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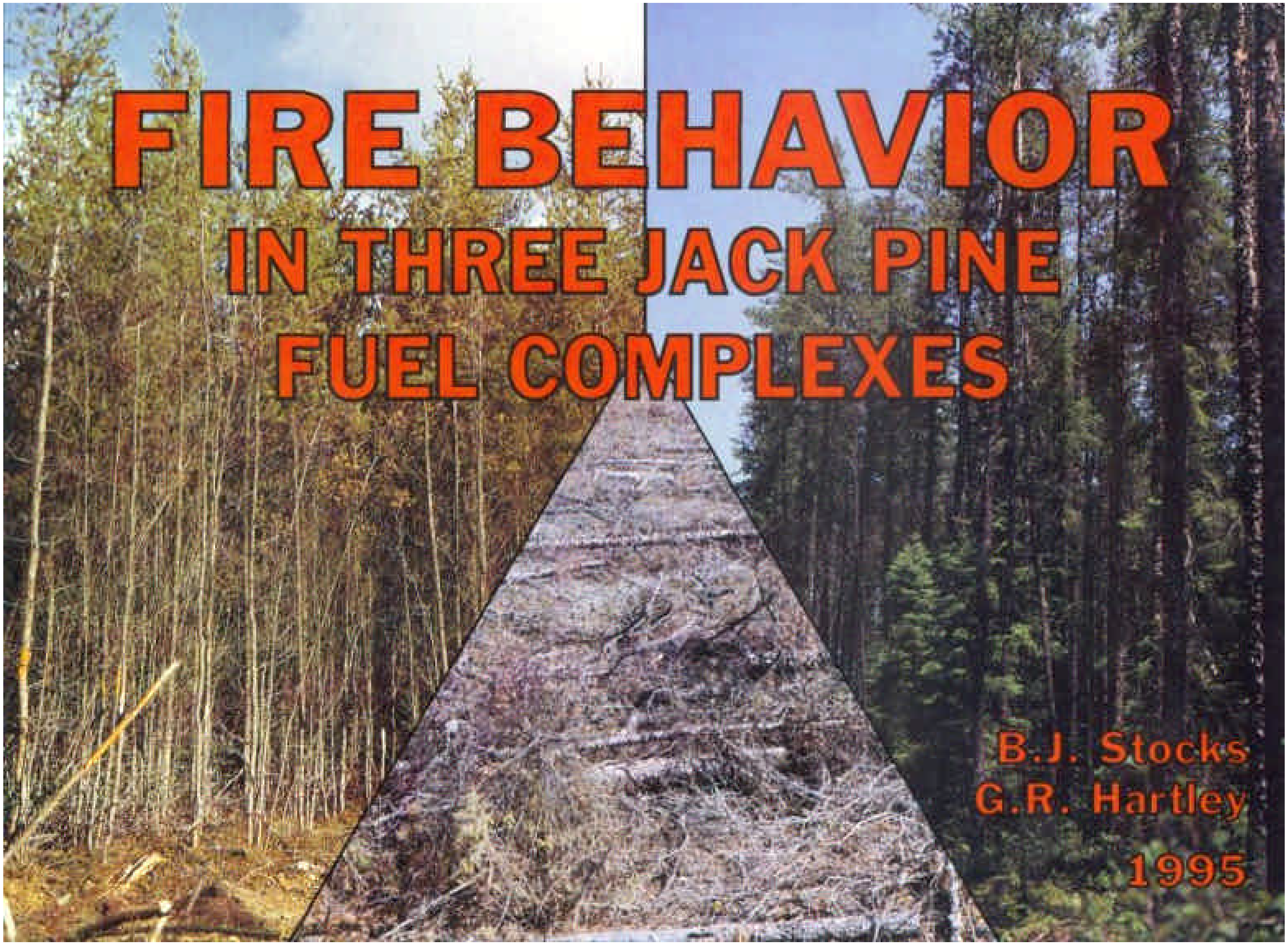

