# Using NEXUS to Assess the Effectiveness of Experimental Black Spruce Forest Fuel Breaks to Reduce Crown Fire Potential in Alaska

*Photo by BLM AFS - Ben Pratt*

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## PHOTO CREDITS

A passive crown fire burns in black spruce feathermoss on the Manchu Range Prescribed Burn near Fairbanks, Alaska. Cover photo by Ben Pratt.

Fuels treatment demonstration site (treatment & control) located near Delta Junction, Alaska. Photos by Randi Jandt.


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***Abstract* –** Alaskan black spruce often exhibits extreme fire behavior that threatens human values. Theoretical crown fire potential at three recently constructed fuel break treatments were assessed to reducing such risks. Available canopy fuels were reduced by 13% to 75% in thinned and pruned units compared to controls. Scenarios were developed under hot, dry windy weather and average summer day conditions using the Nexus 2.0 fire behavior modeling program. Projected fireline intensities and flame lengths were little changed in two of three treated units, while headfire rates of spread were almost doubled in the treatments relative to the control under certain conditions. Simulations indicated fuel modifications did not preclude crown fire activity, but did reduce the crown fraction burned, indicating a lower potential for spotting. The threshold for sustained active crown fire development was substantially higher in the open treated stands compared to the denser control stands. Fuels modifications effectiveness in altering fire behavior was a trade-off under both weather scenarios.

***Keywords* –** fire behavior; crown fire; fuel treatment; Alaskan black spruce

## INTRODUCTION

In recent years, the occurrences of large wildland urban interface fires in the Alaska, particularly the Miller's Reach Fire (1996) in south central Alaska and the Caribou Hills fire on the Kenai Peninsula (2007), have encouraged development of new fire management tactical strategies involving fuels hazard reduction to protect targeted values at risk. Crown fire potential in boreal forest fuels is relatively high due to ladder fuels and the continuity of aerial fuels (Van Wagner 1977, Norum 1982). Fuels reduction treatments involve decreasing fuel loading and modifying stand structure around villages and communities to reduce crown fire potential in case of encroachment by wildfire (Figure 1). Although structures are the most immediately recognized values at risk, wildfires also pose threats to firefighter safety and public health (Cohen & Butler 1998). Fire management efforts to employ fuel breaks are designed to reduce these risks.

Fire behavior is determined by three factors: fuels, weather, and topography (Rothermel 1983). Fuel (vegetation) structure, composition, moisture content, and quantity influence how fuels burn (Agee 2002). Weather (temperature, relative humidity, wind, and precipitation) influences the occurrences and subsequent fire behavior (Rothermel 1991). Topography influences rates of spread, particularly when steep slopes and drainages are present (Rothermel 1983, 1991). Characteristics of fire behavior include: rate of spread (scaled between surface & crown fire "final" headfire spread rates for conifer simulations in chains per hour; Scott 2004), flame length which is directly related to fireline intensity (rate of heat release per until length; Byram 1959), surface fire transition to crown fire, and spotting (ignition ahead of the fire front by airborne embers). Such characteristics are usually defined and modeled, or measured associated with a flaming front spreading with the wind and slope (Van Wagner 1977), or headfire, but can also be a flanking or backing fire (Rothermel 1983).

**Figure 1** – Delta site *(left)* control stand and *(right)* treated 10x10 feet spacing and pruned stand. Photos by R. Jandt.

Boreal forest fuel types are considered to have a high risk of large and destructive fires because they have high potential rates of spread, particularly Alaskan black spruce (*Picea mariana* [P.Mill.] B.S.P.) which often exhibits extreme fire behavior (Norum 1982). Alaskan black and white spruce *(P. glauca* [Monech] Voss) combined cover about 100 million acres of the state. Fire is the dominant disturbance in these fuel types with most fires occurring in black spruce (Foote 1983, Barney et al.1978). Black spruce is a distinctive fuel type because it often features a dense canopy, branches extending to the ground, a dense forest floor of feather moss, and is often continuous in the landscape for many miles (Norum 1982, 1983). Such features allow crown fire initiation at lower fire intensities and high relative humidity. For example, in black spruce forest with a feathermoss understory a fire burns slowly but consistently at 50% relative humidity (RH), at 40% RH occasional torching occurs, at 30% RH increase in intensity and torching behind the front occurs, and at less than 30% RH a hot running fire develops (Norum 1982).

