Fire Behaviour in Jack Pine/Black Spruce Forest Fuels following Mulch Fuel Treatments: A Case Study at the Canadian Boreal Community FireSmart Project

Technical report no. 24 - March 2017

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ABSTRACT

Mechanical mastication (mulching) of forest fuels is a vegetation management practice commonly applied in the wildland urban interface to mitigate the risk of wildfire. This research project conducted at the Canadian Community Boreal FireSmart project was designed to document how a mulch grid fuel treatment, when challenged by an approaching crown fire, would modify high intensity fire behaviour.

The mulch grid treatment technique was applied in jack pine/black spruce forest fuels in March 2011. This experimental fire was conducted on June 30, 2016. Temperature/relative humidity crossover conditions with moderate wind speeds resulted in an hourly initial spread index of 12.6 at the time of ignition. While the ISI was at the 98th percentile, the BUI (81) was at the 78th percentile.

We ignited a strip of untreated fuels upwind of the mulch grid treatment to observe and document changes in fire behaviour as crown fire encountered the mulch fuel treatment. Fire behaviour in the run-up zone and the untreated fuel stand adjacent to the mulch grid was vigorous crown fire with an estimated head fire intensity of 10 000 kW/m. As the fire spread into the treated area, crown fire transitioned to vigorous surface fire in the mulched fuels with intermittent crown fire as the residual clumps of fuel in the treatment were engaged. Fluctuations in wind speed during the experimental fire had an impact on rate of spread and fire intensity.

In the initial stages of fire spread in the treatment area, rate of spread peaked at 14.8 m/min with an associated head fire intensity estimated at 6 000 to 8 000 kW/m. The fire intensity observed in the mulch fuel treatment was less than that predicted by the Fire Behaviour Prediction system for boreal fuel types.

This experimental fire at the Canadian Boreal Community FireSmart project was conducted under conditions of low fuel moisture content with temperature/relative humidity crossover and moderate wind conditions. This case study of fire behaviour in mulched fuel treatments does not address the effectiveness of fuel treatments in other fuel types under different weather conditions.

INTRODUCTION

Forest fuels engineering is one of the primary wildfire mitigation strategies advocated by FireSmart™ Canada (Partners in Protection, 2003) and applied by partnering wildfire management agencies and industry operators. Over the past two decades, mechanical forest fuel treatments (including mulching) have been extensively applied in and around communities in the wildland-urban interface to mitigate the risk of wildfire. Fuel managers and fire operations managers would like to better understand how manual and mechanical fuel treatments modify fire behaviour.

Fuel treatment efficacy has been evaluated through post-wildfire case studies (Mooney, 2014; Pritchard *et al.,* 2011), fire behaviour modelling (Fernandes, 2009; Stephens *et al.,* 2009) and subjective expert opinion based approaches (Hayes *et al.,* 2008). The use of experimental fire to evaluate the effectiveness of fuel treatments is limited.

Experimental fires conducted at the Canadian Boreal Community FireSmart project site (Mooney, 2013; Schroeder, 2010) have evaluated the effectiveness of manual fuel reduction treatments using prescribed FireSmart standards. In Alaskan black spruce fuels, Butler *et al.* (2013) used experimental fire to compare the effectiveness of a mechanical treatment (shearblading) and manual fuel treatments. In 2015, an experimental fire was conducted to evaluate the effectiveness of two mechanical fuel treatments in black spruce in Central Alberta (Hvenegaard, Schroeder, & Thompson, 2016).

The Canadian Boreal Community FireSmart (CBCFS) project was developed to facilitate wildfire-related studies including the effectiveness of forest fuel treatments in boreal fuel types. The CBCFS project continues on the site previously used for the International Crown Fire Modelling Experiment (ICFME) in Northwest Territories. During the ICFME, high intensity experimental crown fires were conducted to collect fire behaviour data which contributed to a better understanding of the characteristics of crown fire in natural forest stands (Stocks, Alexander, & Lanoville, 2004).

In June 2016, FPInnovations collaborated with NWT Environment and Natural Resources to conduct an experimental fire at the CBCFS to evaluate the effectiveness of this treatment in modifying fire behaviour.

STUDY SITE

The CBCFS project site is approximately 50 km northeast of Fort Providence, NWT, along Highway 3 (Figure 1). The CBCFS project site has been established on forested areas within and surrounding the original ICFME site. The mulch fuel treatment under study is adjacent to ICFME plot 8 (Figure 2) which was burned in 1998.

Figure 1. Geographical location of the Canadian Boreal Community FireSmart Project site.