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Introduction

Sound forest fire management decision-making requires a thorough knowledge of forest fire behavior, as influenced by weather, fuels, and topography. However forest fires are complex phenomena that are not easily monitored or documented, and this has slowed the gathering of quantitative data on forest fires that could be translated into decision-making aids for fire managers. Over the past quarter century, Canadian forest fire research scientists have addressed this problem by gathering empirical data on selected wildfires (e.g., Stocks and Walker 1973; Stocks 1975; Alexander et al. 1983; Alexander and Lanoville 1987; Stocks and Flannigan 1987), while concurrently undertaking an ambitious experimental burning program (summarized in McAlpine et al. 1990), with the cooperation of provincial and territorial fire management agencies, aimed at developing quantitative, fuel type-specific fire behavior models for major Canadian forest fuel types. Fire researchers with the Canadian Forest Service (CFS) Ontario Region and fire management personnel with the Ontario Ministry of Natural Resources (OMNR) have worked closely in this undertaking. Experimental burning programs have been completed in jack pine (*Pinus banksiana* Lamb.) logging slash (Stocks and Walker 1972; McRae 1986), boreal mixedwood slash (McRae 1985), immature jack pine (Stocks 1987*b*), mature jack pine (Stocks 1989), and spruce budworm-killed balsam fir (*Abies balsamea* (L.) Mill.) (Stocks 1987*a*). The practical result of this extensive Canadian burning program is the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), a major subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS) (Canadian Forestry Service 1987; Stocks et al. 1989), which is in universal use throughout Canada and in selected countries internationally.

In addition to publishing research results in the scientific literature, Canadian fire researchers have been producing a number of posters for interpretive purposes. These include posters on wildfire occurrence and fire climate patterns (Simard 1973, 1975; Stocks and Hartley 1979), FBP System fuel types (De Groot 1993), ignition probabilities (Lawson et al. 1994), and fire behavior prediction (Alexander and De Groot 1988; Alexander and Lanoville 1989; Alexander et al. 1989). This poster follows that pattern, visually depicting the range of fire behavior exhibited during the Ontario experimental burning programs conducted in three distinct jack pine fuel complexes: logging slash, mature stands, and immature stands.

Methods

Burning Plot Location and Description

Experimental burning sites were selected after consultation with the OMNR fire managers responsible for the ignition, control and suppression of each experimental fire. In 1970 and 1971, a series of 24 burning plots was established at two jack pine logging slash sites located near Matheson in northeastern Ontario. The partially needle-bearing slash fuels resulted from clearcut logging of mature, well-stocked jack pine on the sites 1-2 years earlier. An additional 24 plots were established in a mature (1899-origin), well-stocked (2,000 stems/ha) jack pine stand near White River in north-central Ontario in 1972. This stand averaged 18-20 m in height with a well-developed black spruce (*Picea mariana* (Mill.) B.S.P.) understory (1,100 stems/ha). A further series of 22 burning plots was established in an immature (1948-origin) jack pine stand north of Thessalon in central Ontario in 1973. This was a very dense stand, averaging 10 m in height with approximately 9,000 live and 10,000 dead stems/ha. Additional burning plots were established on this site in 1985. Each of the three experimental burning sites had a well-developed forest floor consisting of feather mosses (*Pleurozium schreberi* (B.S.B.) Mitt. and *Hylocomium splendens* (Hedw.) G.S.G.) over decomposing organic material. Burning plots were located on level ground to eliminate the influence of slope on fire behavior. Each burning plot was 0.4 ha in area (approximately 40 x 100 m), surrounded by a fire line 5-20 m wide, bulldozed to mineral soil. Where possible, plots were oriented to take advantage of prevailing (usually southwesterly) winds.

Fire Weather Monitoring, Fuel Sampling and Fire Behavior Documentation

Comprehensive preburn sampling of all fuels was undertaken on each burning plot. This included detailed inventorying of forest floor organic material in order to determine fuel loads by depth, sampling of downed woody surface fuel and shrub and herbaceous vegetation, and determination of crown fuel weights through destructive sampling. Average fuel loads (kg/m²) are summarized in the accompanying table.

