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Influence of ignition type on fire behavior in semi-mature jack pine

**D.J. McRae, B.J. Stocks, G.R. Hartley, J.A. Mason, T.J. Lynham,
T.W. Blake and C.C. Hanes**



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The Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

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Foreword

The contents of this report are based on older data collected from 1984-1991, therefore the report is written based on the science at that time (~1995) and is a summary of our thoughts on this data alone.

Introduction

During the 1970s and 1980s fire behavior research in Canada focused on the development of empirical fire behavior models for important Canadian forest fuel types. In Ontario, experimental fires were conducted in jack pine (*Pinus banksiana* Lamb.) logging slash, mature (origin 1899) and immature jack pine (origin 1948) stands, and in spruce budworm-killed balsam fir stands. The experimental procedure involved establishing study plots and igniting these plots under a broad range of fire danger conditions while critical fire behavior parameters were measured (e.g., rates of spread, frontal fire intensity, and fuel consumption). At the time of these studies line-ignition was used to best permit the fire to reach an equilibrium (steady-state) rate of spread (ROS) quickly in an attempt to emulate a larger wildfire. These research projects were summarized in a number of papers including Stocks (1987a, 1987b, 1989); Stocks and Walker (1972); Stocks and Hartley (1995); and Van Wagner (1993). The data collected from these Ontario fires were combined with experimental fire data from other provinces (e.g., Lawson 1973; Quintilio et al. 1977; Alexander et al. 1991), and well-documented wildfires, to form the basis of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992).

The initial focus of studying fires burning under equilibrium conditions was important, as these are the fire behavior conditions that most challenge suppression efforts. However, fire acceleration, between a point-source ignition and the time when fire spread reaches equilibrium conditions, is also very important. This is what determines the time and urgency of getting initial attack resources to a fire, and helps with the prioritization of responses to multiple fire starts. Point-source fire growth has received much less attention with only a few Canadian studies conducted in lodgepole pine (*Pinus contorta* Dougl.) and black spruce (*Picea mariana* [Mill.] B.S.P.) (Lawson 1973; Kiil 1975; Alexander et al. 1991). Fire growth has been found to reach equilibrium conditions more slowly from a point-source ignition than from a line ignition (Cheney 1981; Johansen 1987; Weber 1989; Cheney et al. 1993). Many empirical studies have used line ignition techniques in order to reach equilibrium conditions quickly, yet most wildfires start initially as a small point-source ignition. With this in mind, it is important to understand fire growth from a point-source ignition, since it is often the only period of time that fire suppression resources can easily control a fire when fire danger is high.

Line-ignition experimental burning was conducted in jack pine stands in two locations in Ontario. A series of 12 fires were carried out between 1973 and 1983 at Kenshoe Lake near White River, Ontario. In these mature stands only intermittent crowning was observed, even under strong winds. The second study was in immature jack pine (Sharpsand Creek) approximately 60 km north of Thessalon, Ontario (Stocks 1987a). This jack pine stand, which originated naturally following the 1948 Chapleau-Mississauga fire (Stocks and Walker 1973), had undergone a natural thinning process, resulting in a very dense overstory of both living and dead stems. A series of 12 experimental fires were conducted at this site between 1975 and 1981. Most of them sustained high-intensity continuous crown fires, which developed even at low ambient wind speeds (10-15 km hr⁻¹). This is in contrast to the series of experimental fires conducted in mature jack pine stands (Stocks 1989). Spread rates and resulting head fire intensity levels were much higher in the immature jack pine fires. This difference in fire behavior was primarily due to the changed distribution of above-ground fuels as the jack pine stands matured. During the natural thinning process standing dead stems in the immature

stands, with an abundance of flakey bark and fine dead branch material, served as ladder fuels that promoted crown fire initiation. These dead stems were not present in the mature jack pine stand, which created a gap between surface and crown fuels that was difficult to bridge without very strong winds combined with very high surface fire intensity levels.

After the completion of the initial series of experimental line-ignition fires at both Kenshoe Lake and Sharpsand Creek, a decision was made to investigate the growth behavior of point-source ignition fires on an adjacent site at the Sharpsand Creek site. The objective of this new study was to determine the length of time a fire, using point-source ignition, required to reach equilibrium spread rate levels so readily observed during the line ignition studies. It was assumed that all point-source ignited fires would, given time and constant fuel conditions, reach the equilibrium spread conditions observed for the two earlier line-ignition fire studies. This report presents the results from both point- and line- ignition fires conducted between 1984 and 1991 at the Sharpsand Creek site.