Surface fire spreads through the surface fuels, including live mosses, needles, leaves, grass, forbs, dead and downed branches and boles, stumps, shrubs, and short trees, while crown fires burn in the tree canopies. Crown fire initiation occurs when the surface fireline intensity reaches the threshold to ignite the aerial fuels (Van Wagner 1977) or by "mass ignition" from spotting (Byram 1966). Crown fire initiation is dependent on fireline intensity, foliar moisture content, and canopy base height, and crown fire sustainability requires an overstory (canopy bulk density) capable of carrying a crown fire (Rothermel, 1991, Van Wagner 1977). Crown fires are common in black spruce forest because of the low canopy base height (Norum 1982) and very low foliar moisture content relative to other species. Springer and Van Wagner (1984) measured foliar moisture contents in black spruce and found the lowest moisture contents of 75% to 80% from May through mid-June. Fire managers are especially concerned with crown fires as they are more difficult to control because of faster rates of spread and increased flame length when compared to surface fires (Rothermel, 1983).

Van Wagner (1977) described three types of crown fires: passive, active, and independent. A passive, or intermittent, crown fire involves individual tree torching or fire burning into the crown occasionally, but not continuously. An active crown fire is a dependent wall of flames from the surface-into-tree-canopy fuel complex burning as a single unit, but dependent on the surface fire intensity, as well as a continuous and moderately dense canopy. Independent crown fire occurs when the aerial canopy fuels are actually burning in advance of the surface fire, independent of surface fuels. Fires in boreal spruce often burn into the crowns of the trees and tree mortality is usually near 100%, yet an independent crown fire is rare (Norum 1982, Van Wagner 1977). Active dependent crown fires are common in upland boreal spruce with a closed canopy, while passive crown fire characterizes open canopied woodlands (Johnson 1992).

Crown fires present greater challenges to control effects as well as a threat to human values. With the increased flame lengths, larger firefighter safety zones are required (Cohen and Butler 1998). Direct attack is precluded because of flame lengths that are not easily suppressed by normal firefighting tactics. When fire reaches the crown the effect of wind is greater (Norum 1983). Crown fires are associated with frequent spotting up to one mile from the origin in the presence of wind (Albini 1979) because firebrands (small twigs, segments) are produced and blown ahead of the fire and can ignite spot fires facilitating rapid fire growth (Rothermel 1991). Dependent on the probability of ignition, spotting has the potential to span across large natural and man-made barrier and ignite fuels ahead of the front. Spotting and increased flame radiation from crown fires makes structure ignition more likely relative to surface fires (Cohen 1996).

Stand structure and wildfire behavior are strongly associated (Van Wagner 1977), thus the combination of dense tree canopies and low canopy base height with extreme fire weather provides the conditions required for crown fire activity. Treatments targeting removal of ladder fuels and reducing bulk density would be expected to limit or moderate the probability of a crown fire. Yet, recent fuel break treatments in black spruce have been shown to cause understory duff to become drier in opened stands (Jandt et al. 2005) increasing rate of spread and fireline intensity compared to dense stands (Theisen 2003). Furthermore, fuel treatments in boreal forest types have other effects on vegetation, such as drying surface fuels, vegetation type changes, and microclimate changes, and actual fire behavior changes in treated stands have never been observed or tested. Fire managers need a way to assess the effectiveness of these treatments in boreal forest types to determine whether they actually offer protection to communities. The combined reduction of fuel continuity in crown bulk density and removal of ladder fuels would be expected to reduce or moderate potential initiation and propagation of crown fires. Reducing crown fire decreases the chances of developing large and destructive wildfires that threaten human values in the wildland urban interface.