Fuel Complex	Forest Floor	Surface	Crown	Total
Clearcut logging slash	8.1	5.5	-	13.6
Mature stand	6.5	1.4	1.0	8.9
Immature stand	4.6	2.2	1.4	8.2

A complete fire weather station was established and maintained on each site, and continuous daily 1200 LST observations of dry-bulb temperature, relative humidity, 10-m open wind speed and precipitation were taken from May to August each year in order to calculate the codes and indices of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). Experimental burns were scheduled under as broad a range of fire weather conditions as possible, as reflected by FWI System components.

All experimental fires were ignited along the upwind edge of the plot, and allowed to burn freely with the wind. The forward rate of spread of each fire was measured at grid points throughout each plot by means of both visual observation and the use of electronic recording devices buried in mineral soil. Recording anemometers were used to make continuous observations of 10-m open windspeed throughout each fire. In addition, all fires were documents from ground, tower, or helicopter locations using slide and movie film.

After each fire, crown and surface fuels were re-inventoried to determine fuel consumption levels in these strata. Depth of burn pins located systematically throughout each plot were used to determine an average depth of burn for each fire, and this was converted to an organic layer fuel consumption value using prefire forest floor bulk density data.

The following equation (Byram 1959) was used to calculate the frontal intensity of each headfire (I) in kW/m:

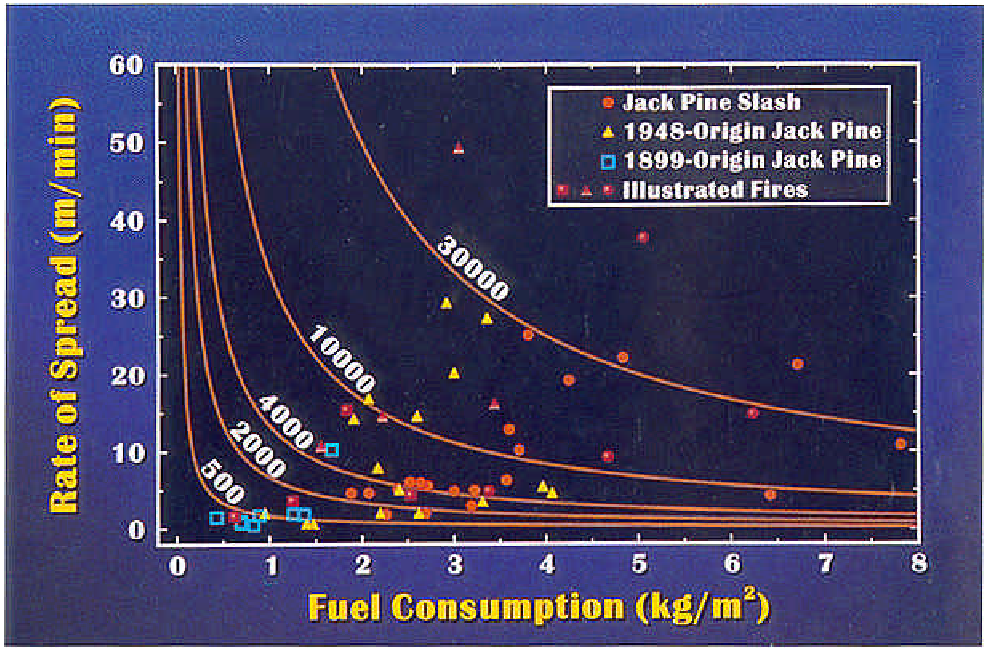
$I=Hwr$

where H is the fuel low heat of combustion (kJ/kg), w is the quantity of fuel consumed during the passage of the flame front (kg/m^2), and r is the linear rate of fire spread (m/s). An H value of 18000 kJ/kg was used for all fires, and all fuel consumption was assumed to have taken place in the flaming front.

