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# EFFECTIVENESS OF RETARDANT ON MULCH FUELS:

## A CASE STUDY AT PELICAN MOUNTAIN, 2018

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This report is intended for readers who have a wildfire operations background

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**ABSTRACT:**

Mulching is a common method of fuel treatment. However, it is not currently listed by the U.S. Forest Service as a fuel type in its recommendations for fire retardant coverage levels. FPInnovations researchers set up plots with different coverage levels of retardant on a mulch fuel bed and collected fire behaviour data when a fire interacted with these plots. The results are intended to help wildfire agencies understand the effectiveness of retardant on mulch fuels in developing better suppression plans.

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# INTRODUCTION

Fuel treatments are important components of community wildland fire prevention plans,[1] and mulching is a commonly used fuel treatment. It is a form of fuel mastication that converts a vertical fuel structure to a horizontal fuel bed to reduce fire intensity and fire behaviour.

Schroeder (2010) found that fuel treatments can moderate fire behaviour and reduce fire intensity, but they cannot stop fire on their own. Wildfire managers accept that fuel treatments are most effective when combined with wildfire suppression tactics. Using air tankers to apply wildfire suppression chemicals on fuel treatments is one of these wildfire suppression tactics.

The effectiveness of a retardant is based on its chemical properties that alter the combustion characteristics of fuel, causing it to char rather than flame (Rothermel & Hardy, 1965).

Only the retardants and their mix ratios that appear on the U.S. Forest Service–maintained qualified products lists[2] can be used in aerial operations in Canada. Canadian wildfire agencies follow the user guidelines developed by Swanson, Luedecke, Helvig, and Parduhn (1975), of the U.S. Forest Service. These guidelines are based on rainfall interpretation, retardant chemical characteristics, and the fuel model from the National Fire Danger Rating System (Bradshaw, Deeming, Burgan, & Cohen, 1978) in the U.S.

The data for the retardant chemical characteristics in the initial version of the user guidelines was gathered from burn table tests and additional modelling (Rothermel & Philpot, 1974). The burn table test is also known as the combustion retarding effectiveness test.[3] This test determines the amount of retardant required to alter fire behaviour. In the effectiveness test, aspen excelsior and ponderosa pine needles are used to build a long fuel bed inside a wind tunnel under controlled environmental conditions. Then the fuel bed is covered with one or two coverage levels (CL)[4] of retardant. The rate of spread and the rate of fuel weight loss are the effectiveness indicators measured following ignition and running a fire from the starting fuel bed. The term "effectiveness" in that report was defined as reducing fire intensity significantly, not extinguishing it.

Based on Rothermel and Philpot's results (1974), the researchers of the current study predict that the amount of retardant required on mulch fuel would be between CL 2.6 (used on light logging slash) and CL 7.5 (used on medium logging slash). The gap is wide between these two required volumes, and thus an air tanker would have to choose one or the other setting to drop the retardant.

George (1984) verified the recommended coverage levels on natural fuels through additional operational studies and found that the recommended levels in the guidelines were reasonable estimates and rules-of-thumb (George, 1988).

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[1] Also known as FireSmart Community Plans

[2] https://www.fs.fed.us/rm/fire/wfcs/index.htm

[3] https://www.fs.fed.us/rm/fire/wfcs/tests/documents/stp_tm02.pdf

[4] Coverage levels refer to the unit of fluid delivery from an air tanker. They are described in terms of U.S. gallons per 100 square feet. Coverage level 1 indicates 1 U.S. gallon per 100 square feet, coverage level 2 indicates 2 U.S. gallons per 100 square feet, and so on

U.S. Forest Service's Wildland Fire Chemical Systems maintains the current recommendations (Table 1) for retardant use in an operational environment (Suter, 2006). However, mulch is not currently listed as a fuel type in the recommendations, and wildfire agencies would like to understand the effectiveness of retardants on mulch fuels to develop better suppression plans.

