations -- i.e., units burned -- was too small to support multiple regression analysis that could define the separate effects of fuel moisture and loading.

[1] Plots with the highest fuel loadings were burned at the highest FFMC and ISI values.

The ISI measured at base camp was a less sensitive index to fire spread than the FFMC. The reason was that 1300-h windspeed varied little during the tests -- 11-18 km/h (6.8-11.2 mph) on six of the seven burning days -- and ISI was, therefore, almost wholly a reflection of FFMC. In an effort to examine more minutely the relation of spread to concurrent ISI, the latter was recalculated for the sites and times of the fires by using stand wind at 1.4 m (4.5 ft) adjusted to 10 m (33.3 ft) (Table 4). Rate of spread was correlated at the 1% level with the recomputed ISI ($r=.93$). the improvement in correlation is attributed to the approximation of the 10 m (33.3 ft) wind at the fire site. The relationship of rate of spread and adjusted ISI can be expressed by the equation:

$$R/S = 0.0454(ISI)^{1.78} \text{ m/min (Fig. 10)}$$

This is similar in form to findings for jack pine and several other fuel types elsewhere in Canada (Van Wagner 1973).

Fuel Consumption

With two exceptions, the fires consumed 43-57% of the woody fuels and 36-76% of the duff by weight and 28-62% of the duff by depth (Table 5). On unit 1 postfire measurements in the 1.1-3 cm (.4-1.2 in.) category showed a 25% increase in wood loading; this would appear to result from errors in intercept tallies on this very lightly loaded unit, although

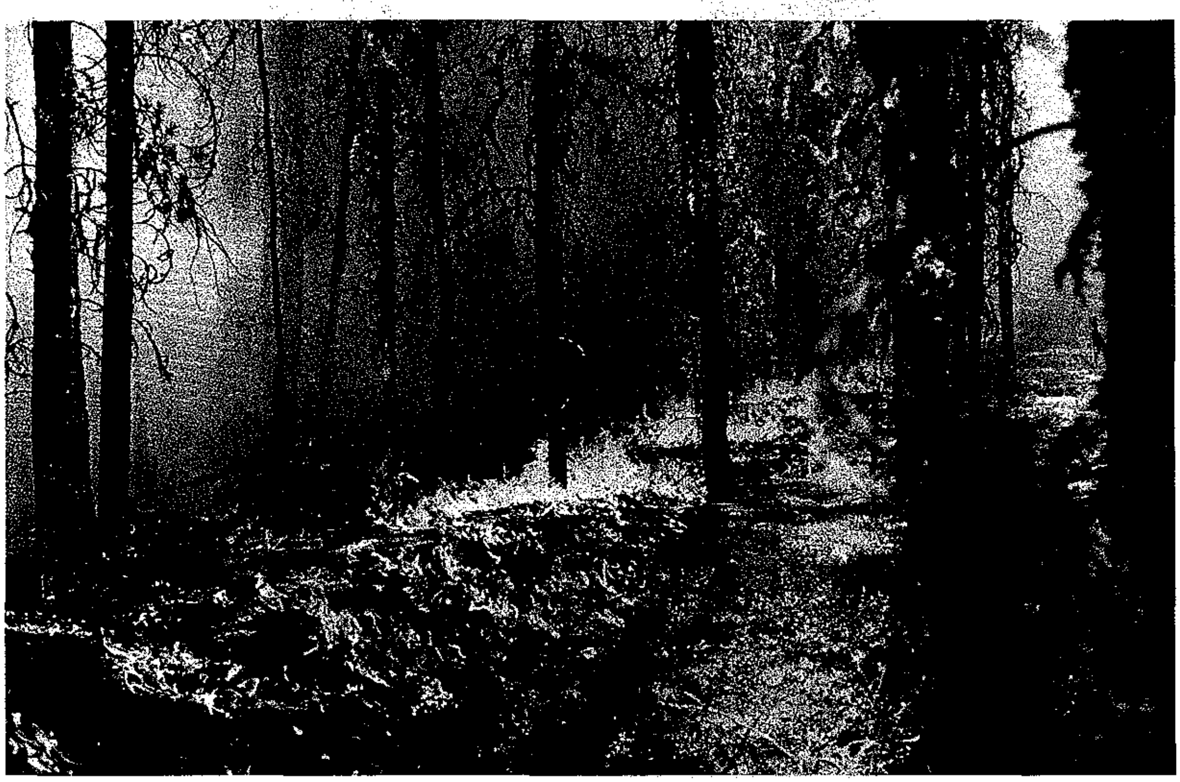

Figure 6. Low vigor surface fire on Unit 3.