The objective of this study was to model fire behavior in three demonstration treated and control stands to assess their effectiveness as defensible space in case of an accidental fire around communities. The experimental five-acre shaded fuel break (thinning and pruning) treatment sites located at Ft. Wainwright, Delta, and Nenana were developed in 2001 and 2002 with support from the Joint Fire Science Program, the Alaska Fire Service, Tanana Chiefs Conference and the State of Alaska, Division of Forestry. Fire weather conditions were simulated in these treatment and control stands for an average summer day and a hot, dry windy day using a fire behavior modeling program (NEXUS 2.0: 2004) to assess the effectiveness of shaded fuel break treatments to reduce crown fire, fireline intensity, and headfire spread rate.

# METHODS

### *Study Area*

This study included three Joint Fire Science Fuels Demonstration sites located in interior Alaska. The Ft. Wainwright shaded fuel break is located on federal lands operated by the U.S. Army, near Fairbanks. The Delta Bison Range site is located approximately 130 mile southeast of Fairbanks near Delta Junction. The Nenana site is on Toghotthele Native Corporation lands located 45 miles southwest of Fairbanks near the village of Nenana (Fig. 2). The sites were treated in 2001, 2002, and 2001 for Ft. Wainwright, Delta, and Nenana respectively.

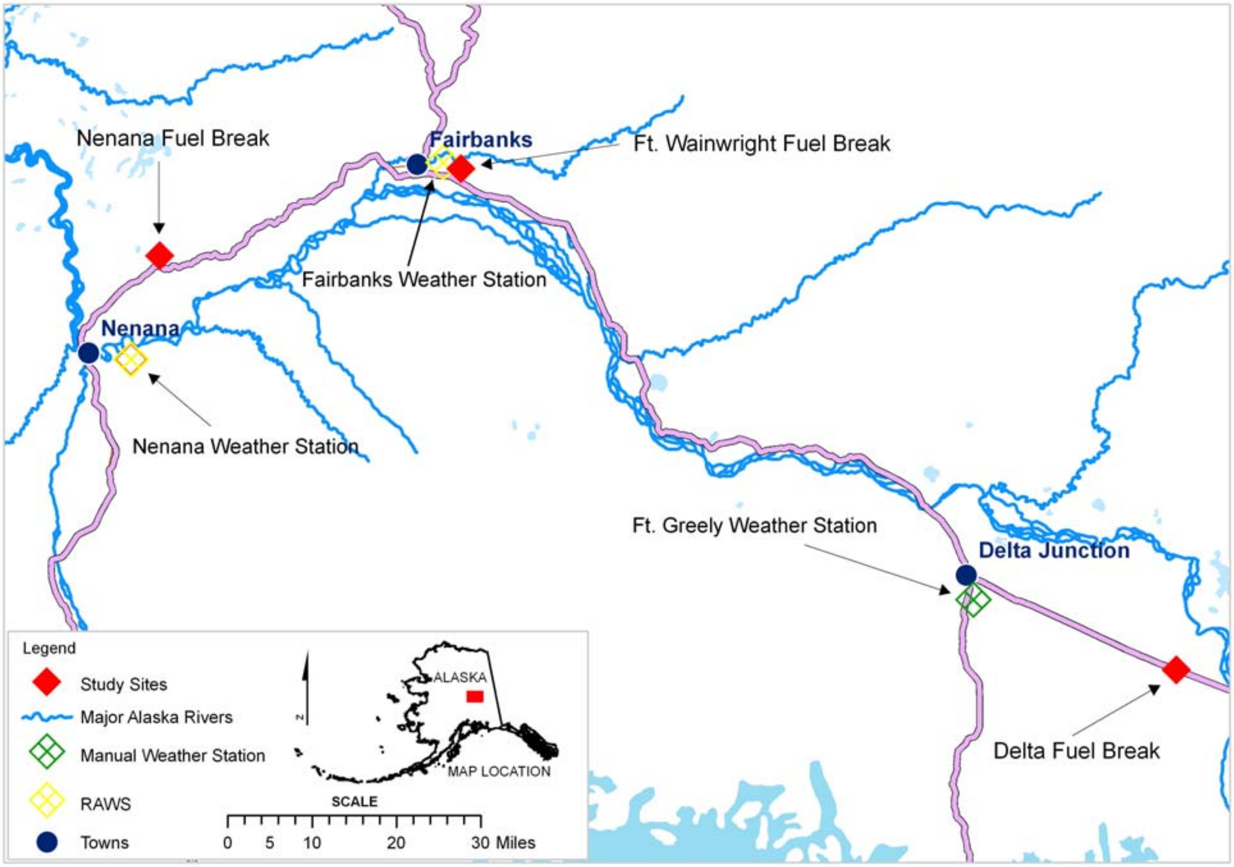


**Figure 2 –** Locations of shaded fuel break demonstration study sites and weather stations.

Vegetation on the sites was closed black spruce (*Picea mariana*) forest with feathermoss understory (*Hylcomium splendens* [Hedw.] Br.Eur.) understory as described by Viereck (1992) and is very representative of interior Alaska fuels. Permafrost underlays all sites with a summer active layer[1] ranging from 20-50 cm. Slopes were generally flat or with a slight northern exposure (Nenana site). Stands ranged from 70 to 80 years old based on tree ring data collected from the sites (Juday pers.comm.). Each of five one-acre blocks at the three locations received different thinning treatments—control, 10'x10' spacing, 10' x10' spacing and pruned, 8' x 8'

[1] The active layer is the layer of soil over permafrost that seasonally thaws.

spacing, and 8’ x 8’ spacing and pruned. For this study, we selected the 10’ X 10’ pruned treatment (10P) and the control for comparisons of modeled fire behavior.