Table 1. Retardant coverage levels recommended by the U.S. Forest Service

| Fuel model | | Coverage level | Flow rate | Fuel description |
|---|---|---|---|---|
| NFDRS[a] | FB[b] | (gal/100 ft$^2$) | (gal/sec) | |
| A, L, S | 1 | 1 | 100–150 | Annual and perennial western grasses; tundra |
| C<br>H, R<br>E, P, U | 2<br>8<br>9 | 2 | 151–250 | Conifer with grass<br>Short-needle closed conifer; spring hardwood<br>Long-needle conifer; fall hardwood |
| T<br>N<br>F<br>K | 2<br>3<br>5<br>11 | 3 | 251–400 | Sagebrush with grass<br>Sawgrass<br>Intermediate brush (green)<br>Light slash |
| G<br>O<br>F, Q | 10<br>4<br>6 | 4<br>6 | 401–600<br>601–800 | Short-needle conifer (heavy dead litter)<br>Southern rough<br>Intermediate brush (cured); Alaska black spruce |
| B, O<br>J<br>I | 4<br>12<br>13 | > 6 | > 800 | California mixed chaparral; high pocosin<br>Medium slash<br>Heavy slash |
| Adjust coverage level based on fire behaviour (e.g., for smouldering fires, decrease the coverage level by 1). | | | | |

a. NFDRS, National Fire Danger Rating System

b. FB, Fire behaviour model

# OBJECTIVE

The objective of this research was to establish plots of mulched fuels with different coverage levels of retardant on them, apply fire to the plots, and document the interaction.

# STUDY SITE

## Locations

Alberta Agriculture and Forestry (AAF) provided the Pelican Mountain FireSmart Fuel Management Research Site for this project. Retardant plots were set up on a mulch fuel bed at the centre of Burn Unit 1 (Figure 1).

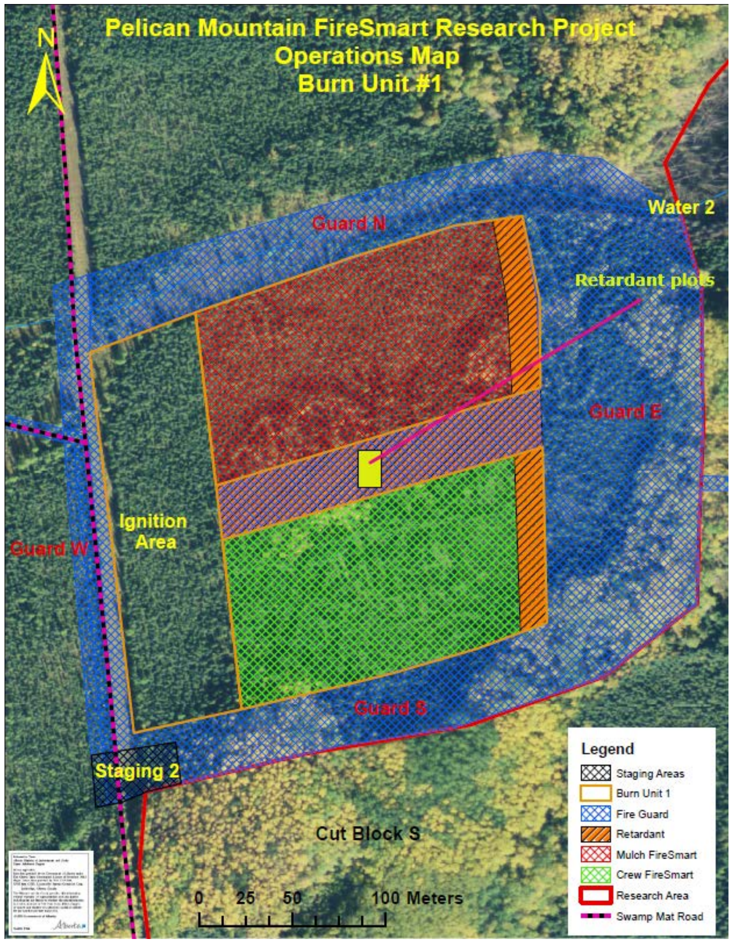


Figure 1. Location of retardant plots at Pelican Mountain at Burn Unit 1. (Image courtesy of AAF.)

# Fuel environment

Before mulching, the forest stand was predominately aspen, with a minor component of jack pine and black spruce. It was mulched in February 2017. The bulk density was 86.93 kg/m$^3$ (data provided by Alberta Wildland Fuels Inventory Program). Hvenegaard and Hsieh (2017) documented the productivity and fuel treatment in detail.