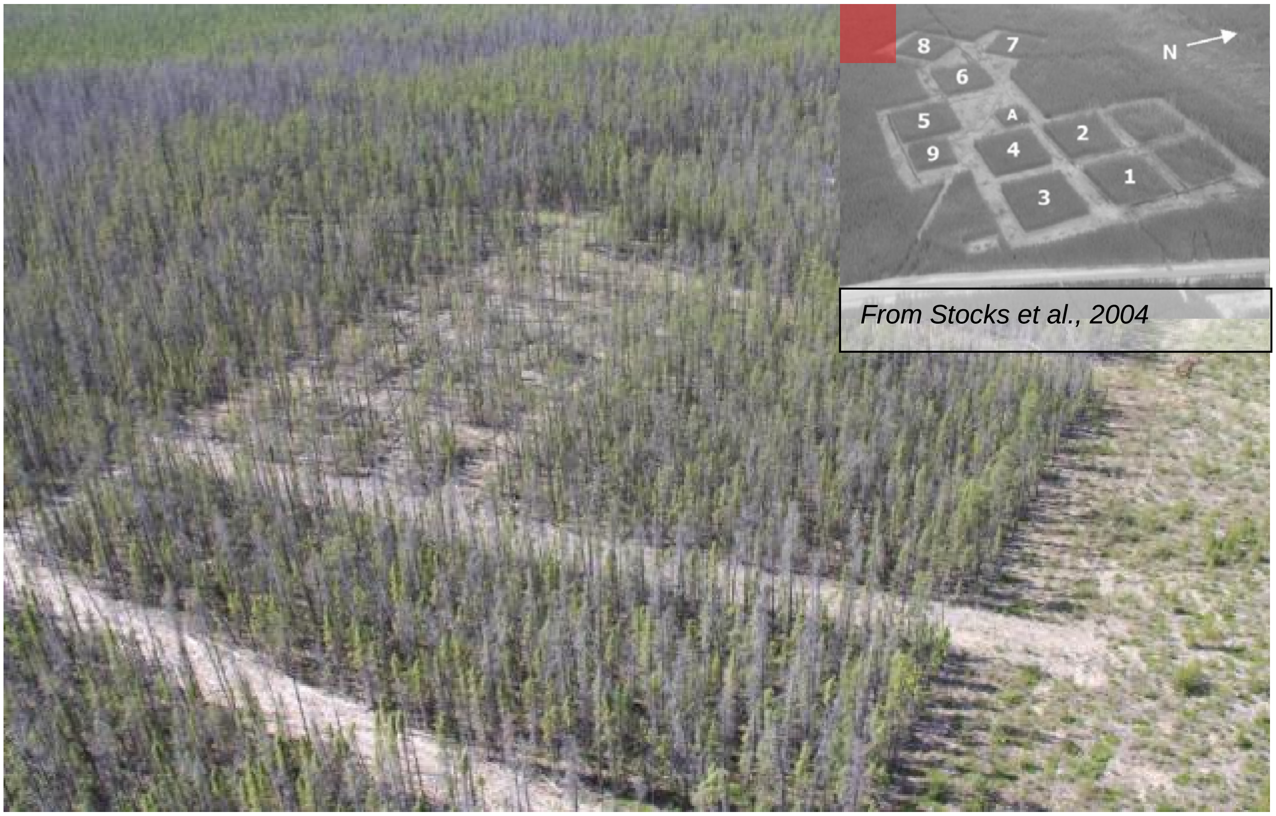

Figure 2. Area of mulch grid plot (red square) in relation to ICFME plots.

Mulch treatment

The mulch fuel treatment was applied at the CBCFS in March 2011. The 0.27 ha forest stand was treated using a GyroTrac GT-18 mulcher producing a grid pattern in which mulched strips result in a checkerboard pattern of residual stems (Figure 2). Mulched alleys were an average of 4 m wide with 6 m wide corridors on the southeast and northwest sides of the plot. This aggressive fuel treatment resulted in stand retention of 28%.

This mulch grid fuel treatment has been commonly applied in dense and homogeneous forest stands with no predominantly larger and healthier stems. As opposed to leaving single stems, this treatment type results in a 'clumping' effect in which the size of clumps and distance between clumps can be adjusted according to the prescription. There was no additional fuel modification (limbing or thinning) in the residual clumps of stems.

This study site was designed with strips of natural fuel stands (run-up zones) on the southwest and southeast sides of the treatment area. These fuel stands were left untreated to serve as ignition zones of natural fuel to build fire intensity and initiate a crown fire to challenge the fuel treatment.

Fuel environment

Fuel inventory

In June 2012, we inventoried four sampling plots in adjacent natural stands to determine pre-treatment stand density, species composition, and diameter at breast height (DBH) (Table 1). The sampled areas of adjacent untreated forest stands are comprised primarily of jack pine in the overstory with a black spruce understory component. The fuel inventory indicated a stand condition of high density, small diameter stems with a considerable dead standing component.

Table 1. Inventory of standing stems in adjacent natural stands

Species	Overall composition (%)	Overall Stem Density (stems/ha)	Size distribution (%)		Condition	
			< 9 cm DBH	>= 9 cm DBH	Live (%)	Dead (%)
Jack pine	41	8 222	47	53	50	50
Black spruce	59		98	2	91	9

In June 2015, we used destructive sampling methods by collecting mulched fuel particles and other debris inside a 50 X 50 cm quadrat to determine mulch coverage (kg/m^2), size class composition (%) and bulk density (kg/m^3). Mulched debris in size classes (McRae *et al.,* 1979) 1 to 3 (less than 3 cm in diameter) made up over 70% of the surface debris (Table 2).