Methodology

Burn plot and fire weather station establishment

The Sharpsand Creek study site (46°47'N, 83°20'W) is located approximately 60 km north of Thessalon, Ontario (Figure 1). The site is located in the Lake Temiscaming Lowland ecoregion (Environment Canada 1996). Soils are of a glaciofluvial origin consisting of stony humoferric podzols. The test sites were all on level ground, eliminating any influence of slope on fire behaviour. Feathermosses (*Pleurozium schreberi* and *Hylocomium splendens*) were the dominant living ground-cover vegetation.

In 1983, a series of ten 40 x 40-m (0.16 ha) burning plots (Fires 1-9) were established at the Sharpsand Creek site (Figure 1). Each plot was surrounded by a 20-m-wide fireline bulldozed to mineral soil. Due to the failure of any of these fires to actually accelerate to equilibrium conditions, a second set of larger plots (Fires 10-21) was established in 1986 in an adjacent area of the same stand. The larger plots, ranging from three to seven hectares in size, were created to allow point-source fires to burn longer to determine if equilibrium spread rates could be attained over longer periods. Plot sizes and shapes were dependent on the location of salvage roads created after the 1948 wildfire. The Sharpsand Creek site was considered a semi-mature stand during all fires conducted between 1984 and 1991.

A complete fire weather station was established and maintained on-site each year, and continuous daily 1200 Local Standard Time (LST) observations of temperature, relative humidity, wind speed (at heights of 10 m in the open and 1.5 m in-stand), and 24-hour precipitation were taken in order to calculate the fuel moisture codes and fire behavior indices of the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1984; Van Wagner 1987). Of the FWI System codes and indices, it was expected that the Fine Fuel Moisture Code (FFMC), and the Initial Spread Index (ISI), were most likely to be best correlated with fire spread rates. The FFMC is an indicator of the relative ease of ignition and flammability of fine fuels, while the ISI is a numerical rating of fire spread (based on the FFMC and wind speed) (Van Wagner 1987). The relative values of these and other FWI System parameters are used to predict potential fire behavior for specific fuel types of the FBP System (Forestry Canada Fire Danger Group 1992).