### *Data Collection*

Five sample plots sized 30’ x 30’ were installed in each of the five treatments to measure and tally trees. Live and dead trees were divided into size classes ( 0-2", 2.1-4", 4.1-9") based on diameter at breast height (DBH). DBH was measured with a metric diameter tape. Trees were tallied and recorded by species. Five trees in each size class were tagged and measured to yield base height to ladder fuels, crown length, and tree height calculated from clinometer measurements. Down woody fuels, understory vegetation and ground cover, overstory cover, and active layer depth were measured along 50’ sample lines that extended diagonally through the tree measurement plots. Fuel loadings were estimated for each treatment block by averaging measurement data from the 30’x 30’ plots.

### *Canopy Fuels Inputs*

Canopy fuel loading and canopy bulk density were estimated using Barney and Van Cleve’s (1973) allometric equations for upland black spruce. The total above ground biomass fuel is assumed uniformly distributed and continuous. Above ground mass (individual tree) total tree dry weight was computed as

$$log_e\, y = a + b\, log_e\, x \qquad (1)$$

where $y$ = the total tree dry weight in grams of an individual tree, $x$ is the average basal diameter, $a$ is 2.74, and $b$ is 2.09, which are regression coefficients. This equation was very predictive for biomass in black spruce ($R^2$ = 0.82). Basal stem diameter was derived from measured diameter at breast height (DBH) by increasing DBH by 11% for black spruce (Juday, pers.comm.). Solving equation (1) gives

$$y = c\, x^{\mathrm{b}} \qquad (2)$$

where $c$ =15.420, and $b$ = 2.09, and $x$ = basal stem diameter in cm. The total canopy fuel loading (available canopy foliage in kg/m$^2$) by plot was then computed as the fuel loading (individual crown foliage tree in grams, value from equation 1) multiplied by the number of stems per acre. Plot averages of tree base height to the height to ladder fuels were used to determine canopy base height. Tree crown length was calculated by subtracting the height to ladder fuels from the total tree height.

Canopy bulk density (CBD; kg/m$^3$) was estimated by dividing canopy fuel loading by the canopy length where canopy fuel loading is the total fuel loading (kg/m$^2$) from equation 2, and canopy length is the average canopy length (m) per diameter class. To obtain available canopy foliage and canopy fine dead fuels as required for NEXUS input, the total above ground mass and canopy bulk density was computed as 42% of the total tree biomass value after Barney and Van Cleve (1977).