Table 2. Post-treatment inventory of surface debris

Surface debris loading (kg/m^2) and percentage (%) of total						Overall Bulk Density (kg/m^3)
Fine Organics	Mulched debris					
	Size class 1 (less than 0.5 cm)	Size Class 2 (0.5 to 0.99 cm)	Size class 3 (1 to 2.99 cm)	Size class 4 (3 to 4.99 cm)	Overall Loading	
0.19 (4.7%)	0.99 (24.6%)	0.62 (15.5%)	1.27 (31.6%)	0.95 (23.6%)	4.02 (100%)	135

Fuel moisture

One hour before ignition, we collected and weighed samples of mulch debris from the uppermost surface fuel layer in size classes 1 to 4. These samples were oven dried at 80°C for 48 hours and reweighed to determine moisture content of samples by size class. We also collected samples of old and new growth in the conifer foliage.

The moisture content in foliage samples indicated the typical ‘spring dip’ pattern (Jolly *et al.,* 2014) of higher moisture content in the new growth with relatively low moisture content in the old growth (Table 3). Moisture content in the mulch size classes showed somewhat atypical moisture content pattern with higher moisture content in the fine fuels with lowest moisture content in the largest size class measured.

Table 3. Fuel moisture content prior to ignition (standard deviation in parentheses)

Fuel moisture content (%)			
Mulched debris	Size class 1 and 2 (less than 1 cm)	Size class 3 (1 to 2.99 cm)	Size class 4 (3 to 4.99 cm)
	7.7 (1.8)	5.2 (1.4)	4.9 (0.5)
Foliage		New growth	Old growth
	Jack Pine	153.2 (87.0)	87.0 (5.0)
	Black Spruce	149.2 (10.9)	81.3 (3.9)

Historical weather conditions

Using archived weather data[1] (1982 to 2014) for the Fort Providence weather station (50 km to the southwest) we determined that the 90th percentile Initial Spread Index (ISI) value was eight. At the time of ignition, the hourly ISI (12.6) was at the 98th percentile (Table 4). The historical 90th percentile Buildup Index (BUI) value was 105 while the BUI on June 30 (81) was at the 78th percentile.

Table 4. Initial spread index and percentile values for June 30, 2016

Time	Wind Speed (km/h)	Initial Spread Index	Percentile
13:00	9.2	10	93
16:07 (prior to ignition)	14.1	12.6	98

[1] Archived in the NWT Environment and Natural Resource SPARCS system

METHODS

Weather data collection

The CBCFS remote automatic weather station (RAWS) was located 500 m to the northeast of the mulch grid plot. In addition to the basic weather data and Fire Weather Index (FWI) values (Van Wagner, 1987) provided by the RAWS, we also collected on site weather data at the burn site. We applied these on site weather values and baseline data from the CBCFS RAWS in REDapp[2] to calculate hourly FFMC, ISI, and FWI values (Lawson *et al.,* 1996) at the time of ignition.

Fire behaviour data collection and processing

We placed 20 data loggers in a grid pattern in the treated area and in the natural stand to the northeast of the treated area. The data loggers were placed so that they could capture rate of spread data appropriately with either a southeast or southwest wind direction. Data from the data loggers was downloaded and processed to calculate rate of spread along the four lines at four different intervals. We captured video from five in-fire cameras (Figure 3) located in the burn area. We used still images and video footage to analyze fire behaviour and determine fire spread rate and estimate fire intensity through the treatment area.

We used photos and screen captures from video to compare with photos from documented experimental fires in which head fire intensity had been calculated. This photo reference aided us in estimating head fire intensity in the CBCFS experimental fire.

Extensive video was available from the Red Earth Creek experimental fire. We used this video to compare with fire behaviour captured on video at the CBCFS experimental fire. Analysis of the entire video of fire progression through both plots provided a valuable overall comparison of fire behaviour characteristics. Selecting relevant screen shots of fire behaviour at specific moments of fire development is subjective; however, careful attempts were made to capture fire behaviour at moments when there was strong confidence in the documented rate of spread.