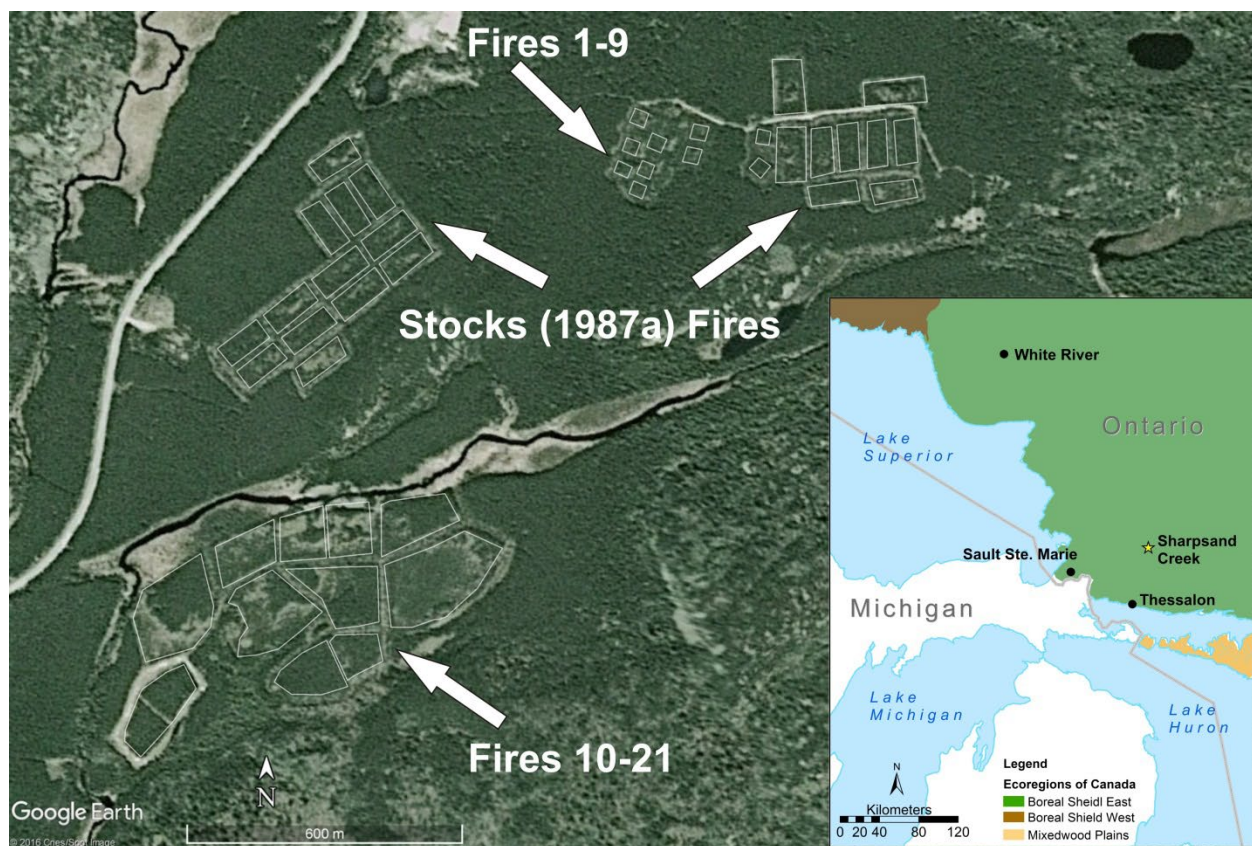


Figure 1. Google Earth view of all Sharpsand Creek burning plots. Map insert shows the location of Sharpsand Creek (yellow star) in northern Ontario.

Fuel sampling

Pre- and post-burn fuel measurements were collected for all plots. Down dead woody fuels were measured using the line-intersect method (McRae et al. 1979) adapted for the use of fuel triangles with 15-m sides. All fuel diameter size classes were measured over the entire triangle, including smaller diameter size classes. One triangle was randomly placed on the smaller fires (1-9), while two triangles were used on the larger fires (10-21). Depth-of-burn pins (McRae et al. 1979) were also placed along each line to measure forest floor (duff) reduction. These were placed one meter on either side of the inner sample pins used to permanently delineate the triangle. A number of trees were selected and cut based on their diameter at breast height (dbh). These trees were destructively sampled to obtain oven-dry weights of the foliage and the various woody diameter size classes (as in Stocks 1987a) to determine crown fuel loadings and consumption.

Burning procedures and fire behavior monitoring

Between 1984 and 1985, nine point-source fires (Fires 1-9) were conducted on the 40 x 40-m plots at the first test site. After conducting four point-source fires (Fires 10-13) in 1987 on the larger plots, it was noted that fire acceleration had not increased on these fires as expected, despite the larger plot size. As a result, the ignition strategy was changed for the last series of fires between 1988 and 1991 (Fires 14-21). Line-ignition was again utilized to determine whether the changes in fuel composition at the Sharpsand Creek site were significantly different enough to alter fire behavior from that observed in the original series of fires in the 1970s and early 1980s (Stocks 1987a). In conjunction with those line-ignition fires that had reached a crowning threshold (Fires 16-19, 21), point-source fires were ignited immediately afterwards to observe whether they would accelerate to the spread rates just observed with the line-ignition fires. These fires were conducted on plots immediately adjacent to the line-ignition plots that had just been burned.

All point-source fires in this study (Fires 1-13) were ignited after an ignition location was selected on the upwind side of the plot to ensure the maximum possible spread distance before reaching the leeward plot edge. Ignition for all point-source fires was completed at least 10 m from the nearest plot edge to avoid any possible edge effects on fire behavior (e.g., wind speed, fuel moisture) caused by the surrounding fire lines. Ignition involved soaking a preselected 20-cm diameter area of feathermoss with 0.5 L of diesel fuel, and igniting this area with a match. This was done to create a sustained ignition source. All fires were ignited between 14:00 and 15:00 LST, when peak burning conditions generally existed. All fires were documented using ground- and helicopter-based video and slide film.

Prior to burning the point-source fires, a metal pin was used to mark the chosen ignition point. From this pin, several reference lines radiating outwards, at set compass bearings, were delineated by string strung between metal pins. More reference lines were placed on the downwind side where faster rates of spread were expected. Research personnel were assigned to drop similarly numbered metal tags at the leading edge of the flame base, where it intersected with each reference line. Tags were dropped at short intervals of 1-2 minutes initially, followed by every five minutes up to 40 minutes after ignition. Thereafter, tags were dropped every ten minutes until the fires were either extinguished because they had reached a plot edge or it appeared further monitoring was futile, since rates of spread had not accelerated. After each fire, the reference lines were re-established using the metal reference pins to assist in tag recovery. Post-burn measurements were made of spread distances between tags along each line. Rates of spread were calculated for specific periods of the fire based on the time when tags were dropped and measured distances between tags.