Percent canopy closure (percentage of cover from the canopy that shades the understory fuels) was computed as the number of hits (number of points which cover occurred at) divided by points (the total number of points possible on the transect).

### *Weather Analysis*

Weather in treatment (10P) and controls was collected on-site using Hobo weather data loggers to record microclimate differences in percent relative humidity, eye-level windspeeds, and dry bulb temperatures. Differences in paired weather data were applied to treatment stand values to adjust it relative to standard percentile weather (Table 6). On-site weather data was collected at a different site each year, i.e. Ft. Wainwright was collected in summer of 2002, Delta in 2003 and Nenana in 2004. On-site weather data was collected from June 20 to Aug. 31, June 7 to July 22, and June 4 to Aug.12 for Ft. Wainwright, Delta, and Nenana respectively.

Historical weather observation data was ranked by percentile using FireFamily Plus 3.0 (Bradshaw & McCormick 2000) fire climatology software program. Weather stations with the closest proximity to fuel treatment sites were utilized (Fig 2). Fairbanks (FBK) Remote Automated Weather Station (RAWS) data was available from 1998 to 2004 and Delta/Ft. Greely (PABI) and Nenana (PANN) manual stations data was available from 1955 through 2004.

### *Fuel & Fire Behavior Model*

Dynamic new behavior fuel models were recently developed by Scott and Bergan (2005) in addition to the standard 13 fuel models from Anderson (1982) to improve accuracy of fire behavior predictions. New fuel models incorporate moisture of extinction and the ability to simulate surface to crown fire initiation. Alaskan black spruce feathermoss fuel type was determined as dwarf conifer with understory (TU4; Scott & Burgan 2005). The primary carrier of fire in TU4 is short conifer trees with grass or moss understory. Spread rate and flame length are moderate. Fine dead fuel load is estimated at 6.5 tons/ac and moisture of extinction is 12%.

The fire behavior program NEXUS 2.0 (Scott 2004) is a modeling program developed to predict crown fire behavior potential in different treatments using either the new standard or original fire behavior fuel models. NEXUS uses inputs of surface fuel moisture (1-hr, 10-hr, 100-hr), foliar and woody fuel moisture contents, canopy fuel loading and bulk density, open windspeeds and direction, and slope to simulate surface and transitional fire behavior (type of fire, crown fraction burned, spread rate, fireline intensity, flame length), and crown fire potential indices (torching, crowning, & surface index), critical initiations and sustainable crown fire behavior thresholds for a given treatment. NEXUS and Behave modeling programs both use Rothermel's spread equation, but NEXUS links existing models of surface fire behavior and crown fire behavior to estimate "surface-through-crown" fire behavior and compare relative crown fire potential differences in fuels treatments (Scott & Reinhardt 2001, Scott 2004).

### *Simulation Inputs*

Scenarios were developed in NEXUS to compare the most extreme treatment (10P) of the four treatments and control. Simulations were run using the dwarf conifer with understory (TU4) fuel model. Because black spruce has a canopy that overlays the surface fuels, the conifer crown fire simulation was selected. Conditions used to calculate percent fine dead fuel[1] moisture content from a period of solar noon (1400 ADT) to peak burning (1600 ADT) conditions are summarized in Table 1. The conditions were entered into NEXUS 2.0 Fire Behavior Analyst (FBA) moisture lookup utility.[2] Average summer 1-hour timelag fuel moisture conditions and

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[1] 0 to 0.25 inch diameter fuels—needles, deadwood, and fine fuels—expressed in dry weight.
[2] Equivalent to Rothermel's (1983) tables.