[2] REDapp is a fire management decision support tool. http://redapp.org/

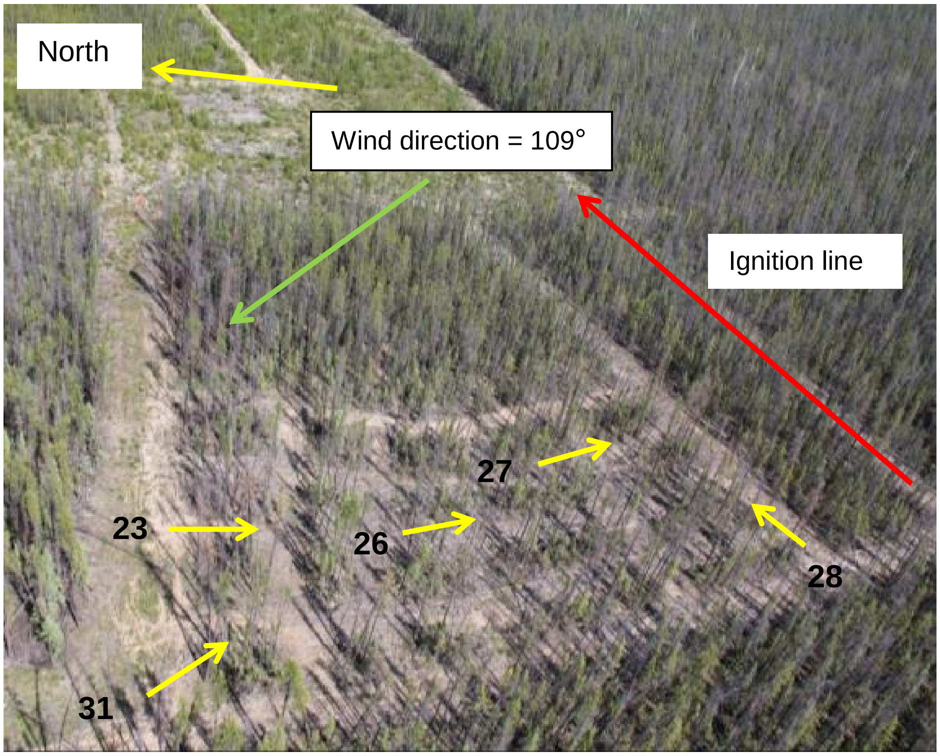

Figure 3. In-fire camera locations in mulch grid with ignition line along 'run-up' zone.

Ignition

The mulch treatment was laid out with the primary ignition zone on the southwest side of the plot to take advantage of southwest winds pushing crown fire into the mulch plot along the longer side of the treatment area. With the strong likelihood of southeast winds for June 30, the ignition plan was altered to ignite the secondary ignition zone on the southeast side. Ignition of the fuels in the run-up zone southeast of the mulched grid was achieved using the ground-based Dackermin[3] torch.

[3] http://wildfire.fpinnovations.ca/110/FinalReport-TerraTorch_v6FINAL.pdf

RESULTS

Weather

The 2016 fire season in the NWT started with a relatively low Drought Code (264) compared to the previous three fire seasons. Frequent rain events through the spring season tempered the fire hazard in the weeks leading up to the scheduled 2016 research work. The RAWS at the CBCFS recorded approximately 60 mm of cumulative precipitation in the spring season up to June 18. On June 27, 5 mm of rain was collected in the rain gauge placed at the mulched fuel treatment site. In the next three days, a building upper ridge (Figure 4) produced low relative humidity through the day and minimized relative humidity recovery through the evening. On June 30, the positioning of the ridge produced ESE winds at the burn site.

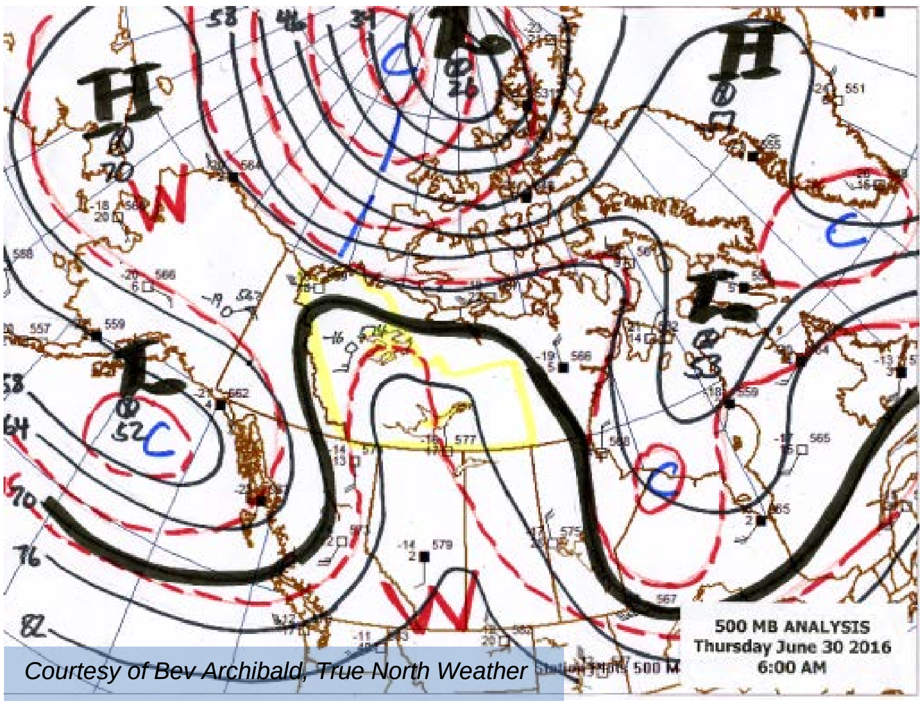

Figure 4. 500 MB chart showing upper ridge established over CBCFS project site.