Control and suppression of all experimental fires were the responsibility of the Ontario Ministry of Natural Resources (OMNR) fire management personnel. As with the 1970s and 1980s Sharpsand Creek fires (Stocks 1987a), all line-ignition fires were ignited with a pneumatic flame thrower along the windward edge of each plot. Two flame throwers were utilized to quickly establish the ignition line starting at the centre of the windward plot edge and moving out to the corners. The forward ROS was measured over a 20x20-m sampling grid, marked by steel survey pins, by means of time-referenced visual observations.

Results

When compared with the earlier stand composition data (1973) for the immature Sharpsand Creek stand (Stocks 1987a), measurable changes with aging were obvious a decade later (Figure 2). The number of live and dead stems was reduced by 47% and 37%, respectively (Table 1) between 1973 and 1984. Because of the high number of original stems at the immature stage, this still left a dense, closed-canopy stand in the mid-1980s. The average dbh for dead stems was larger than the earlier immature survey (Walker and Stocks 1975). The small diameter dead trees from 1973 had fallen over and had been quickly incorporated into the living feathermoss forest floor. This prevented a large fuel buildup of down dead woody fuels lying on the ground. Most of the mid-1980s dead standing inventory was a result of stems alive in the earlier survey, which died through the natural thinning process in the interim period between studies.



Figure 2. An aerial view of the small point-source ignition plots (Fires 1-9). Smoke can be seen from a small surface fire in one of the plots (left side). The scorched trees in the adjacent plots (top right-hand corner) show the extent of fire spread from previous point-source ignitions.

A notable characteristic of the semi-mature stand was the general lack of understory conifer species and ladder fuels from standing dead stems. The lack of understory conifer, to act as ladder fuels, and an increased height to live crown was probably a major factor in explaining why crowning was difficult to obtain during these experimental fires for the point-ignition fires. Natural thinning resulted in a large number of standing dead trees during the earlier immature jack pine fires, and this fuel complex structure contributed significantly to the onset and maintenance of crowning during those fires (Stocks 1987a).

Table 1. Stand structure characteristics for the semi-mature jack pine forest (36 years old) at Sharpsand Creek.

The characteristics found in the earlier immature jack pine (26 years old) study (from Walker and Stocks 1975) are also included to indicate how conditions changed with time.

Tree species	Stem density (trees ha ⁻¹)	DBH ^A (cm)			Height (m)	Basal area (m ² ha ⁻¹)
		\bar{x}	SD	SE		
Semi-mature stand (current study):						
Live jack pine	4375	8.79	0.5	0.18	12.8	28.4
Dead jack pine	3830	3.60	0.2	0.08	5.7	4.5
Immature stand (Walker and Stocks 1975):						
Live jack pine	9276	5.14	2.2	0.03	9.5-10.0	18.6
Dead jack pine	10229	1.66	0.8	0.01	4.5-5.5	2.2

^A Diameter at breast height.

Fuel moisture codes and fire behavior indices of the FWI System at the time of burning for Fires 1-9, and the observed fire behavior, are shown in Table 2. The ROS value for each fire in Table 2 is based on the head fire, and was averaged over the time that the fire was allowed to spread. There were no acceleration trends in any of these fires (Table 3), as might be theoretically expected from a point-source ignition (Weber 1989). In fact, all fires had numerous periods where acceleration was actually negative due to lulls in the wind. The spread rates on all of these slow-spreading fires (Table 2) averaged only 0.4 m min⁻¹ (range 0.13-0.94 m min⁻¹) with frontal fire intensities ranging from 40 to 328 kW m⁻¹ (Fig. 2). At no time did these surface fires accelerate to a level that would support even intermittent torching, or approach spread rates similar to those reported in either of the earlier immature or mature jack pine fire studies (Stocks 1987a, 1989). All fires were suppressed once they had reached the plot edge, or were not accelerating after one hour. The exception was Fire 4, which was suppressed after only thirty minutes, since spread was 0.13 m min⁻¹, the slowest rate recorded during this study.

Fires 10-13, although ignited on larger plots, behaved in a similar fashion to Fires 1-9, spreading slowly with low frontal fire intensities (Table 4). The increase in plot size did not result in any significant fire acceleration over time. Average fuel consumption (1.8-2.3 kg m⁻²) was very similar to the surface fires that had been observed during the line-ignition experimental fires in mature jack pine (Stocks 1989). This indicated that sufficient available fuel was present and was not a limiting factor in producing similar fire intensities.