low 1-hour fuel moisture summer conditions were both calculated using historical percentile relative humidity (RH) and temperatures. To approximate 10-hour timelag fuel moistures, 1% was added to the fine dead fuel moistures calculated and 2% was added to 1-hour for 100-hour timelag fuel moistures (Rothermel 1983). Live woody fuel moisture was estimated at 100% in both fuel moisture simulations (J. Scott, pers. comm.). Foliar moisture content was also estimated at 100% (mature foliage) based on Norum's (1982) data for live fuel moisture contents. To simulate times of high fire danger (hot, dry and windy) 90$^{th}$ percentile weather was used and to simulate average summer weather conditions, 70$^{th}$ percentile weather was used. On-site weather data collected with paired dataloggers was used to indicate microclimate differences between treated and control stands (Ott and Jandt, 2005). These differences were used to adjust temperature and RH in the treated stands from historical averages.

| ***Input*** | ***Value*** |
|---|---|
| Time of day | Daytime |
| Temperature, degrees F | Corrected percentile weather |
| Relative humidity, percent | Corrected percentile weather |
| Season | Summer |
| Shading | Exposed > 50% canopy cover<br>Shaded < 50% canopy cover |
| Time of day | 1400-1600 |
| Elevation | Level |
| Aspect | North |
| Slope steepness | Flat |

**Table 1 –** Summary of conditions used to calculate fine dead fuel moisture content.

Because wind is restricted by friction near the surface, the 20-ft windspeed is normally adjusted to a height above the surface fuels equivalent to the "mid-flame" (mid-level height of flames) windspeed in order to more accurately predict fire behavior[1] (Norum 1983, Rothermel 1983). For these simulations, wind adjustment input values of 1.0 were used in all treatment and controls because actual on-site eye-level wind observation data was collected. Midflame windspeed differences were used to adjust treatment stands wind input value by using on-site weather data from Ott and Jandt (2005). Since open-treated (thinned) stands had more wind than dense-control stands, the input windspeed was adjusted by adding the mean difference in windspeed when wind was present from on-site weather to the percentile wind value (Tables 3&4).

**Table 2 –** Summary of **canopy fuels** simulation inputs. The treated stand was thinned to 10'x10' spacing and pruned to four feet.

| | Treated Stand | | | Control Stand | | |
|---|---|---|---|---|---|---|
| *Input* | Ft. Wainwright | Delta | Nenana | Ft. Wainwright | Delta | Nenana |
| Canopy bulk density, kg/m$^3$ | 0.07 | 0.12 | 0.15 | 0.34 | 0.45 | 0.23 |
| Canopy base height, m | 0.92 | 1.62 | 0.98 | 0 | 0.40 | 0.64 |
| Canopy fuel load, ton/ac | 1.58 | 3.10 | 5.36 | 5.89 | 12.32 | 6.18 |

[1] Wind adjustment values in Alaskan black spruce normally ranges from 0.13 to 0.30 depending on canopy cover (Norum 1983).

**Table 3** – Summary of fuel moisture and wind simulation inputs for **dry, windy conditions** (90th percentile weather). Treated stand is 10’x10’spacing and pruned.

| | Treated Stand | | | Control Stand | | |
|---|---|---|---|---|---|---|
| | Ft. Wainwright | Delta | Nenana | Ft. Wainwright | Delta | Nenana |
| *Parameter* | | | | | | |
| 1-hr timelag moisture content, % | 3 | 4 | 4 | 3 | 7 | 4 |
| 10-hr timelag moisture content, % | 4 | 5 | 5 | 4 | 8 | 5 |
| 100-hr moisture content, % | 5 | 6 | 6 | 5 | 9 | 6 |
| Open windspeed, mi/hr | 7 | 17 | 13 | 6 | 15 | 12 |

**Table 4 –** Summary of fuel moisture and wind simulation inputs for **average summer day** fuel moisture conditions (70$^{th}$ percentile weather). Treated stand is 10’x10’ spacing and pruned.