The average size class of mulch fuel was not measured due to time constrains. Hvenegaard (2019) classified the following three mulch fuel environments after different treatment intensities:

- Coarse mulch fuel bed, resulting from a low-intensity mulch treatment
- Regular mulch fuel bed, resulting from a normal-intensity mulch treatment
- Fine mulch layer, resulting from a high-intensity mulch fuel treatment

By using visual comparison with the above size descriptions, the mulch fuel bed at the experiment site was considered regular, based on the normal-intensity mulch treatment.

# METHODS

## Plot setup

Four plots 2.5 m by 2.5 m in size were set up with different retardant coverage levels: CL 2, CL 4, CL 8, and CL 0 (control plot). The researchers covered these plots with retardant (except the CL 0 plot) before noon to simulate an indirect aerial attack. One additional plot with CL 4 was covered with retardant right before the ignition to simulate wet retardant on the ground. Figure 2. Layout of retardant plots shows the plot layout.

Four flagged pins were set up at the corners of each plot for better visibility.

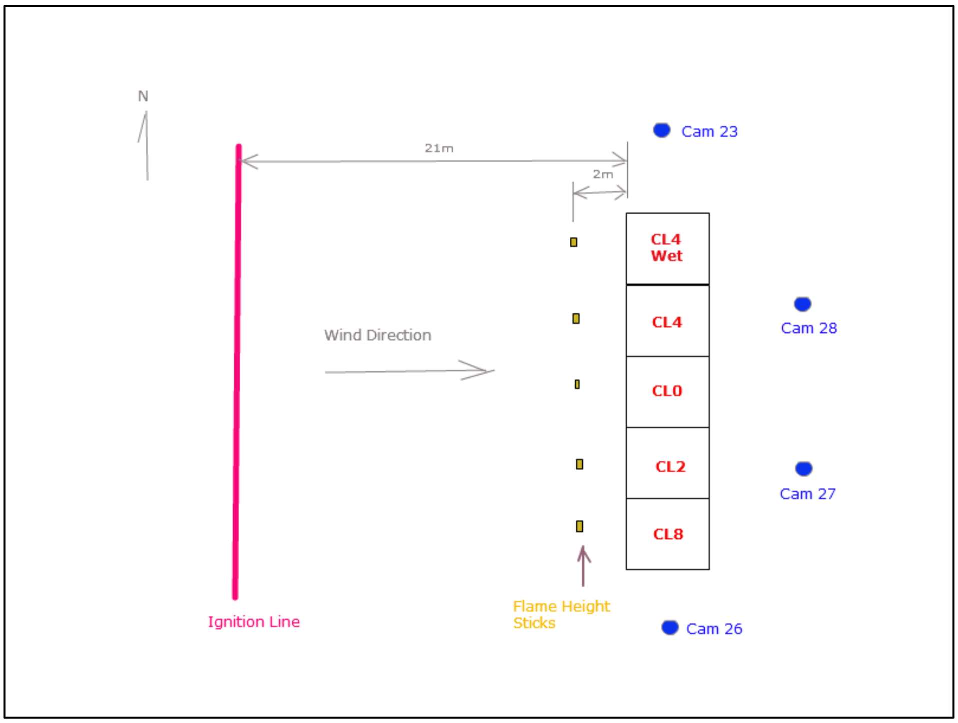


Figure 2. Layout of retardant plots.

## Retardant preparation

The retardant product used in this experimental fire (Phos-Chek LC-95A-R) was provided by the Slave Lake tanker base and was mixed on May 14, 2018, at 10:06 a.m. The Reichert IFT40 Refractometer reading was 14.0 after mixing, which was within the acceptable salt content of the U.S. Forest Service's mixing requirement for this retardant product.[1] The retardant was then transported to the burn site.

[1] https://www.fs.fed.us/rm/fire/wfcs/products/index.htm

The retardant was spread on the plots using 6 L garden watering cans. It was applied to the dry plots on May 15 between 11:00 a.m. and 11:30 a.m., and was dry to the touch on the CL 8 plot by the time of ignition, at 2:54 p.m.

For the CL 4 wet plot, retardant was applied at 2:10 p.m.