Figure 7. Vigorous surface fire on Unit 4A involving aerial bark flakes and epidendric lichens

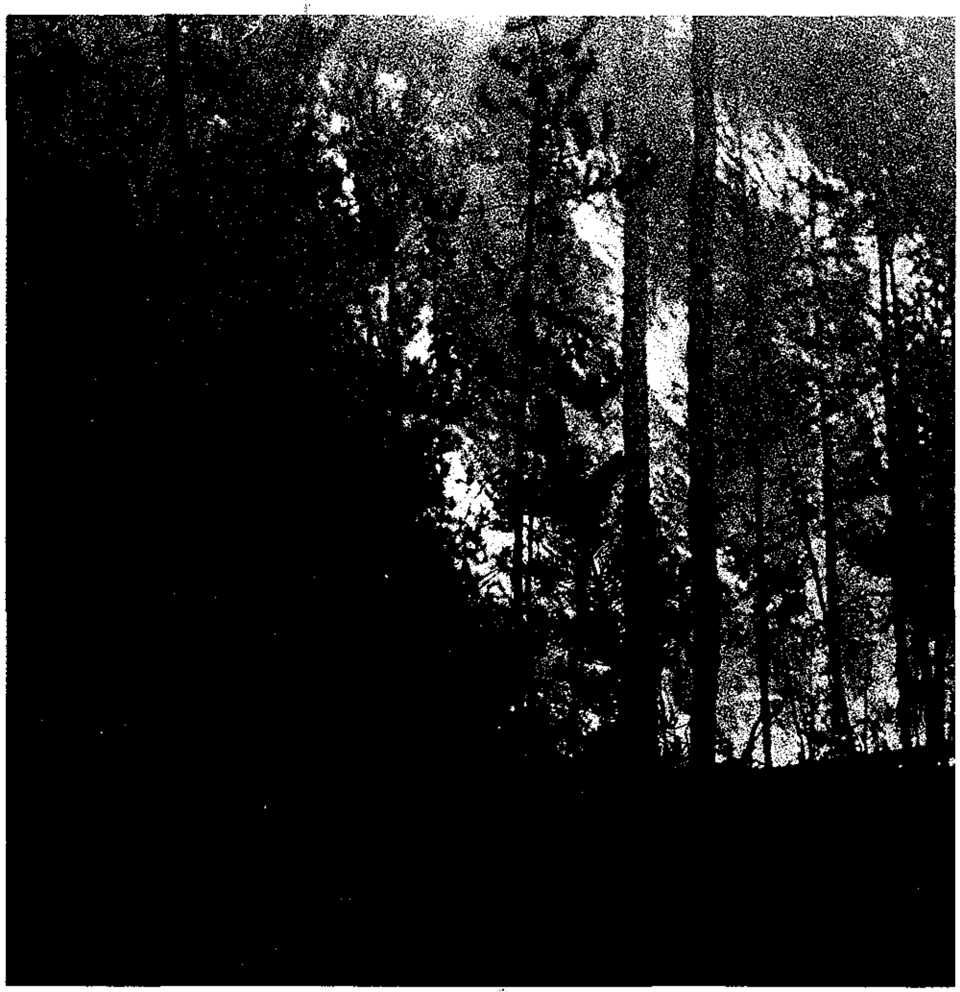

Figure 8. Full crown involvement on Unit 6.