Results and Discussion

During the summers of 1970 and 1971, a total of 24 successful experimental fires were carried in jack pine logging slash fuels in northeastern Ontario (Stocks and Walker 1972). However, the burning programs in mature and immature jack pine took much longer to complete, primarily due to a combination of poor burning weather and resource-consuming wildfire situations. Between 1973 and 1983, a series of 12 experimental fires was conducted at the mature jack pine site (Stocks 1989), while an additional 12 experimental fires were carried out at the immature jack pine site during the 1975-81 period (Stocks 1987*b*). Some additional fires were conducted at the immature jack pine site during the 1988-91 period, although the fuel complex was altered somewhat by this time through self-thinning, averaging 14 m in height with approximately 4300 living and 3800 dead stems/ha.

The fire behavior characteristics chart (Andrews and Rothermel 1982; Alexander et al. 1991) provides a useful means of visualizing the relative contribution of the two main variables influencing frontal fire intensity. ON the accompanying graph, rate of spread and fuel consumption data are plotted, relative to five distinct levels of frontal fire intensity, for all Ontario jack pine slash and mature and immature jack pine experimental fires. An additional eight fires, carried out at the 1948-origin jack pine site in the 1988-91 period, but not previously reported in the literature, are also included on this graph. As the Ontario experimental burning program was designed so burns were conducted under a broad range of weather, fuel moisture and fire danger conditions, it is not surprising that the fire behavior exhibited in each fuel type varied widely. The fires selected for display in this poster were intended to cover this range in fire behavior, and these fires are separately identified on the fire behavior characteristics chart.



Ontario experimental line-ignition fires plotted as a function of head fire spread rate and fuel consumption in relation to five distinct levels of frontal fire intensity based on experimental fires in three Ontario jack pine fuel complexes.

The Ontario jack pine slash fires, in which large quantities of dead fuel were distributed close to the ground, often generated substantial frontal fire intensity levels due to a high degree of fuel consumption (generally 2-7 kg/m^2) in combination with significant spread rates. In the immature jack pine fuel complex, the dense nature of the stand and vertical fuel continuity resulted in crowning at lower fire danger levels than is the case with mature jack pine. Intermittent crown fires, with intensity levels above 5,000 kW/m occur with forward spread rates of 10 m/min, while fully-developed crown fires (intensities above

10,000 kW/m) occur when spread rates approach 15 m/min, assuming fuel consumption levels above 2 kg/m². In the mature jack pine fuel complex low to moderate intensity surface fires were common, as there was a large gap between surface and crown fuels, making the transition from surface to crown fire more difficult. Vigorous surface fires with intermittent crowning were achieved, however, indicating that full-developed crown fires in this fuel type, with frontal fire intensity levels above 10,000 kW/m are possible when spread rates approach 20 m/min and fuel consumption levels are between 2 and 3 kg/m², with e multi-layered black spruce understory contributing significantly to this process.

Concluding Remarks

Experimental fires, although generally smaller in scale than wildfires, permit a degree of sampling and monitoring that is impossible with wildfires, due to access and control difficulties. Wildfires, however, represent real-world, larger-scale situations, making even general wildfire information valuable. Canadian fire researchers strongly believe that merging general wildfire information with specific, detailed data from experimental fires provides the best and most practical method of modeling fire behavior in Canadian forests.

This series of experimental fires demonstrated quite conclusively that certain components of the FWI System are very useful as predictor in the estimation of fire behavior and impact characteristics in the three jack pine fuel complexes studies in Ontario. The initial Spread Index (ISI) is strongly correlated with headfire spread rate, and the Buildup Index (BUI) correlates well with fuel consumption, particularly for ground and surface fuels. These relationships were central to the development of the Canadian FBP System, the core of which is a series of fuel-specific fire behavior models that predict, in absolute terms, forward rate of spread, fuel consumption, and fireline intensity for 16 prominent Canadian fuel types. A significant portion of the experimental fire data used in developing the FBP System have been produced through the cooperative experimental burning program carried out in important Ontario fuel types over the past 24 years.