# Weather recording

Weather is an important attribute to fire behaviour analysis. A Campbell Scientific weather station was installed on site 15 m west of the ignition line. Air temperature, relative humidity, wind speed, gusts, wind direction, precipitation, and solar radiation were recorded every 2 minutes. Canadian Forest Fire Weather Index (FWI) values were calculated from the weather data provided by this on-site weather station. REDapp[1] was chosen to calculate hourly FWI values (Wagner, 1987) during the burn period.

# Fuel moisture sampling

Fuel moisture data is important for describing the ignition conditions. Multiple samples were collected from surface mulch in front of individual plots before ignition.

# Fire behaviour analysis

In-fire cameras were positioned to record the fire interactions with the retardant plots and the resulting changes in fire behaviour from several viewpoints (indicated by Cams 23, 26, 27, and 28 in Figure 2. Layout of retardant plots).

Multiple researchers also walked along the fire front after ignition to take notes on the rate of spread and height of flame as additional information.

# Depth of burn and area burned measurement

After the prescribed fire was extinguished, researchers collected data on the depth of burn and the area burned at each plot. Four depth-of-burn pins were planted in each plot before ignition and were measured after the fire passed through. The area burned was visually estimated using images taken after the fire passed through.

# Fire intensity calculation

The fire intensity calculation incorporates an assertion outlined by Hvenegaard, Schroeder, and Thompson (2016) that only 50% of mulch fuel is consumed in the active flaming zone. The adjusted value for the weight of fuel consumed is applied in Bryam's (1959) equation, as follows:

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

**FI = Hwr**

Where:

FI = fire intensity (kW/m)
H = fuel low heat of consumption (kJ/kg); 300 kJ/kg is the accepted value when the rate of spread is input as m/min
w = weight of fuel consumed in the active flaming zone (kg/m$^2$)
r = rate of spread (m/min)

Fire intensity in the individual retardant plots was not calculated because the low heat of combustion value (H) of the retardant-covered mulch was unknown; the chemical interactions between the retardant and the mulch would change this value. Therefore, flame height and rate of spread were measured and used as the comparative indicators of the difference in fire intensity among the plots.

# RESULTS

## Weather

Appendix 1 shows the weather conditions between the time of ignition (2:54:22 p.m.) and the time of fire passage through the retardant plots (3:45:26 p.m.). Appendix 1 also shows that the wind direction was variable, shifting from southwest to west-northwest during this period. The wind speeds and directions were affected by nearby trees, causing wind to swirl during the burn. Therefore, the weather station was installed on site, 15 m west of the ignition line, to record on-site weather conditions.

The FWI values were calculated and an extra record was incorporated to account for wind speed gusts of up to 13 km/h, which changed the Initial Spread Index (ISI) and FWI values (Table 2).

Table 2. Weather data and hourly[1] FWI values during fire passage through the testing area

| Temperature (°C) | Relative humility (%) | Wind speed (km/h) | Wind direction (degrees) | Hourly FFMC | Hourly ISI | DMC | DC | BUI | Hourly FWI |
|---|---|---|---|---|---|---|---|---|---|
| 23 | 21 | 7[a] | 254 | 92 | 8.4 | 30 | 206 | 44 | 18.4 |
| 23 | 21 | 13[b] | 254 | 92 | 11.6 | 30 | 206 | 44 | 23.2 |

[a] Average wind speed
[b] Wind gust
BUI, Buildup Index
DC, Drought Code
DMC, Duff Moisture Code
FFMC, Fine Fuel Moisture Code

[1] Adjusted according to Lawson, Armitage, & Hoskins (1996)

## Fuel moisture

AAF collected fuel moisture samples from the surface mulch before ignition. The results are shown in Table 3.

Table 3. Fuel moisture content in the surface mulch at 2 p.m.

| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Average |
|---|---|---|---|---|---|---|
| Moisture content (%) | 4.5 | 7.4 | 2.4 | 6.4 | 1.9 | 4.5 |

## Fire behaviour

Ignition took place at the south end of the ignition line and continued to the north by a hand torch. The head of the fire was not uniform as it approached the testing plots and reached the plots at different times and with different intensities. The following notes summarize the major events during the experiment:

**14:55:13** Wind: 9G15SSW[1]

- Line ignition started from south to north.