At the time of ignition, crossover conditions with moderate ESE (109°) winds produced an hourly ISI of 12.6 (Table 5).

Table 5. Weather data from CBCFS RAWS and hourly FWI[a] values at the time of ignition

Temperature (Celsius)	Relative Humidity (%)	Wind Speed (km/h)	Wind Direction (degrees)	Hourly FFMC	Hourly ISI	DMC	DC	BUI	Hourly FWI
30.6	30	14.1	109	93	12.6	54	400	81	33.1

[a] *Adjusted according to Lawson et al.(1996)*

Fire behaviour

Ignition along the ignition line (Figure 3) commenced at 16:08:05 and was completed at 16:10:30. In spite of the short span (15 m) of untreated fuels from the ignition line through the run-up zone, a vigorous crown fire (Figure 5) had developed by the time it entered the treatment area. Stocks and Hartley (1995) was used as an interpretative photo reference to estimate head fire intensity (HFI). With regard to flame height and flame depth, experimental fire # 5/75 was deemed to be a reasonable match to fire behaviour observed in the run-up zone. Head fire intensity in the run-up zone was estimated at 10 000 kW/m. With an elapsed time of 1 minute and 15 seconds for passage of the fire through the run-up zone this yields a spread rate of 12 m/min.

Courtesy of Stephen Paskalak, University of Alberta

Figure 5. Crown fire in the run-up zone entering the mulched area.

Short-range spotting within the mulch fuel treatment was evident from in-fire video capture. Forward spread of these spot fires was limited by the convective indraft of the main fire front. Long-range spotting was not observed in the plots or natural stands downwind of this experimental fire.

As the fire crossed into the treated area, the fire intensity dropped with a reduction in flame length to approximately 1 to 1.5 metres in the surface fuels of the mulched area (Figure 6).

Figure 6. Photo sequence of fire behaviour at time after ignition in line with camera 27 (minutes:seconds).

As the fire moved through the treated area, fluctuations in wind speed had a large influence on fire intensity and rate of spread (Table 6). With the initial winds, the fire advanced 35 m into the treated area at a spread rate of 14.8 m/min. At this point, a lull in wind speed reduced the spread rate to 4.2 m/min and the fire crawled another 11 m. A final wind gust accelerated the rate of spread to 14.4 min/m through the remainder of the plot. The overall rate of spread through the treated area was 10.7 m/min.

Table 6. Fire progression influenced by variations in wind speed

	Time interval (time from fire entering treatment area)	Wind Speed (km/h)	Spread Distance (m)	Interval Spread Distance (m)	Interval Spread rate (m/min)	Overall Spread Rate (m/min)
Phase 1	2:22	14.1	35	35	14.8	
Phase 2	5:00	n/a	46	11	4.2	10.7
Phase 3	7:05	n/a	76	30	14.4	

Crown fraction burn was estimated at 90%. Depth of burn (DOB) in the surface fuel layer was variable throughout the inconsistent surface fuels. The range in DOB was between 0 and 4 cm in depth.

DISCUSSION

Modification of fire behaviour in the mulch grid

Fire behaviour in untreated forest stands was observed in the run-up zone and in the untreated fuels northeast of the mulch grid (Figure 7), and the HFI at these times was estimated to be approximately 10 000 kW/m. These observations were of short duration (less than one minute) and fire behaviour had not grown to a fully developed continuous crown fire with steady state fire behaviour.

Courtesy of Veronica Clifford, Scion Research Group

Courtesy of Stephen Paskaluk, University of Alberta

Figure 7. Crown fire in the run-up zone (left) and fuel stand northeast of mulch grid (right).

As fire moved from the run-up zone and entered the mulch grid, change in fire behaviour was documented through the in-fire video capture. This initial decrease in flame length and fire intensity as the fire moved from the untreated fuels to the mulched fuels was the first indicator of fire behaviour modification. Another key indicator of fuel treatment effectiveness is the reduction in fire intensity throughout the fuel treatment area relative to that in untreated forest stands. The most intense fire behaviour (flame length and depth of flame front) observed in the treatment area during wind gusts (Figure 6) was regarded as lower than that observed in the untreated forest stands (Figure 7).

Fire Behaviour Prediction system projections

The stand conditions in the run-up zone – high density immature jack or lodgepole pine with a heavy loading of dead standing stems – are characteristic of the C-4 (immature pine) Fire Behaviour Prediction (FBP) system fuel type (Forestry Canada Fire Danger Group, 1992). However, the density of this untreated area (8 222 stems/ha) is below the suggestive density of 10 000 to 30 000 stems/ha for the immature pine fuel type. Given the abundance and continuity of ladder fuels in the black spruce understory, C-2 (Boreal Spruce) could also be applied as a representative FBP fuel type. FBP fire behaviour projections (Table 7) calculated using weather and FWI values at the time of ignition (16:08) indicate continuous crown fire with a projected HFI above 23 000 kW/m.