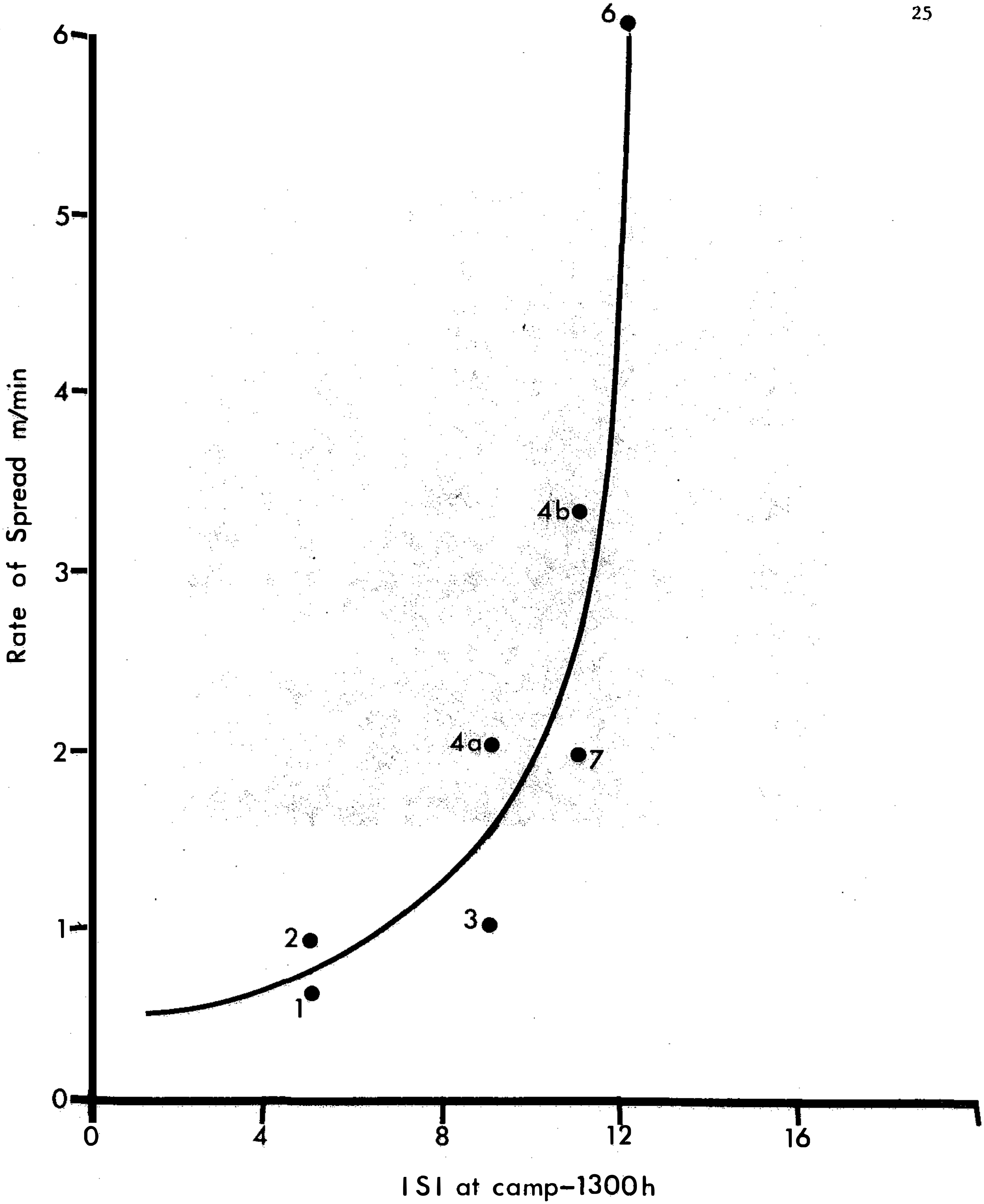

Figure 9. Relation of Observed Rate of Spread to ISI

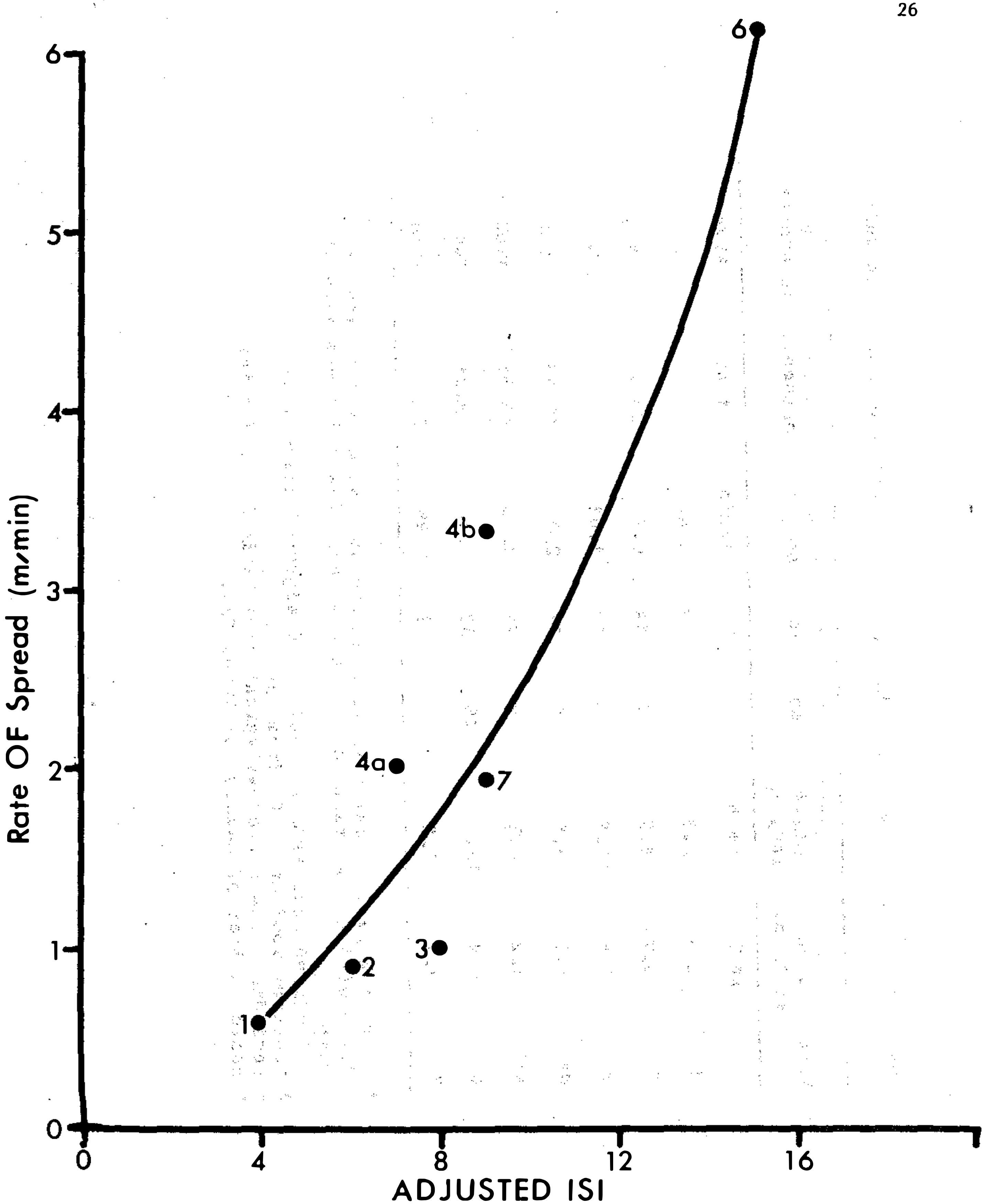

Figure 10. Relation of Observed Rate of Spread and Adjusted ISI

Table 4. Adjusted winds, indices, and fire behavior for seven units

Unit	Stand wind at 1.4m,	Adjusted[1] stand wind, W_f	ISI,[2] adj	FWI, adj	Rate of spread	Fuel[3] consumed,	Fire[5] intensity,
	km/h	km/h			m/min	t/ha	KW/m
1	2.4	6.3	4	7	0.61	--	--
2	3.2	8.5	6	14	0.91	23.9	670
3	5.6	14.8	8	13	1.01	--	--
4a	3.2	8.5	7	17	2.02	15.43	950
4b	3.2	8.5	9	21	3.35	18.56	1900
6	6.4	16.9	15	33	6.10	39.2[4]	7460
7	3.2	8.5	9	23	1.98	20.2	1230