[1] In this notation, 9 refers to the average wind speed, as 9 km/h; G15 refers to the wind gust, as 15 km/h; SSW refers to the wind direction, as south-southwest

**15:07:20** Wind: 6G13W

- Fire reached the front of the CL 8 plot, the most southerly plot.
- The head of the fire hit the plot directly (Figure 3).


Figure 3. The image captured from Cam 26 video footage when fire reached the front of the CL 8 plot.

**15:07:57** Wind: 7G12SSW

- Fire with a flame height of 0.8 m reached the front of the CL 2 plot.
- The fire burned the untreated mulch fuel outside the CL 8 plot quickly. Fire whirls were observed, the rate of spread did not slow down, and the flame height did not drop in that area.
- Only one-quarter of the CL 8 plot was burned at the time, and the flame height was below 0.5 m inside the plot.
- The fire front was drawn southeast due to higher fire intensity in the south, despite the wind direction shifting south-southwest (Figure 4).


Figure 4. The image captured from Cam 26 video footage when fire reached the CL 2 plot.

**15:10:05** Wind: 6G15SW

- Fire with a flame height of 1.5 m reached the front of the CL 0 (control) plot.
- Most of the CL 8 plot was consumed; the flame height was 0.3 m inside the plot.
- 50% of the CL 2 plot was consumed; the flame height dropped to 0.4 m.
- Wind shifted and the head of the fire switched from the south side to the east side in front of the CL 0 plot (Figure 5).


Figure 5. The image captured from Cam 27 video footage when fire reached the CL 0 (control) plot.

**15:13:57** Wind: 7G15SW

- Fire with a flame height of 0.5 m reached the front of the CL 4 plot.
- The CL 8, 2, and 0 plots were totally consumed by fire.
- There was visible charring from the retardant on the CL 8 and 2 plots.
- The south side of the CL 4 plot was burning before fire reached the west side of the plot due to the higher fire intensity inside the CL 0 plot and wind direction from the southwest (Figure 6).


Figure 6. The image captured from Cam 28 video footage when fire reached the CL 4 plot.

**15:28:51** Wind: 6G12NNW

- Fire with a flame height of 0.3 m reached the front of the CL 4 wet plot.
- 50% of the CL 4 plot was consumed, and the flame height dropped to 0.3 m.
- Due to the wind direction, the flame was pointed southeast, parallel to the fire line. Fire spread toward the CL 4 wet plot eastward slowly and was driven by fuel, not the wind (Figure 7).


Figure 7. The image captured from Cam 28 video footage when fire reached the CL 4 wet plot.

**15:43:28** Wind: 7G10WSW

- Fire with a flame height of 0.2 m reached the end of the CL 4 wet plot.
- Patchy flames were visible inside the CL 4 wet plot.
- Most of the CL 4 plot was smouldering.

# Comparisons of fire intensity and area burned

Table 4 shows the comparison in fire intensity between the plots. The CL 8 plot had 95% burned area, and the CL 4 and 2 plots had 100%. The reduction in flame height was noticeable (Table 5). An 80% reduction in flame height was recorded for the CL 8 plot, 40% for the CL 4 plot, and 50% for the CL 2 plot.

Table 4. Fire intensity comparison

| Plot | Location | Flame height (m) | Rate of spread (m/min) | Average depth of burn (cm) | Fuel consumption (kg/m$^2$) | Fire intensity (kW/m) | Area burned (%) |
|---|---|---|---|---|---|---|---|
| CL 0 | In front of | 1.5 | 0.45 | 5.5 | 4.8 | 648.0 | |
| | Inside | 1.2 | 1.29 | 5.25 | 4.6 | 1766.2 | 100 |
| CL 2 | In front of | 0.8 | 0.87 | 6.5 | 5.7 | 1487.7 | |
| | Inside | 0.4 | 0.44 | 4.0 | 3.5 | N/A | 100 |
| CL 4 | In front of | 0.5 | 0.44 | 5.0 | 4.3 | 567.6 | |
| | Inside | 0.3 | 0.17 | 7.5 | 6.5 | N/A | 100 |
| CL 4 wet | In front of | 0.3 | 0.25 | 5.0 | 4.3 | 322.5 | |
| | Inside | 0.2 | 0.15 | 1.9 | 1.7 | N/A | 80 |
| CL 8 | In front of | 1.5 | 0.88 | 6.5 | 5.7 | 1504.1 | |
| | Inside | 0.3 | 0.81 | 4.0 | 3.5 | N/A | 95 |