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The Ontario experimental burning program would not have been possible without the cooperation and logistical support of numerous OMNR fire management personnel at the provincial, regional, and district levels in the planning and conduction of all fires. The forward-looking recognition by OMNR fire managers of the need for this type of burning program in order to secure answers to important fire behavior questions is greatly appreciated.

Jack Pine Logging Slash

Experimental Fire #: 11/71 **Date:** August 25, 1971

Fire Weather Observations

Dry-bulb temperature	16.1°C
Relative humidity	45%
10-m open wind	10 km/h
Days since rain	2

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	86.4
Duff Moisture Code (DMC)	15
Drought Code (DC)	238

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	4.5
Buildup Index (BUI)	26
Fire Weather Index (FWI)	8

Fire Behavior Characteristics

Head fire rate of spread	4.8 m/min
Fuel Consumption	3.38 kg/m^2
Frontal fire intensity	4867 kW/m

Experimental Fire #: 5/71 **Date:** July 11, 1971

Fire Weather Observations

Dry-bulb temperature	18.9°C
Relative humidity	49%
10-m open wind	19 km/h
Days since rain	2

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	87.3
Duff Moisture Code (DMC)	27
Drought Code (DC)	222

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	7.7
Buildup Index (BUI)	42
Fire Weather Index (FWI)	17

Fire Behavior Characteristics

Head fire rate of spread	9.2 m/min
Fuel Consumption	4.67 kg/m^2
Frontal fire intensity	12 889 kW/m

Experimental Fire #: 4/71 **Date:** July 7, 1971

Fire Weather Observations

Dry-bulb temperature	18.3°C
Relative humidity	57%
10-m open wind	22 km/h
Days since rain	2

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	86.9
Duff Moisture Code (DMC)	22
Drought Code (DC)	193

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	8.6
Buildup Index (BUI)	34
Fire Weather Index (FWI)	16

Fire Behavior Characteristics

Head fire rate of spread	14.8 m/min
Fuel Consumption	6.24 kg/m^2
Frontal fire intensity	27 706 kW/m

Experimental Fire #: 3/71 **Date:** July 4, 1971

Fire Weather Observations

Dry-bulb temperature	27.2°C
Relative humidity	36%
10-m open wind	26 km/h
Days since rain	3

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	90.8
Duff Moisture Code (DMC)	20
Drought Code (DC)	171

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	17.6
Buildup Index (BUI)	30
Fire Weather Index (FWI)	26

Fire Behavior Characteristics

Head fire rate of spread	37.7 m/min
Fuel Consumption	5.06 kg/m^2
Frontal fire intensity	57 229 kW/m

1899-Origin Jack Pine

Experimental Fire #: 2/76 **Date:** May 26, 1976

Fire Weather Observations

Dry-bulb temperature	20°C
Relative humidity	33%
10-m open wind	11 km/h
Days since rain	9

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	7.7
Buildup Index (BUI)	28
Fire Weather Index (FWI)	14

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	90.2
Duff Moisture Code (DMC)	23
Drought Code (DC)	92

Fire Behavior Characteristics

Head fire rate of spread	1.6 m/min
Fuel Consumption	0.62 kg/m^2
Frontal fire intensity	298 kW/m

Type of Fire: Low intensity surface fire

Experimental Fire #: 11/71

Date: August 25, 1971

Fire Weather Observations

Dry-bulb temperature	29°C
Relative humidity	36%
10-m open wind	12 km/h
Days since rain	4

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	91.4
Duff Moisture Code (DMC)	34
Drought Code (DC)	169

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	9.6
Buildup Index (BUI)	46
Fire Weather Index (FWI)	20

Fire Behavior Characteristics

Head fire rate of spread	3.6 m/min
Fuel Consumption	1.25 kg/m^2
Frontal fire intensity	1350 kW/m