Table 2. Canadian Forest Fire Weather Index (FWI) System component values associated with 0.16-ha experimental fires (1984-85) along with fuel and fire behavior characteristics.

Fire No.	Date	Codes and indices of the FWI System ^A						Wind speed (km h ⁻¹)	Depth of burn (cm)	Total Fuel consumption (kg m ⁻²)	Rate of spread (m min ⁻¹)	Frontal fire intensity (kW m ⁻¹)	Fire type
		FFMC	DMC	DC	BUI	ISI	FWI						
1	01/06/84	88.9	19.2	115	27.1	5.9	10.8	9.4	2.2	0.65	0.59 (40) ^B	114	Surface
2	04/06/84	92.8	22.0	127	30.7	16.3	24.7	18.7	2.7	1.15	0.94 (39)	328	Surface
3	21/06/84	90.0	18.1	176	28.8	5.5	10.5	4.9	2.8	0.71	0.19 (110)	40	Surface
4	29/07/84	85.5	20.9	142	30.6	3.5	7.4	9.2	2.7 ^C	1.15 ^C	0.13 (30)	46	Surface
5	30/07/84	88.5	24.4	150	34.7	7.3	14.4	15.0	3.0	1.01	0.34 (60)	104	Surface
6	28/06/85	90.6	25.7	115	33.0	6.7	13.2	7.0	3.5	1.51	0.22 (75)	101	Surface
7	01/07/85	88.9	35.4	140	43.3	6.7	15.3	11.6	3.7	1.20	0.42 (65)	153	Surface
8	03/08/85	89.7	34.9	258	52.2	7.2	17.9	11.0	4.1	1.50	0.27 (65)	123	Surface
9	04/08/85	89.8	37.9	266	55.9	8.4	20.8	14.3	4.6	1.79	0.48 (45)	203	Surface

^A Abbreviations are: FWI-Fire Weather Index, FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, and BUI-Buildup Index. Further component descriptions of the CFFWI System may be found in Van Wagner (1987).

^B The number in parentheses indicates the total time in minutes during which observations were taken before the fire was extinguished.

^C Total fuel consumption and depth-of-burn values of Fire 4 were assumed to be similar to Fire No. 2 (similar BUI values) since the final fire size was too small to burn any of the depth-of-burn pins.

Table 3. Rate of spread values observed at different times during Fire 7 (Table 2). Note that there is no trend in fire acceleration.

Time period after ignition (min)	Distance of head-fire travel in time period (m)	Rate of spread (m min ⁻¹) during time period
0-1	0.9	0.70
1-3	0.9	0.45
3-5	1.5	0.75
5-7	0.6	0.30
7-10	1.1	0.37
10-15	1.6	0.32
15-20	0.9	0.18
20-25	3.8	0.76
25-30	2.5	0.50
30-35	0.7	0.14
35-45	1.2	0.24
45-55	0.7	0.01
55-65	1.8	0.36

The subsequent line-source ignition fires (Fires 14-21) displayed much higher rates of spread compared to the earlier point-source fires (Table 5). However, they did not result in the crown fires that were so common on the immature study (Stocks 1987a). Torching or intermittent crowning was observed on some fires (Fires 15-19), resulting in higher frontal fire intensities ranging from 3473-6425 kW m⁻¹ (Figure 3). The final experimental fire (Fire 21) was the only fire in this series of burns that produced a sustained high-intensity crown fire (Figure 4). Extremely flammable conditions (FFMC of 93.4) and a substantially higher average wind speed (18.9 km h⁻¹), producing an ISI of 17.8, aided crown fire initiation and this fire spread quickly through the entire length of the plot. The average spread rate was 49.4 m min⁻¹ with a frontal fire intensity of 45216 kW m⁻¹.

All point-source ignition fires, conducted immediately after and adjacent to Fires (14-21) spread slowly and at rates similar to the earlier point source surface fires (Fires 1-13), and no acceleration was observed. Aerial observers situated in a helicopter above the plot failed, even for the point-source fire that was ignited immediately after Fire 21, to detect any smoke from these low-intensity fires.



Figure 3. Stand profile of A) an immature (26year old) jack pine fuel complex from Stocks (1987a) compared to B) a semi-mature (~36-year old) jack pine fuel complex at the Sharpsand Creek experimental burning project in 1984-1991.



Figure 4. An aerial view of intermittent crown fire development (Fire 17).



Figure 5. Sustained crown fire behavior as seen aerially during Fire 21.