Table 5. Decrease in fire intensity variables between the front and inside of the plots

| Plot | Flame height decrease (%) | Rate of spread decrease (%) | Average depth of burn decrease (%) |
|---|---|---|---|
| CL 0 | 20 | –187[a] | 5 |
| CL 2 | 50 | 49 | 38 |
| CL 4 | 40 | 61 | –50 |
| CL 4 wet | 33 | 40 | 62 |
| CL 8 | 80 | 8 | 38 |

[a] Negative value indicates rate of spread increase

Images were taken before and after the fire passed through the testing plots and were compiled in Table 6 to determine the area burned.

Table 6. Visual comparison of the plots before and after the fire passed through

| Plot | Before | After |
|---|---|---|
| CL 0 |  |  |
| CL 2 |  |  |
| CL 4 |  |  |

| | | |
|---|---|---|
| CL 4 wet | N/A |  |
| CL 8 |  |  |

# DISCUSSION

The data from this experiment shows that the retardant reduced fire intensity effectively on mulch fuel, but it did not extinguish the fire, and active flames were still visible in all plots (Figure 8. Fire intensity comparison between the control and retardant plots). Eventually, fire burned most of the surface area of the dry retardant-covered plots. In-fire camera footage showed that the retardant plots continued to smoulder after the head of the fire passed through.


Figure 8. Fire intensity comparison between the control and retardant plots.

Since the fire encroached all retardant plots, the researchers concluded that the size of the test plots (2.5 m by 2.5 m) was too small for the retardant to reduce fire intensity below the combustion point before reaching the end of a plot. The fire would stop if the fire intensity was lower than the combustion point of the adjacent fuels because the effect of retardants on fire is to form more char and fewer flammable volatiles, thereby reducing the overall intensity of flaming combustion (Rothermel & Philpot, 1974). Therefore, a wider testing plot is required in the future to observe the extinguish.

Furthermore, the fire within a plot influenced the fire behaviour in the adjacent plots because the plots were connected. For example, the intense ground fire in the CL 0 plot ignited the south side of the CL 4 plot before the main fire front arrived at the west side. In future experiments that challenge a testing plot in one direction, it is important that the approaching fire be controlled.

Figure 9 shows a retardant drop from an AT-802 air tanker using the CL 4 setting. The drop footprint averaged 18 m wide and 80 m long (Solarz & Jordan, 2000). In future experiments, it would be more realistic to replicate a test plot the size of a tanker drop and increase the coverage levels gradually toward the centre of the plot.

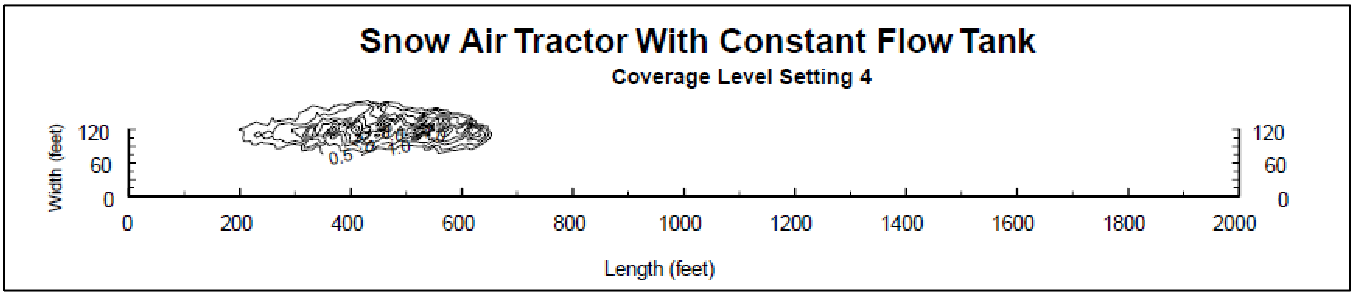


Figure 9. Drop pattern characteristics of the Snow Air Tractor using a coverage level setting of 4. The contour lines are at coverage levels of 0.5, 1, 2, 3, 4, 5, 6, 8, and 10 (Solarz & Jordan, 2000).