Type of Fire: Moderate intensity surface fire

Experimental Fire #: 1/79 **Date:** July 8, 1979

Fire Weather Observations

Dry-bulb temperature	27°C
Relative humidity	45%
10-m open wind	18 km/h
Days since rain	15

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	89.9
Duff Moisture Code (DMC)	42
Drought Code (DC)	145

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	10.5
Buildup Index (BUI)	49
Fire Weather Index (FWI)	22

Fire Behavior Characteristics

Head fire rate of spread	4.3 m/min
Fuel Consumption	2.53 kg/m^2
Frontal fire intensity	3264 kW/m

Type of Fire: Very active surface fire/intermittent crown fire

Experimental Fire #: 1/75

Date: May 17, 1975

Fire Weather Observations

Dry-bulb temperature	23.0°C
Relative humidity	39%
10-m open wind	29 km/h
Days since rain	6

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	89.5
Duff Moisture Code (DMC)	28
Drought Code (DC)	65

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	17.3
Buildup Index (BUI)	28
Fire Weather Index (FWI)	24

Fire Behavior Characteristics

Head fire rate of spread	15.4 m/min
Fuel Consumption	1.83 kg/m^2
Frontal fire intensity	8455 kW/m

Type of Fire: Intermittent crown fire

1948-Origin Jack Pine

Experimental Fire #: 1/75

Date: June 26, 1975

Fire Weather Observations

Dry-bulb temperature	25.5°C
Relative humidity	40%
10-m open wind	11 km/h
Days since rain	2

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	89.4
Duff Moisture Code (DMC)	25
Drought Code (DC)	73

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	6.8
Buildup Index (BUI)	27
Fire Weather Index (FWI)	12

Fire Behavior Characteristics

Head fire rate of spread	10.7 m/min
Fuel Consumption	1.55 kg/m^2
Frontal fire intensity	4976 kW/m

Type of Fire: Intermittent crown fire

Experimental Fire #: 5/75 **Date:** July 1, 1975

Fire Weather Observations

Dry-bulb temperature	29.5°C
Relative humidity	48%
10-m open wind	11 km/h
Days since rain	7

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	91.1
Duff Moisture Code (DMC)	48
Drought Code (DC)	117

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	8.7
Buildup Index (BUI)	48
Fire Weather Index (FWI)	19

Fire Behavior Characteristics

Head fire rate of spread	14.6 m/min
Fuel Consumption	2.22 kg/m^2
Frontal fire intensity	9724 kW/m

Type of fire: Intermittent/fully-developed crown fire

Experimental Fire #: 8/76 **Date:** July 9, 1976

Fire Weather Observations

Dry-bulb temperature	25°C
Relative humidity	40%
10-m open wind	15 km/h
Days since rain	2

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	8.7
Buildup Index (BUI)	67
Fire Weather Index (FWI)	23

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	89.7
Duff Moisture Code (DMC)	50
Drought Code (DC)	245

Fire Behavior Characteristics

Head fire rate of spread	16.2 m/min
Fuel Consumption	3.44 kg/m^2
Frontal fire intensity	16 718 kW/m

Type of Fire: Fully-developed crown fire

Experimental Fire #: 3/91 **Date:** June 19, 1991

Fire Weather Observations

Dry-bulb temperature	29.4°C
Relative humidity	26%
10-m open wind	19 km/h
Days since rain	4

FWI System Fuel Moisture Codes

Fine Fuel Moisture Code (FFMC)	93.4
Duff Moisture Code (DMC)	57
Drought Code (DC)	231

FWI System Fire Behavior Indices

Initial Spread Index (ISI)	17.8
Buildup Index (BUI)	70
Fire Weather Index (FWI)	39

Fire Behavior Characteristics

Head fire rate of spread	49.4 m/min
Fuel Consumption	3.05 kg/m^2
Frontal fire intensity	45 200 kW/m

Type of Fire: Fully-developed crown fire