Wind is blowing from the bottom right corner to the top left corner. Note the green strip of unburned trees that identifies the plot side where the line ignition took place. This is a common occurrence, as the fire accelerates from the ignition line and frontal fire intensity increases to a point where crowning occurs somewhere downwind from the ignition line. Given the short length of this unburned strip, it is quite impressive how quickly a fire can build up and crowning is initiated when line ignition is used.

Discussion

Despite the high number of dead standing trees resulting from the self-thinning of the immature stand, rapid incorporation of down dead woody fuels into the forest floor helped to retain surface fuel loads at low levels as the jack pine stand aged to a semi-mature stage. Incorporation was accelerated as the down dead woody fuel was quickly covered by the living feathermoss, which then provided a moist site for more rapid decomposition. Based on the difference between fuel surveys, only 10 years apart, it was apparent that the small diameter pieces of this down woody material made rapid incorporation possible. If this fuel had still been present in the understory, frontal fire intensities would have been much higher, probably assisting in crown fire initiation.

Often, the conifer understory in many jack pine stands consists of spruce (*Picea* spp.) or balsam fir (*Abies balsamea*), which typically provides important ladder fuels for initiating a crown fire. High conifer understory densities improve the probability of surface fires reaching a crowning threshold. It should be noted that the absence of understory conifer at this site and on many dry semi-mature jack pine forest sites is common, so the fire behavior observed in this study can be assumed to be normal. Ladder fuels, often consisting of tree foliage extending down to the ground surface, disappear with age as the trees become taller and undergo self-pruning which removes the foliage and fine twig structure that would contribute to crown fire development.

Comparison of all the small initial point-source fires (Fires 1-9) indicated that Fire 1 was a possible outlier based on a plot of residuals for ROS (Table 2). The ROS for this fire was much higher than any other plots given the low ISI value at the time of burning. Further examination of this fire revealed that it was, despite our study design, actually ignited very close to the plot

edge and probably experienced an unintended edge effect (i.e., reduced ground fuel moisture due to increased solar radiation and stronger edge-effect winds). The remaining fires (Fires 2-9) were used in developing the following equation:

$$[1] \quad \text{ROS} = -0.134 + 0.066 \text{ ISI}; n = 8; R^2 = 0.93; SE = 0.07; \text{ISI} \geq 3.5$$

The relationship is strong over the ISI conditions observed. However, the difference in actual ROS increases only marginally as ISI values become higher. Given the tree density of the stand (Table 1), the low ROS prediction should not be surprising given the low in-stand wind speeds, due to the inability of the ambient wind to penetrate inside the jack pine stand at ground level. For example, the average ambient wind speed in the open was measured as 9.6 km h^{-1} over a 60-minute period on Fire 10, while the average wind speed within the stand was only 0.1 km h^{-1} . At these open wind speeds, and with an ISI value of 11.5, the equilibrium ROS predicted for immature jack pine by Stocks (1987a) would have been 24.2 m min^{-1} , which is substantially higher than was observed on this fire (0.27 m min^{-1}). Wind direction within the stand was also much more variable because of wind eddying, which caused the head fire location to shift continually throughout the fire. Any fire acceleration from a point-source ignition would have been reduced by this continual shifting in wind direction.

The slow development of these point-source fires was not significantly altered by extending the fire growth period through the enlargement of plot size (Fires 10-13). Even when plots were allowed to burn for up to ninety minutes, ROS remained low. No recognizable fire acceleration with time could be documented during these fires. Combining the larger point-source fires of 1987 (Table 4) with the 1984-85 data set (Table 2) further illustrates that predicted ROS are very low. Analysis of this combined data set for all point-source ignited fires resulted in the following equation:

$$[2] \quad \text{ROS} = -0.082 + 0.052 \text{ ISI}; n = 12; R^2 = 0.66; SE = 0.13; \text{ISI} \geq 9.4$$

This new equation is very similar to Equation 1, where the slope is very small; indicating that any increases in the ROS will be small given any unit increases in the ISI. The point-source fires of our study appear to be in equilibrium with the interior burning conditions that are present, and were unable to reach the higher line-ignition equilibrium spread rates predicted by the FBP System. The present results indicate the extreme difficulty that a surface, point-source fire burning in the understory of a thick jack pine stand has in accelerating and in reaching a crowning threshold, where a higher ROS might be expected.

Table 4. Canadian Forest Fire Weather Index (FWI) System component values for 1987 experimental fires along with fuel and fire behavior characteristics.