There was a measurable decrease in flame height, rate of spread, and average depth of burn in most plots (Table 6). All plots varied in terms of the degree of fire behaviour reduction. Therefore, there was no consistent pattern of reduction in fire behaviour between coverage levels. Other than being influenced by the retardant's chemical effects, fire behaviour was affected by the combination of wind speed and direction, fuel moisture, fuel structure, retardant coverage level, and changes in retardant moisture following application. In future experiments, these factors should be controlled or closely monitored.

There were two exceptions when comparing the reduction in fire behaviour between plots: the rate of spread increased by 187% at the CL 0 plot, and the average depth of burn increased by 50% at the CL 4 plot. The causes are presumed to be either a sudden gust of wind or changes in the fuel structure. However, these two exceptions could not be explained by the weather data that was collected because it did not show a significant difference in wind speed.

The on-site weather station recorded weather conditions every 2 minutes and thus could not show the timing of wind gusts in more detail. Wind speed is one of the most important environmental factors in changing fire behaviour. By compiling the data from Rothermel and Philpot (1974), the researchers of the current study concluded that the rate of spread increased due to an increase in wind speed (Appendix 2). These experiments were conducted on a fuel bed covered with retardant chemicals on a burn table inside a wind tunnel. Reducing the time between data collection will help to understand the effects of wind gusts on retardant-covered fuels in more detail and is recommended for future experiments.

Garden watering cans were chosen for applying retardant on plots because they were readily available at hardware stores and are easy to operate. However, the holes in the sprinkling heads became plugged by retardant residue over time, and it became difficult to apply the retardant on the plots evenly. This resulted in gaps in retardant coverage on the mulch surface. Researchers need to explore a new method for applying retardant on the ground in the future.

The researchers of the current study tried to compare the difference in performance between the dry and wet retardant. In this experiment, 20% of the area was unburned at the CL 4 wet plot and 100% was burned at the CL 4 dry plot. The fuel consumption was 3.8 kg/m2 in the CL 4 wet plot and 7.4 kg/m2 in the CL 4 dry plot. However, the fire intensity approaching these two plots was different. The flame height was 0.2 m higher in front of the CL 4 dry plot than the CL 4 wet plot. The rate of spread was 0.19 m/min faster in front of the CL 4 dry plot than the CL 4 wet plot. The data from this experiment cannot be used to demonstrate the difference in performance between dry and wet retardant because the intensity of the fires approaching the two plots was different.

Sullivan's experiment (2014) of using a radiant panel to radiate chemical-covered trees was a better demonstration of the performance of dry and wet retardant. In this study, the tree branches covered with wet retardant did not burn after being radiated for 7 minutes, and the branches covered with dry retardant had a mean ignition time of 67 seconds.

Rothermel and Hardy (1969) showed that the rate of spread increased significantly (7% to 90%) by reducing the moisture content of long-term retardant from 33% to 15%. The authors explained that this effectiveness resulted from chemicals preventing flaming and the additional moisture content preventing combustion; therefore, a higher moisture content in retardant is more effective in retarding wildfire.

These two studies provide conclusive evidence of the flame-retarding properties of dry and wet retardants, and future investigation is not required.

The following lessons were learned:

- The retardant reduced fire intensity, but the fuel continued to smoulder after the flame front passed.
- The size of test plots was too small compared to an air tanker drop.
- Increasing the frequency of weather data collection will help gain insight about fire behaviour.
- Using a garden watering can to apply retardant resulted in coverage gaps on a horizontal mulch surface. Another method of applying retardant is needed.

After consulting with other experts,[1] it is suggested that future experiments replicate drop patterns from air tankers by using different retardant applicators.

# VIDEO

Live video footage of parts of the experiment is available at https://youtu.be/tbVlowwlMm8.