[1] $W_f = w_f \times W_c / w_c$, in which W_f is adjusted 10-m wind at the fire, w_f is 1.4-m wind at the fire, and W_c and w_c are 10-m and 1.4-m wind at camp.
[2] Calculated from FFMC at 1300 h and adjusted stand wind
[3] Combined wood and duff from Table 7
[4] Includes 0-.64 cm. crown weight from Table 5 (6.87 t/ha)
[5] Based on heat of combustion 18400 J/g.

Table 5. Dead surface fuels consumed by fires on Darwin Lake units

Unit	Weight of Woody Fuel by diameter class (cm)								Duff[1]	
	0-.2	.21-.5	.51-1.0	1.1-3	3.1-10	All ≤10	>10	Total	Weight	Depth of burn
	t/ha[2] percent of prefire (second line)									cm
1	.16	.41	.13	(.30)[3]	.94	1.94	1.35	3.29	--	.5
	70	52	57	125	40	50	20	31	--	28
2	.29	.88	.23	.47	2.09	3.96	5.62	9.58	14.3	.9
	88	92	82	64	56	65	41	48	68	50
3	.30	.44	.07	.26	4.19	5.26	2.83	8.09	--	.8
	98	85	37	19	64	59	47	54	--	50
4A	.36	1.10	.31	.57	0	2.34	2.89	5.23	10.2	(1.8)[3]
	100	100	84	50	0	41	64	51	68	120
4B	.37	.88	.26	.27	3.32	5.10	3.26	8.36	10.2	(1.8)[3]
	100	100	81	28	56	60	59	60	68	120
6	- - - -		5.66[4]	- - - -	1.71	7.37	8.85	16.22	16.1	1.6
			100		16	45	41	43	76	62
7	- - - -		3.57[4]	- - - -	4.96	8.53	4.52	13.05	7.2	1.5
			100		59	71	30	48	36	62

[1] Includes some living mosses, lichens, and creeping vascular plants.
[2] 1 t/ha = .45 short ton/acre.
[3] Values in parentheses are increases over prefire weights and depths (see text).
[4] Material ≤3 cm not tallied after burning; loss estimated to be 100%.

some addition of surface fuel did occur through burning down of dead standing trees. On Unit 4 (A and B) measured depth of burn exceeded initial depth of forest floor, presumably because of actual variation in forest floor thickness from point to point. Percentage reduction in weight should roughly represent depth of burn. It is safe to say that at least two-thirds of woody material ≤3 cm in diameter burned when FWI was above the "Low" range - i.e., on all units except 1. Percentages for larger material varied unsystematically with size class and FWI.

Weight of woody material consumed bore a strong (r=.94), straight-line relation to initial loading, expressed by the regression equation $y=0.42+.44X$ (Figure 11). The relationship for all dead surface fuel consumed was weaker because of relatively light duff loadings and the presence of thick bearberry mats that may have affected depth of burn.

DISCUSSION

The stable, drying air mass that developed and persisted from August 1 to August 6 allowed four burns of high vigor, culminating with a crown fire on Unit 6. Comparing Darwin Lake results with similar burns at the Petawawa Forest Experimental Station (Van Wagner 1973), it can be hypothesized that fires in upland jack pine behave similarily across the range of the species. The regressions of rate of spread on ISI are very similar, emphasizing the