Fire No.	Date	Codes and indices of the FWI System ^A						Wind speed (km h ⁻¹)	Depth of burn (cm)	Total Fuel consumption (kg m ⁻²)	Rate of spread (m min ⁻¹)	Frontal fire intensity (kW m ⁻¹)	Fire type
		FFMC	DMC	DC	BUI	ISI	FWI						
10	19/06/87	93.6	46.1	193	57.8	11.5	26.4	9.6	5.0	1.82	0.27 (60) ^B	145	Surface
11	21/06/87	93.3	55.5	204	66.1	9.8	25.3	7.3	4.9	1.78	0.29 (90)	153	Surface
12	23/07/87	92.9	65.3	217	74.5	10	27.3	8.8	6.0	2.27	0.35 (80)	239	Surface
13	02/07/87	91.8	73.4	283	89.1	9.4	28.5	10.5	5.5	2.04	0.45 (50)	279	Surface

^A Abbreviations are: FWI-Fire Weather Index, FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, and BUI-Buildup Index. Further component descriptions of the CFFWI System may be found in Van Wagner (1987).

^B The number in parentheses indicates the total time in minutes during which observations were taken before the fire was extinguished.

^C Total fuel consumption and depth-of-burn values of Fire 4 were assumed to be similar to Fire No. 2 (similar BUI values) since the final fire size was too small to burn any of the depth-of-burn pins

Table 5. Canadian Forest Fire Weather Index (FWI) System component values for larger 1987 experimental fires along with fuel and fire behavior characteristics.

Fire No.	Date	Codes and indices of the FWI System ^A						Wind speed (km h ⁻¹)	Depth of burn (cm)	Total Fuel consumption (kg m ⁻²)	Rate of spread (m min ⁻¹)	Frontal fire intensity (kW m ⁻¹)	Fire type
		FFMC	DMC	DC	BUI	ISI	FWI						
14	25/05/88	88.9	33.7	110	38.1	6.0	13.2	10	3.2	2.20	2.1	1385	Surface
15	02/06/88	89.5	42.4	153	50.1	6.3	15.9	9	4.9	2.62	2.1	1650	Surface
16	03/06/88	91.3	46.7	161	54.1	8.1	20	9	4.6	3.31	3.5	3473	Some torching
17	04/06/88	92.4	51.9	169	58.7	10.0	24.4	10	5.7	3.97	5.4	6425	Torching
18	01/06/90	89.9	31.5	78	31.5	9.4	17.8	16	2.5	3.07	4.6	4231	Some torching
19	07/06/91	92.2	49.4	161	55.9	10.9	25.0	13	4.3	2.41	5.1	3678	Torching
20	13/06/91	88.6	70.2	205	75.6	5.7	18.5	10	4.4	1.41	0.8	336	Surface
21	19/06/91	93.4	56.5	231	70.2	17.8	38.8	19	3.7	3.06	49.4	45 216	Crown

^A Abbreviations are: FWI-Fire Weather Index, FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, and BUI-Buildup Index.

The actual fire behavior experienced in a closed canopy forest is difficult to predict, since two fire types can be involved (i.e., surface and crown) dependent upon whether a crowning threshold has been attained. The Forestry Canada Fire Danger Group (1992) describes what they refer to as a dual-equilibrium ROS for this fuel type. They reasoned that surface fires are influenced only by the wind that may penetrate the forest stand under the canopy. However, an established crown fire is exposed to, and influenced directly by, the ambient winds found above the canopy. To transition from a surface to a crowning fire, especially in a densely-closed canopy common to jack pine sites, it appears that some type of fuel discontinuity is required to allow the ambient wind to penetrate to ground-level, where it can have a more direct effect on the surface fire. The penetration of stronger winds can then induce torching (if available ladder fuels are present), which can lead to sustained crowning under proper conditions. Once established, the crown fire remains connected to the surface fire, and is maintained by the higher and steadier wind speeds found above the canopy. Lulls in the wind can cause a crowning fire to revert quickly back to a surface fire. In such cases, once ambient winds strengthen again, the surface fire may fail to revert back to a crown fire if the winds cannot penetrate to the ground again. This may occur when the lull occurs in a dense, closed-canopy stand. However, large burned-out areas behind the fire, where the fire has crowned, can often allow wind penetration that could readily influence the fire again. This would be true only if the wind lull is short and the burned-out area remains adjacent and upwind of the active fire front. The Forestry Canada Fire Danger Group (1992) felt that the probability of changing from the lower ROS (surface fire) to the higher line-ignition equilibrium ROS (crowning fire) depended on local fuel-type characteristics (size, number, and distribution of openings in the canopy), local topography (small hills and ridges), and localized weather conditions (sun exposure, time of day, wind speed and direction variation). The slow point-source fires (Fires 1-13) of the present study would indicate that reaching the second phase (i.e., crowning) in this dual-equilibrium process is often very difficult based on the burning conditions experienced in this study.