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- AAF
- Campbell Scientific Canada
- Canadian Forest Service, Natural Resources Canada
- University of Alberta

[1] Ray Ault, Dave Schroeder, and Greg Boyachuk

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# APPENDIX 1: WEATHER DATA DURING THE PRESCRIBED BURN ON MAY 15, 2018

| Time | Air temperature | Relative humidity | Wind speed | Gust | Wind direction | Precipitation | Solar radiation |
|---|---|---|---|---|---|---|---|
| hh:mm | °C | % | m/s | m/s | degree | mm | W/m$^2$ |
| 14:54 | 23.1 | 22.7 | 2.46 | 4.05 | 252.5 | 0 | 804 |
| 14:56 | 22.8 | 22.7 | 2.06 | 3.34 | 205.3 | 0 | 430 |
| 14:58 | 22.3 | 22.8 | 1.71 | 2.81 | 221.2 | 0 | 183 |
| 15:00 | 22.2 | 22.9 | 1.75 | 2.62 | 249 | 0 | 278 |
| 15:02 | 22.3 | 23.0 | 2.34 | 3.88 | 259.7 | 0 | 777 |
| 15:04 | 22.9 | 22.7 | 2.44 | 3.61 | 251.6 | 0 | 812 |
| 15:06 | 22.4 | 23.0 | 2.92 | 5.69 | 260.3 | 0 | 815 |
| 15:08 | 23 | 22.0 | 1.9 | 3.39 | 194.2 | 0 | 825 |
| 15:10 | 23 | 21.8 | 1.7 | 4.17 | 229.6 | 0 | 747 |
| 15:12 | 22.8 | 21.9 | 1.87 | 4.33 | 217.5 | 0 | 796 |
| 15:14 | 22.9 | 21.4 | 2.02 | 4.58 | 228.6 | 0 | 766 |
| 15:16 | 22.6 | 22.1 | 1.66 | 3.69 | 276.5 | 0 | 750 |
| 15:18 | 22.7 | 22.0 | 1.56 | 2.95 | 293.5 | 0 | 509 |
| 15:20 | 22.4 | 22.2 | 1.63 | 3.34 | 333.8 | 0 | 462 |
| 15:22 | 23 | 21.3 | 1.14 | 2.63 | 304.8 | 0 | 723 |
| 15:24 | 22.8 | 21.9 | 1.45 | 1.79 | 341.3 | 0 | 613 |
| 15:26 | 22.9 | 21.9 | 1.79 | 2.57 | 279.6 | 0 | 740 |
| 15:28 | 23.6 | 21.4 | 2.65 | 4.68 | 240.9 | 0 | 735 |
| 15:30 | 23.6 | 21.3 | 3.23 | 5.04 | 227.5 | 0 | 723 |
| 15:32 | 23.4 | 21.2 | 2.71 | 4.72 | 224.7 | 0 | 716 |
| 15:34 | 23.7 | 20.9 | 3.23 | 5.55 | 233.7 | 0 | 716 |
| 15:36 | 23.3 | 20.3 | 1.88 | 3.12 | 225.9 | 0 | 719 |
| 15:38 | 23.3 | 20.0 | 1.71 | 2.71 | 266.1 | 0 | 718 |
| 15:40 | 23.4 | 20.7 | 2.68 | 4.68 | 253.7 | 0 | 712 |
| 15:42 | 23.6 | 19.9 | 1.82 | 2.51 | 254.1 | 0 | 715 |
| 15:44 | 24 | 19.0 | 1.91 | 2.87 | 251 | 0 | 709 |
| 15:46 | 23.8 | 20.0 | 3 | 4.42 | 285.4 | 0 | 702 |

# APPENDIX 2: RATE OF SPREAD INCREASES WITH WIND SPEED INCREASE[a]

| Retardant | Fuel[b] | Average rate of spread increase (%) | Average rate of spread increase (%) |
|---|---|---|---|
| | | Wind speed increase from 0 to 2 mph (0 km/h to 3.2 km/h) | Wind speed increase from 2 to 5 mph (3.2 km/h to 8 km/h) |
| None | Pine needles | 67 | 132 |
| | Excelsior | 79 | 69 |
| | ¼ inch sticks | 296 | 37 |
| Diammonium phosphate | Pine needles | 58 | 74 |
| | Excelsior | -5 | 172 |
| | ¼ inch sticks | 72 | 104 |
| Ammonium sulphate | Pine needles | 45 | 195 |
| | Excelsior | –5 | N/A |
| | ¼ inch sticks | 504 | 50 |

[a] Calculation from Rothermel and Philpot (1974)

[b] Fuel was dipped into the solution to ensure that it was covered in retardant

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