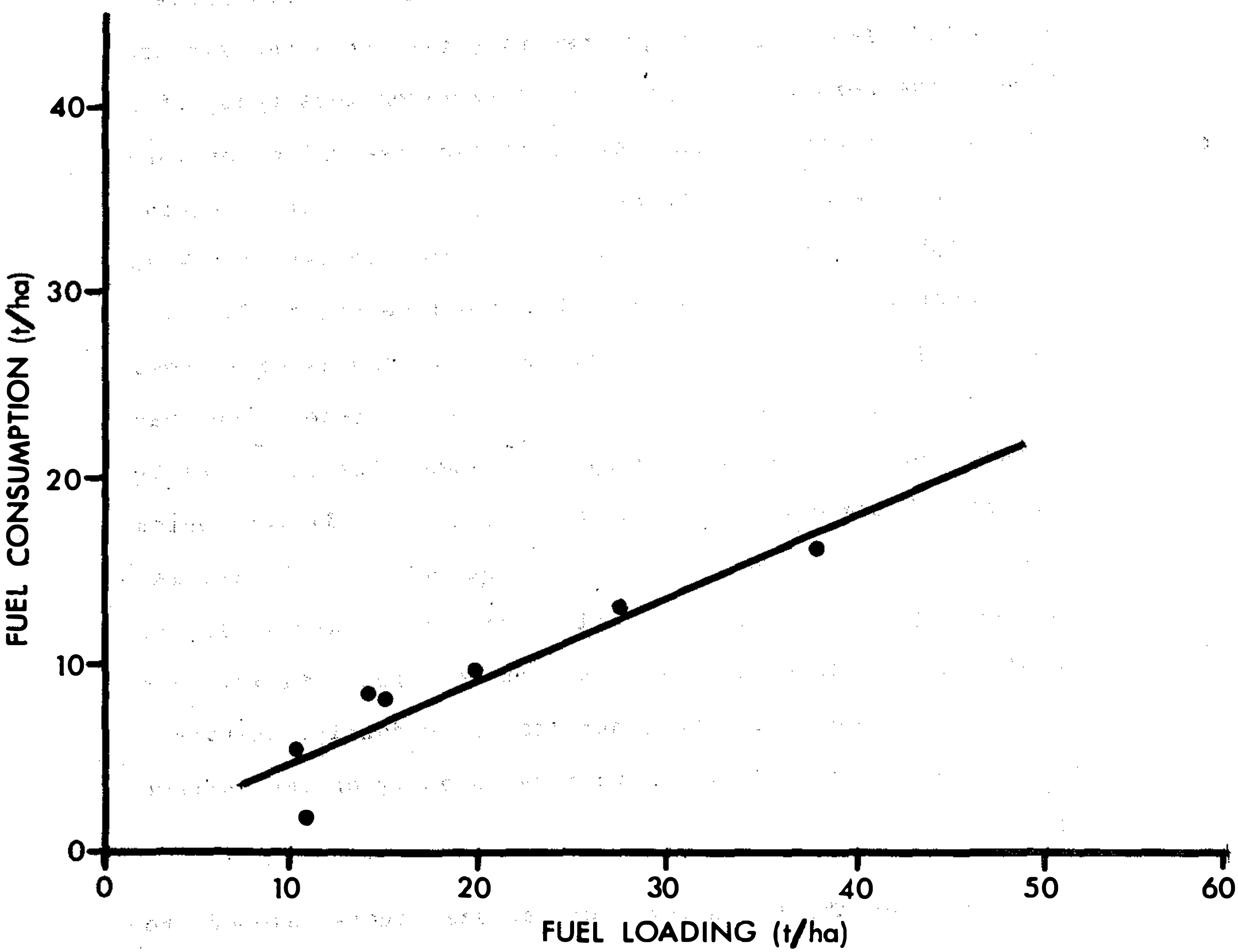

Figure 11. Relation of Woody Surface Fuel Consumption to Loading

relevance of the weather parameters integrated by the ISI.

On-site observations and examination of a series of 35 mm slides provided several interesting fire behavior descriptions of surface to crown interaction. Crown involvement ranged from a silent flash in the beard lichens to a solid flame front of greater intensity than the surface fire. Flame height on units 1 and 3 averaged less than .5 m yet the lichens carried flame into the tree crown for very brief periods. Bark flakes on Units 4A and 4B were burning the length of the trees and out into the branches, but even an intense core of fire surrounding the tree trunk for its full length was not enough to torch out the average tree. Full crowning developed only when the surface fire was intense and continuous enough to preheat the lower needle foliage and branchwood over a large area, a condition which occurred only on Unit 6. Flame heights of the initial surface fire on Unit 6 were well into the canopy layer, resulting in simultaneous ignition of bark flakes and needles. Although the fire front leaned slightly downwind, the crown fire did not move independently of the surface fire.

Stand density and height of aerial fuels seemed to affect crown involvement significantly during moderate and high hazard burns. Plots 4A and 4B were of mixed density, and height and fire behavior differences were noted at the fuel type boundaries. The west side of the plots was denser, and ladder fuels extended to within a metre of the ground.

Fire spread was slower and more uniform in this area, with very little torching, presumably a result of higher moisture contents from shade effect. On the more open east side of the plots spread was faster and the surface fire more intense, which promoted torching even though ladder fuels were higher and less concentrated horizontally. In the extreme hazard, on Unit 6, crowning occurred throughout the plot regardless of density and crown height variations.

The experimental fires spread at rates that were correlated significantly with elements of the Canadian FWI. Because wind speed was low and varied little from one burning day to another, FFMC was the best base-station predictor of spread. The ISI recalculated to the sites and times of fires yielded a slightly stronger correlation than did ISI in camp at 1300 h. The relationship of rate of spread to ISI resembled that found in other studies, but the data were too limited to support safe numerical prediction. The same shortage of data prevented separating the effects of fuel moisture and fuel loading, which were confounded by the sequence of burning. Of the two factors, moisture appeared to have much the stronger influence on rate of spread.

Better understanding of the phenomenon of crowning emerged from the project, as a result of the steady progression of fire vigor up to the crowning threshold. Fire followed beard lichens into the tree crowns at all values of FWI and its separate elements, and bark flakes became effective ladder fuel at about FFMC 90. However, crown materials themselves -- foliage, twigs, branches -- were not ignited consistently by even hotly flaming bark all along trunks and major branches. A relatively high-intensity surface fire, at FWI 28, was the triggering mechanism for the general crown fire on unit 6. Significant variation in wind, which was not involved at Darwin Lake, would complicate the prediction problem.

Jack pine needles had the same moisture content, and the amount of dead crown material was essentially the same on all units. Thus, crowning at Darwin Lake was strictly a function of dead surface fuel quantity and geometry, moisture content, and to a lesser extent, wind.

The foregoing study confirmed the fact that the behavior of fire in natural fuels is an exceedingly complex process that is influenced by many critical factors, singly and collectively. Continuing observations over the full range of prescribed burns and wildfires are necessary to determine fire behavior prediction criteria and guidelines for use in fire management.