Fires 14-21 supported the fact that line-ignition fires in semi-mature jack pine spread much faster than point-source fires (Fires 1-13) under similar burning conditions. Generally, when the FFMC was below 90 and ambient winds were less than 10 km h^{-1} , only line-ignition surface fires occurred (Fires 14-15, 20). Under higher FFMC values of 90 and greater, intermittent crowning was possible (Fires 16-17, 19) with wind speeds as low as 9 km h^{-1} . At lower FFMC values, higher ambient wind speeds appeared to compensate for a lower FFMC value (Fire 18) to allow intermittent torching to occur. The only sustained crown fire (Fire 21, Figure 5) during the study occurred when both the FFMC value was extreme (>93.0) and ambient wind speed was higher (18.9 km h^{-1}). However, it should be noted that this wind speed was much lower than the 29 km h^{-1} necessary to support intermittent crowning in an older mature stand (Stocks 1989). The development of this crown fire was important in verifying that crowning could be attained in a semi-mature stand under relatively moderate wind speeds. This indicates the conditions required for crown fire development in a semi-mature jack pine stand are lower than those required in a mature stand, and higher than those required in an immature jack pine stand.

An equation based on Fires 14-20 (Table 5) was developed for the fire spread of a line-ignition surface fire:

[3] **ROS = -3.132 + 0.807 ISI**; $n = 7$; $R^2 = 0.94$; $SE = 0.49$; $ISI \geq 5.7$

This model shows that spread rates were higher than for the point-source fires (Equations 1 and 2). While many of the same ISI values were associated with a crowning fire in the earlier immature jack pine study (Stocks 1987a), the inability of most of the present line-ignition fires to achieve a crowning threshold showed that burning conditions had changed as the jack pine stand aged. Equation 3 is comparable to the ROS Equation 8a developed by Stocks (1989) for surface fires in mature jack pine. Combining both data sets gives the following ROS prediction, which is very similar to the one given by Stocks (1989):

$$[4] \quad \text{ROS} = -5.436 + 1.101 \text{ ISI}; n = 19; R^2 = 0.88; SE = 1.29; \text{ISI} \geq 3.3$$

The actual ROS of 49.4 m min⁻¹ for the 1991 wind-driven crown fire (Fire 21) is the same as the highest measured by Stocks (1987a) immature jack pine study (Fire 11b). The ISI values for these two fires were 17.8 and 19.7, respectively. This ROS value is only slightly higher than the predicted value of 44.9 m min⁻¹ obtained from Stocks (1987) Equation 7a. However, our experimental value is much higher than the 33.1 m min⁻¹ value that is predicted by Stocks (1987a) Equation 9, which also incorporated wildfire data to supplement the experimental study data, and the 28.5 m min⁻¹ value predicted by the FBP System for immature jack pine fuel type (C-4) (Forestry Canada Fire Danger Group 1992). It should also be noted that the FBP System basic ROS curve for mature jack pine (Forestry Canada Fire Danger Group 1992) does show that these high spread rates are possible.

Summary

A replicated series of twenty-one experimental fires in semi-mature jack pine (age 36-43 years old) showed attainment of a crowning threshold from point-source ignited surface fire was not possible when the fire was ignited and remained inside a fully-stocked closed stand. This is important because most wildfires develop from a point-source ignition (e.g., lightning, cigarette, etc.). Our findings support the thesis that a dual equilibrium ROS situation exists, since the ambient wind can rarely penetrate a forest stand with a dense overstory canopy to influence a surface fire burning within a dense stand. This was supported by large observed differences between ROS for point-source fires ignited within the stand and fires ignited as line-ignition on the plot edge under the direct influence of the ambient wind. It appears that it is important to have some type of fuel discontinuity (e.g., canopy gaps, blowdown, edge effects from natural water bodies, etc.) to allow the ambient wind to penetrate to ground-level, where it can have a more direct effect on fire spread. Fuel structure (e.g., presence of ladder fuels, presence of sub-canopy conifer species, down dead woody fuels, etc.) is equally important. Ladder fuels disappear as a jack pine stand matures, because the dense nature of these stands promotes self-pruning that result in the loss of fine fuels (e.g., fine twigs, foliage, etc.) in the sub-canopy close to the ground. Our findings may assist in prioritizing fire suppression responses when multiple fire starts occur in an extreme fire danger period.

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