Table 7. Forecast fire behaviour for representative FBP fuel types

	Wind Speed (km/h)	Rate of Spread (m/min)	Head Fire Intensity (kW/m)	Fire Type	Surface Fuel Consumed (kg/m^2)
C-4	14.1	20.9	23 155	Continuous crown	2.51
C-2	14.1	20.5	23 481	Continuous crown	3.03

Comparative fire behaviour analysis with other experimental fires

ICFME Plot 8

Documented fire behaviour in ICFME Plot 8 in 1998 provides a good reference point for comparison of potential fire behaviour in untreated fuel stands with the observed fire behaviour at the CBCFS mulch grid experimental fire in 2016. There are some notable similarities between these two experimental fires. Very similar burning conditions (Table 8) including date and time, weather and FWI values set a good framework for comparing fire behaviour.

Table 8. Comparison of weather and FWI values for two experimental fires

	Date / time	Temp (C)	Rh (%)	WS (km/h)	WD (°)	FFMC	ISI	DMC	DC	BUI	FWI
CBCFS	June 30, 2016 16:08	30.6	30	14.1	109	93	12.6	54	400	81	33
ICFME[a]	July 4, 1998 16:04	30.2	26	11.0 (14.3)[b]	135	91.9	9.8 (11.6)	37	343	58	24 (27)

[a] *from Stocks* et al., *2004*

[b] *This line indicates wind gust with adjusted ISI and FWI*

During both experimental fires, fluctuating wind speed contributed to rapid changes in rate of spread and explosive increases in fire intensity. With a wind speed of 11.0 km/h in the initial stages of fire growth in the experimental fire in ICFME Plot 8, the calculated head fire intensity was 34 321 kW/m (Stocks *et al.,* 2004). Midway through the plot, after a lull in wind speed, a wind gust of 14.3 km/h accelerated the rate of spread to 54.0 m/min.

Major differences between the two experimental fires are the age of the forest stand, and associated differences in fuel loading and stand composition. After 20 years of aging and natural thinning of the forest stand, it appears that the CBCFS mulch grid plot and the surrounding untreated stands had evolved to a state of reduced stem density and fuel loading in the understory.

Taylor *et al.* (2004) describes the ICFME research area as ‘1931-origin jack pine stands with a black spruce understory’. Fuel inventories conducted in 1995/1996 indicate Plot 8 contained a very abundant black spruce understory with density of 6 780 stems/ha (Stocks *et al.,* 2004). The 29% dead component (Alexander *et al.,* 2004) in this heavy understory was likely a major contributor to the calculated peak head fire intensity of 76 270 kW/m (Stocks *et al.,* 2004) illustrated in Figure 8.


Courtesy of Canadian Forest Service

Figure 8. Peak fire intensity during ICFME Plot 8 experimental fire.

CBCFS fuel reduction treatments

Other experimental fires at CBCFS conducted under similar burning conditions demonstrate that vigorous crown fire is easily initiated and sustained in the untreated jack pine/black spruce fuel environment. Of the experimental fires that challenged treatment areas, treatments that reduce fuel volume in all of the fuel layers (surface, understory, and overstory) have resulted in the greatest reduction in fire behaviour (Baxter, 2015; Mooney, 2013; Schroeder, 2010). During the experimental fire in the mulch grid plot, we observed a reduction in flame length and fire intensity as the crown fire encountered the mulch grid. However, unlike the fire behaviour in the previously mentioned fuel reduction treatments, the increased volume of chipped debris in the treatment area fuelled a vigorous surface fire with intermittent crown fire.

Red Earth Creek mulch fuel treatments

The mulch fuel treatments at the Red Earth Creek (REC) experimental research site (Hvenegaard, Schroeder, & Thompson, 2016) share some common fuel modification objectives and techniques with the CBCFS mulch treatment. At the REC site, the objective of crown fuel reduction was achieved by applying a strip mulch fuel treatment and a mulch thinning treatment. These resulted in 50% and 32% stem retention, respectively. The mulch thinning treatment included limbing to a height of 2 m, while there was no limbing in the strip mulch treatment. The mulch fuel treatment at CBCFS applied a clumping technique and resulted in 28% stem retention. This treatment did not include limbing or thinning of stems in the residual clumps (Table 9).

Each of these treatments attempted to increase crown separation with different techniques and results. At the REC site, the mulch thinning treatment resulted in a 5–7 m crown separation while the strip mulching treatment resulted in a 4 m crown separation. The clumping technique at CBCFS resulted in clumps of stems with 0–2 metre crown spacing. The spacing between clumps was approximately 4 m.