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APPENDIX I -- General Vegetation Description

History -- Past forest fires in the nearly pure jack pine forest on upland in the study area were largely responsible for the mosaic of stands having different combinations of age, height, and density. The oldest trees occur as scattered individuals in the more open stands (A1P, A2P). The two oldest found were 198 and 200 yr old, suggesting a fire around 1770. Enough fire scars were aged to definitely identify fires in the early 1820's, 1843, 1865, 1887, 1906, and 1944. The 1843 fire apparently gave rise to the B2P stands in study units 1, 2, 6, and 7; and the B1P and C1P stands containing units 3-5 apparently originated after the 1906 fire. The 1944 fire was widespread in the region; on the study area it burned with low intensity, scarring many trees but killing few even in the young stands resulting from the 1906 fire. A higher-intensity phase of this same fire may have produced the extensive young (B0P) stands north of the study area.

Forest stand -- Burning units occupied essentially two situations in the forest mosaic: (1) stands typed B1P and C1P, 60+ yr old, averaging 2189 trees/ha (886/acre) with mean dbh 9.9 cm (3.9 in.); and (2) stands typed B2P, 125+ yr old, with 655 trees/ha (265/acre) and mean dbh 17.9 cm (7.0 in.) (Table 6). Mean basal area did not differ appreciably between the two general types -- 16.5 vs. 16.2 m^2/ha (71.9 vs. 70.6 ft^2/acre). Variations in stocking and mean dbh reflect the inclusion of occasional small openings and dense clumps of smaller-than-average trees. The measurement grids of units 1-7 occupied the more uniform portions of the stands, hence tended to have greater densities than the entire mapped stands--well over 50% for all of the B1P and C1P, and 40-50% for the B2P. Heights of dominants were close to 12 m (40 ft) in the B1P and C1P types and around 19 m (62 ft) in the B2P type. Standing dead trees were few and scattered, as were the small living aspen and birch. More conifer reproduction (virtually all jack pine) occurred in the older stands (444/ha vs. 218/ha; 178/acre vs. 87/acre), more hardwood (all aspen and white birch) in the younger (1456/ha vs. 300/ha; 582/acre vs. 120/acre).

Shrubs -- Twelve[1] shrub species occurred on the burning units, and five of these were ericaceous. Only ericads had frequencies greater than 40% on any unit, and one or the other of two prostrate species was most frequent, and estimated to be most important, on every unit: dry-ground cranberry on units 4-7, and bearberry on units 1-3 (and second in importance on units 4-7). These two species were usually closely associated and together provided average cover of 27%. No other shrub species averaged as much as 1% cover on any unit. As expected, more shrub species occurred on the larger plots, and mean height increased with the frequency of Alnus, Amelanchier, and Prunus.

[1]Aspen reproduction was considered a component of the shrub layer.

Table 6. Forest stand on the Darwin Lake experimental units

Unit	Jack pine				Other species[1]		Basal area
	Living		Dead				
	Trees /ha	Mean dbh	Trees /ha	Mean dbh	Trees /ha	Mean dbh	
	No.	cm	No.	cm	No.	cm	m²/ha
1	764	15.9	34	17.6	0	-	15.09
2	731	18.1	60	10.2	0	-	18.66
3	2,417	10.0	0	-	0	-	18.75
4	1,877	10.7	0	-	85/0	7.3/-	16.62
5	2,272	8.9	0	-	53/48	8.7/7.4	14.05
6	532	18.4	4	20.0	7/65	4.8/4.0	14.03
7	594	19.2	0	-	0	-	16.98

[1] Aspen/white birch

Herbs -- Thirteen herbaceous species (counting *Pyrola* as a single species) plus various unidentified representatives of the genus *Carex* and the *Gramineae* were present on the experimental units. The number of species on any one unit ranged from 6 to 11. *Anemone multifida*, *Linnea borealis*, *Maianthemum canadense*, and *Gramineae* occurred on all units; *Geocaulon lividum* and *Pyrola* spp. on all but one; and *Cornus canadensis* on all but two. The other species were sporadic. Cover by all species combined averaged only about 2%, and mean heights only 2.4-8.2 cm (.94-3.23 in.). Lichens, mainly *Cladonia* and *Alectoria* spp., were the most conspicuous quasi-herbaceous ground cover, with frequency averaging 79% and cover 13%. Mosses had nearly as high frequency (67%) but covered much less area (2%). Litter was exposed, without covering vegetation, on 27-59% of the area (average 47%).

APPENDIX II -- Synoptic Weather

Prior to July 17. A cold low moving through northeastern British Columbia had an associated surface and upper air trough moving through northern Alberta. This system brought extensive rain to the Darwin Lake area, and the FWI dropped to 0.

July 18 to 20. The cold trough was actually dumbbelling around the cold core off the Queen Charlotte Islands. This cold core drifted inland over British Columbia. On July 18 and 19 a moist, unstable flow aloft on the east side of the cold core brought afternoon showers and thundershowers to the Darwin Lake area. Finally the cold trough had moved far enough inland to set off a vigorous surface low that moved through Darwin Lake on the evening of the 19th. This system produced a line of thunderheads which had heavy rain and hail associated, and was reponsible for giving the study area a thorough soaking.

July 21 to 24. During most of this period a weak high pressure ridge at the 500 mb level drifted across northern Alberta, and a surface low developed in the Northwest Territories around Great Bear Lake. The resulting southwesterly surface flow over Darwin Lake was quite unstable and gave gusty surface winds. The lake was very choppy during this period, and aircraft on one or two occasions had difficulty landing and taking off. Cumulonimbus and Towering Cumulus were evident during the afternoons. The FWI rose rapidly; burns were executed on

July 23 and 24. This was the windiest period of the entire project, mainly on account of the unstable air mass and the southwesterly gradient.

July 25 to 30. The cold front and associated showers that moved through the Darwin Lake area late on the 24th and early 25th brought an end to any hopes for further burns for a few days. The huge rain area in the lower Mackenzie (Fig. 5) moved southeastward but missed the Darwin Lake area. However, northeastern Alberta was in a cool moist, northwesterly flow. The troublesome feature aloft was a cool trough persisting over Great Slave Lake. This trough finally slipped south of the Darwin Lake area by July 30.

July 31 to August 2. A 500 mb ridge moved into the area east of Great Slave Lake as the cool trough slipped southward into Alberta. This brought about drying at upper levels and also the establishment of a flat-surface high pressure area. Although skies were mainly clear throughout much of this period, the light easterly circulation was not conducive to warming the lower atmosphere.

August 3 to 6. A warm, flat, high pressure ridge aloft during this period was accompanied by subsidence, resulting in a fairly stable air mass. With a flat surface low in the upper Mackenzie Valley, a warm southerly flow developed over the Darwin Lake area. Owing to the stability of the air mass, however, winds remained quite light. The FWI remained extreme and the highest value, 28, was recorded on August 5.

August 7 to 10. The ridge aloft that gave the warm dry weather early in the month gradually moved eastward as a vigorous low aloft moved inland from the Pacific. This spawned surface systems that moved northeastward through the upper Mackenzie Valley and northwestern Alberta. Although the main shower area remained well west of the Darwin Lake area, the air mass became much more unstable as cooler air moved in around the upper low. Increasing convective activity, culminating with the afternoon thundershower of August 7 (which put out the unit 5 fire in progress), marked the end of the project. The surface trough moved by on August 8 and was followed by a cool northwesterly flow which persisted until the middle of the month.

APPENDIX III - Details of Individual Fires

Unit 1 -- The fire spread readily across litter and *Cladonia* only when pushed by small gusts. Spread became slower with the passage of time because average wind speed in the stand decreased from 4.8 km/h (3 mph) to less than 3.2 km/h (2 mph). Rates observed for 20 and 50 min at two points averaged .6 m/min (2 ft/min). The extensive mats of bearberry and dry-ground cranberry proved to be effective fire barriers, seldom being penetrated more than a few centimetres; consequently, the fire covered only 60% of the unit. Flames exceeded a few centimetres in height only in the occasional small concentrations of woody fuels and in the lowest, lichen-covered, dead branches of few young trees. The fallen trunks of several long-dead trees smoldered overnight and in the end were almost totally consumed. At least one standing dead tree burned down overnight.

Unit 2 -- The first attempt to burn this unit showed that the strongest wind during the study blowing upslope from the east could not cause fire to spread in the face of high fuel moisture content and humidity. The second (successful) attempt also started to use the slope along the east edge; but a very light, on-shore breeze shifted to steady southwesterly, and ignition was shifted to the western boundary of the unit. Fire spread was slow but rather steady, averaging about .9 m/min (3.0 ft/min) over a 40-min period. Flames were generally ≤60 cm (2 ft) high. A few trees torched, and one spot fire occurred within the unit. Some of the denser patches of bearberry did not burn, but the fire covered 84% of the unit and scorched the surface vegetation on another 5%. In the absence of a fire line, the northeast corner of the fire burned into a small muskeg bordering the lake and produced an active flame front in Labrador tea (__Ledum groenlandicum__) that moved about 6 m (20 ft) before subsiding.

__Unit 3__ -- Getting the headfire started across this unit proved unexpectedly difficult because of a combination of minor fuel discontinuities and variable wind. High stand density and minor topographic features appeared to have a disproportionate effect on wind direction and velocity. However, the fire ultimately burned over virtually 100% of the surface, 72% of which was bare litter and Cladonia. Spread was slow; the average rate was 1 m/min (3.3 ft/min) at six points observed for 5-27 min each. Flames generally were ≤.6 m (2 ft) high, but brief flare-ups occurred in occasional patches of fine dead fuels, low brush, and small pines. Some very short-range spotting occurred just ahead of the fire front. Fire not uncommonly ran to the tops of pines in the abundant, epidendric beard lichens and bark flakes, but almost never involved other aerial fuels. Burning was shallow; the fire merely passed over the surface of a squirrel cache that would be expected to smolder for days under drier conditions.

__Unit 4A__ -- A gentle, steady, southerly wind dictated ignition across the south boundary of the unit, with the fire advancing parallel to the long axis of the measurement grid. Some variation in wind speed and direction was noted outside the unit, but southerly flow at an average of 3.2 km/h (2.0 mph) was measured 1.5 m (5 ft) above ground over a 2-h period. Fire spread was correspondingly steady, averaging 2.0 m/min (6.5 ft/min) (Fig. 8). Spread tended to be slowest toward the western edge because of high stand density. Fire frequently burned into the crowns, using epidendric lichens and bark flakes as ladder fuels. Occasionally enough heat was generated to torch out the green foliage. Short-range spotting occurred around hotspots. Essentially the entire surface area burned over. Fire behavior was so consistent that burning was terminated in order to provide an additional observation in the same fuels but with different weather.