Table 9. Variations in mulch fuel treatment results at CBCFS and Red Earth Creek sites

Site	Treatment technique	Stem retention (%)	Crown separation (metres)	Limbing height
CBCFS	Clumping	28	within clumps: 0 to 2 between clumps: 4	N/A
Red Earth Creek	Strip Mulching	50	4	N/A
	Single stem mulch thinning	32	5 to 7	2 m

One striking difference in the fuel environment at the REC site was the relatively fresh layer of mulch debris suspended in the dry feathermoss beds (Figure 9). This combination of fine fuels in the surface fuel layer was suspected to be a large contributor to the vigorous surface fire observed at the REC experimental fire. In contrast to the surface fuel environment at the REC experimental fire, the CBCFS mulch grid had a relative absence of mosses with a more compacted layer of aged mulch debris.

Figure 9. Surface fuel layers at Red Earth Creek (left) and CBCFS (right).

During the early stages of fire growth at the REC experimental fire (Figure 10), the rate of spread was measured at 14 m/min, with HFI calculated at 8 368 kW/m using adjustments for fuel consumption during the active flaming phase of the head fire passage (Hvenegaard, Schroeder, & Thompson, 2016). At a similar rate of spread in the later stages of fire growth at the CBCFS experimental fire, an organized fire front is developing with hints of fire whirl development (Figure 10).

Figure 10. Fire behaviour in mulch thinning plot at Red Earth Creek (left) and the CBCFS plot (right).

Using the HFI calculated at Red Earth Creek for this timeframe (8 368) as a visual reference, the HFI in the mulch grid treatment at the CBCFS was estimated at 6 000 to 8 000 kW/m in the later stages of fire growth when more aggressive fire behaviour was observed.

The surface fuel layer is only one component of these complex fire environments under study and the overall influence of each individual fuel component is difficult to quantify. However, a qualitative evaluation of these individual fuel components is valuable when evaluating potential fire behaviour.

Fire behaviour observed and documented at the REC experimental fire, compared to fire behaviour at the CBCFS experimental fire, can be characterized as more intense with greater rate of spread. This difference in fire behaviour can be partially attributed to lower relative humidity and lower fuel moisture at the REC site during the experimental fire with consistently higher wind speed.

Impact on suppression

The estimated peak fire intensity observed in the mulch treatment (6 000 to 8 000 kW/m) would likely preclude a safe and effective direct attack on the head of the fire by fire suppression crews (Alexander & Cole, 1995). However, direct attack may have been successful along the flanks of the fire where there was lower fire intensity. Operations personnel onsite during the experimental fire suggested that aerial suppression with airtankers or medium helicopters would be successful in controlling the fire given the size of the fire and the observed fire intensity.

During the CBCFS mulch grid experimental fire, NWT firefighting crews were diligent in wetting surrounding forest fuels to prevent unwanted fire spread. This operation was successful in that there was no spread to adjacent forest stands or spot fire development. During these operations, a small amount of water spray inadvertently drifted to the mulched fuels in the plot. We observed that this minimal amount of water prevented fire spread to the wetted mulched fuels. In spite of the anecdotal nature of this result, it demonstrates the notion that supplemental treatment (wetting) in mulched treatments can be a viable means of bolstering a fuel treatment’s resistance to ignition and fire spread.

The wide alleys in the CBCFS mulch grid plot and the firm ground surface would have allowed easy access for suppression crews and vehicles delivering water. During a wildland-urban interface fire when spot fires are developing from ember transfer, quick access is important for extinguishing spot fires. Additionally, easy and well-defined egress will be critical to safe suppression operations.

Recognizing the rapid increase in fire intensity and rate of spread observed with an increase in wind speed, the surface fuel bed should be considered a flashy fuel. With this in mind, suppression personnel must be wary of wind shifts or gusts and the potential for being outflanked by the fire.

Rapid moisture exchange in mulched debris

On June 27, 5 mm of precipitation was collected in the rain gauge set up at the mulch grid plot. Under the influence of low humidity conditions in the next three days, the FFMC recovered to an hourly adjusted value of 93 at the time of ignition. This recovery in FFMC translated to low moisture content in mulch debris samples taken on June 30 prior to ignition.

During the experimental fire, the small volume of water that drifted onto the mulch debris had a large impact on the flammability of mulch debris. The application of water through sprinkler systems in other forest fuels (Barnes, 2017) has shown promising results in reducing the flammability of the surface fuel layer. Given the open nature and the ease of access in a fuel treatment such as the CBCFS mulch grid, sprinkler systems would be easy to set up and provide good coverage with minimal interception from the canopy fuels. Future research can explore required volumes of water and longevity of applications.