Unit 4B -- A 14% drop in relative humidity (to 26%) was the main change from the conditions that had affected unit 4A. Wind speed at 1.5 m (5 ft) increased slightly during the latter part of the fire; however, the 2 km/h mean wind speed was similar to unit 4A. Rate of fire spread increased to a mean of 3.35 m/min (11.0 ft/min), with a range of .4-6.7 m/min (1.3-21.8 ft/min). Increased fire intensity was apparent from taller flames and faster spread immediately upon ignition, with open conditions contributing to increased fire vigor. Torching of crowns was common, and mass torching occurred when the fire reached a slight depression containing more woody surface fuel than usual for the unit as a whole. Every case of torching resulted in abundant spotfires, which considerably increased spread rate over that attained through continuous spread in surface fuel.

Unit 5 -- The first attempt to burn was aborted moments before ignition because of a reported wildfire that might require attack by the project fire crew. On the second attempt, one day later, the east edge was ignited in spite of a threatening thundershower, and the fire began to spread evenly. However, the shower arrived less than half an hour later, humidity quickly rose to 90% (from 40%), temperature fell to 17°C, and 1.8 mm of rain fell. As a result, half of the unit did not burn at all, and the fire was spotty on the remainder, missing 30% entirely and merely scorching another 20%. No rate-of-spread estimates were obtained.

Unit 6 -- Weather was essentially a continuation of that in effect for unit 4B; temperature was 1°F lower and relative humidity 7% higher (33%). Before ignition virtual calm prevailed at the 1.5-m (5-ft) level on the unit, increasing to 6.4 km/h (4 mph) during the fire. Despite the relative scarcity of low, dead branches draped with lichens on the 20-m-tall (66-ft.) trees, a crown fire developed almost immediately. Flames were about 30 m (98 ft) high, 10 m (33 ft) higher than the trees. Rapid development of the crownfire prevented reliable estimation of fire spread except for the plot as a whole. However, by quite conservative estimate, the fire moved 160 m (525 ft) across the unit in about 26 min, giving an average rate of spread of 6.1 m/min (20 ft/min). Spread was essentially a function of heavier fuel loading -- the heaviest on any unit for all fuel categories (Table 2). Surface wind accelerated as fire intensity increased but appeared to be mainly in-draft. Wind of 8-16 km/h (5-10 mph) at tree-top level may have encouraged crowning. Only a few rocky and/or moist spots on the ground surface failed to burn -- less than 2%. Spotting and high fire intensity resulted in a small, quickly controlled escape along part of the north unit boundary.

Unit 7 -- Passage of a weak cold front signalled the arrival of a cooler airmass and was accompanied by light showers that missed the study area to the north. Midday temperature dropped to 23°C from the preceding day, and relative humidity rose 13% (to 46%). However, fuelstick moisture content did not change, and only 1- and 2-point drops occurred in FFMC and FWI, respectively. Wind shifted to slightly west of south (200°) and was steady at 12.8-16.0 km/h (8-10 mph) from the surface to 1000 m (3300 ft). At the unit, 1.5 m (5 ft) wind averaged 3.5 km/h (2.2 mph). Ignition began at the south corner and proceeded both ways. Spread was brisk along the southwest side where exposure to wind was greatest. Limited crowning occurred in the northwest quarter of the unit, but elsewhere steady surface fire prevailed. Mean rate of spread was 1.98 m/min (6.5 ft/min). The fire burned over 85% of the surface and scorched another 5%. Extensive ground cover (27%) by bearberry and dry-ground cranberry noticeably reduced fire spread rate and coverage. Numerous small spot fires developed just outside the windward side of the unit, and the only long-range spot of the study, 140 m (459 ft) distant. The helicopter-with-bucket assigned to the project facilitated control of the spot fire.

Unit 8 -- One line of fire was set to see if it would run across a small muskeg. In addition, two spot ignitions were studied through the afternoon burning period (1300-1900 h) on August 8. The showery weather that prevented a satisfactory burn of unit 5 had raised fuel moisture and lowered elements of FWI to about the levels that had prevailed during the first successful burns (Table 4). The line fire (No. 9, for convenience) spread at an average rate of 1.6 m/min (5.4 ft/min), with a range of .6-3.1 m/min (1.9-10.2 ft/min). As on unit 2, the fire ran perhaps 10 m (33 ft) into the muskeg but did not cross it completely and did not burn deep into the organic layer. Spotfire No. 10, on dry upland, attained a final size of about 1.3 ha (3.3 acres) at 1900, with an average rate of spread along the cardinal directions of 12.6 m/h (41 ft/h). Sample rates measured between 1350 and 1610 along the more active north and east vectors averaged .4 m/min (1.4 ft/min), with a range of .2-.9 m/min (.5-2.9 ft/min). The outline was fairly regular in a somewhat ovate ellipse. Spotfire No. 11 was set in a lower, moister, more sheltered situation, where the small, dense jack pine had a heavier understory. The resulting shape was quite irregular, with a maximum dimension at 1900 of slightly less than 30 m (160 ft), and an area of perhaps .1 ha (.25 acre). Rate of spread for a 5-h period was 3.4 m/h (11.2 ft/h).