Influence of the adjacent untreated fuel stand

The untreated fuel stand adjoined to the mulch grid on northeast side may have provided a sheltering effect and buffered the full effect of wind on fire behaviour in the mulch grid. However, a more pronounced influence was the strong convective indraft generated by the high intensity fire in the untreated stand directly adjacent to the mulch grid. As noted in Hvenegaard, Schroeder, and Thompson (2016), fuel practitioners should be aware of the potential influence that fire behaviour in untreated areas can have on fuel treatments. Planning of future research areas will consider this influence to minimize this effect and isolate the intended research variables.

An evolving fuel environment

The mulch grid fuel treatment at CBCFS was conducted in March 2011 and had five seasonal cycles of snow press, vegetative regrowth and debris decomposition prior to this experimental fire. The extent to which this influenced fire behaviour has not been well documented. Six months after the mulch treatment, ignition tests in the mulched debris demonstrated easy ignition and sustained burning with vigorous fire behaviour (Figure 11). However, continued ignition tests over the last five seasons of research at CBCFS suggest that under similar weather condition and FWI values (Table 10), the mulched debris is becoming less receptive to ignition and exhibits less vigorous sustained burning. Had the experimental fire in the mulch grid plot been conducted in June 2011, there may have been a different result in fire behaviour.

Figure 11. Evolving surface fuel environment and sustained burning two minutes after ignition.

Table 10. Factors influencing ignition and sustained burning during comparative ignition tests

Date /time	Temp (C)	Rh (%)	FFMC
June 22, 2011 13:00	24	45	88
June 22, 2013 16:00	34	17	93
June 30, 2016 12:00	28	32	93

Productivity and other fuel treatment innovations

Even though we did not collect productivity data during fuel treatment operations at CBCFS, it was apparent the fuel removal (manual) treatments were very manpower-intensive compared to the mulch fuel (mechanical) treatment. Fuel managers agree that manual fuel reduction treatments are more expensive than mechanical treatments (Hvenegaard, 2012). The benefits and disadvantages of manual and mechanical fuel treatments with regard to productivity and effectiveness are ongoing operational concerns that will be addressed in future research projects.

Fuel managers are interested in the effectiveness of different types of fuel treatments. Fuel reduction treatments reduce the volume of fuel available for consumption through removal of canopy fuels, ladder fuels, and surface debris. However, mulching fuel treatments convert and displace canopy fuels, ladder fuels, and surface debris to a layer of chipped debris in the surface fuel layer. Relative to fuel reduction treatments at CBCFS that were challenged by crown fire, this mulch fuel treatment did not reduce fire behaviour to the same extent. Even though this is a limited data set for comparison, it suggests that fuel reduction treatments have a greater capacity for reduction in fire behaviour potential.

Mulchers are unable to remove lower branches from stems or treat the understory fuels in clumps of residual stems. Semi-mechanized fuel treatments will include motor manual operations (chainsaw and brush saws) to remove ladder fuels and thin closely-spaced stems. These additional processes can reduce the potential for crown fire to improve the overall effectiveness of mulch treatments. However, this will add to the overall cost of the treatment. Innovations in mulching equipment such as biomass recovery units (Gardeski & Keddy, 2017) may be effective in mulch fuel treatment operations to reduce the volume of fuel displaced to the surface layer.

CONCLUSION

This experimental fire conducted under high fire hazard conditions demonstrated that a mulched fuel treatment in mature jackpine/black spruce can modify an encroaching crown fire to a vigorous surface fire with intermittent crown fire. Compared to the fire intensity exhibited in untreated forest stands during this experimental fire, fire suppression efforts would have been more successful in the mulch treatment area.

As observed in other experimental fires in mulched fuel treatments and fuel reduction treatments, fuel treatments can modify an encroaching crown fire, but do not stop wildfire under high to extreme fire hazard conditions. As this certainty becomes more universally appreciated, fuel treatment planners, fuel managers, and fire operations personnel can plan additional suppression strategies to take advantage of these fuel treatments. Supplemental treatment techniques such as sprinkler lines can rapidly change fuel moisture in the surface fuel layer, which can help to reinforce the fuel treatment. Reduced canopy interception in the mulch treatment area would enhance retardant application by improving coverage on the surface fuel layer.

While fuel reduction treatments are accepted as a preferable fuel management technique, mulch fuel treatments in dense forest stands may not achieve this goal as effectively as manual fuel reduction techniques. However, a semi-mechanized fuel treatment technique which combines mulching with thinning and limbing by hand crews should be explored as an option to achieve fuel reduction and maintain productivity.

Even though mulch fuel treatments are not an absolute wildfire mitigation technique, these treatments should be recognized for their positive benefits. The thinned stand will enhance detection of spot fires and improve access for suppression personnel to extinguish spot fires. Safety of fire crews is enhanced through improved egress and increased situational awareness of changes in weather and fire behaviour. Additionally, well-planned mulched corridors in these treatments can provide improved access for suppression equipment.

This case study is one of few case studies documenting the effectiveness of mulch fuel treatments in modifying high intensity fire behaviour. The presentation of these observations and data is intended to further the understanding of fire behaviour in boreal fuels and how fuel treatments can mitigate the risk of wildfire.

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