| | Treated Stand | | | Control Stand | | |
|---|---|---|---|---|---|---|
| | Ft. Wainwright | Delta | Nenana | Ft. Wainwright | Delta | Nenana |
| *Parameter* | | | | | | |
| 1-hour timelag moisture content, % | 5 | 6 | 6 | 5 | 9 | 6 |
| 10-hour timelag moisture content, % | 6 | 7 | 7 | 6 | 10 | 7 |
| 100-hour timelag moisture content, % | 7 | 8 | 8 | 7 | 11 | 8 |
| Open windspeed, miles/hr | 5 | 11 | 10 | 4 | 9 | 9 |

## RESULTS

### *Canopy Fuels Differences Among Treatments*

Available canopy fuel loading, available canopy bulk densities, and canopy fuels reduction for treatment and control sites are summarized in Table 5. Available canopy fuels were reduced by 13% to 75% in the thinned (10 ft. spacing) and pruned (4 ft) treatment blocks relative to controls (Table 5). Available canopy bulk density was reduced by 79% at Ft. Wainwright, 73% at Delta, and 35% at Nenana, ranging from 0.07 kg/m$^3$ to 0.15 kg/m$^3$ in the treated and 0.23 kg/m$^3$ to 0.45 kg/m$^3$ in the more dense control stands.

Canopy closure yielded greater than 50% in all treated stands ranging from 10% to 30 % (Fig 3). At two of the control stands (Delta & Nenana sites) canopy closure was at least 50% and one control site (Ft. Wainwright) was less than 50% cover. The understory fuels were simulated as shaded when canopy closure was greater than 50% and exposed for less than or equal to 50%.

**Table 5** – Summary of available canopy fuel loading (foliage and fine dead fuels) and available canopy bulk density by diameter class. Treated stand is 10'x10' spacing and pruned.

| | Treated Stand | | | | Control Stand | | | |
|---|---|---|---|---|---|---|---|---|
| | *diameter class* ▫ | | | | *diameter class* ▫ | | | |
| *parameter* | ≤ 2 *inches* | 2.1 – 4 *inches* | 4.1 – 9 *inches* | Total | ≤ 2 *inches* | 2.1 – 4 *inches* | 4.1 – 9 *inches* | Total |
| **Ft. Wainwright** | | | | | | | | |
| Canopy fuel loading, kg/m$^2$ | 0.05 | 0.16 | 0.15 | **0.35** | 0.87 | 0.38 | 0.06 | **1.32** |
| Canopy fuel loading, ton/acre | 0.21 | 0.72 | 0.65 | **1.58** | 3.89 | 1.71 | 0.29 | **5.89** |
| Canopy bulk density*, kg/m$^3$ | 0.02 | 0.04 | 0.02 | **0.07** | 0.26 | 0.07 | 0.01 | **0.34** |
| *Difference in Canopy Fuel Load* | | | | **-73%** | | | | |
| **Delta** | | | | | | | | |
| Canopy fuel loading, kg/m$^2$ | 0.02 | 0.37 | 0.31 | **0.69** | 0.36 | 2.17 | 0.23 | **2.76** |
| Canopy fuel loading, ton/acre | 0.10 | 1.63 | 1.37 | **3.10** | 1.60 | 9.69 | 1.03 | **12.32** |
| Crown bulk density*, kg/m$^3$ | 0.01 | 0.07 | 0.04 | **0.12** | 0.10 | 0.32 | 0.02 | **0.45** |
| *Difference in Canopy Fuel Load* | | | | **-75%** | | | | |
| **Nenana** | | | | | | | | |
| Canopy fuel loading, kg/m$^2$ | 0.01 | 0.31 | 0.88 | **1.20** | 0.19 | 0.84 | 0.43 | **1.39** |
| Canopy fuel loading, tons/acre | 0.04 | 1.38 | 3.94 | **5.36** | 0.53 | 3.73 | 1.93 | **6.18** |
| Crown bulk density*, kg/m$^3$ | 0 | 0.05 | 0.10 | **0.15** | 0.04 | 0.14 | 0.05 | **0.23** |
| *Difference in Canopy Fuel Load* | | | | **-13%** | | | | |

▫ measurements taken at diameter at breast height (DBH).
* using height to ladder fuels

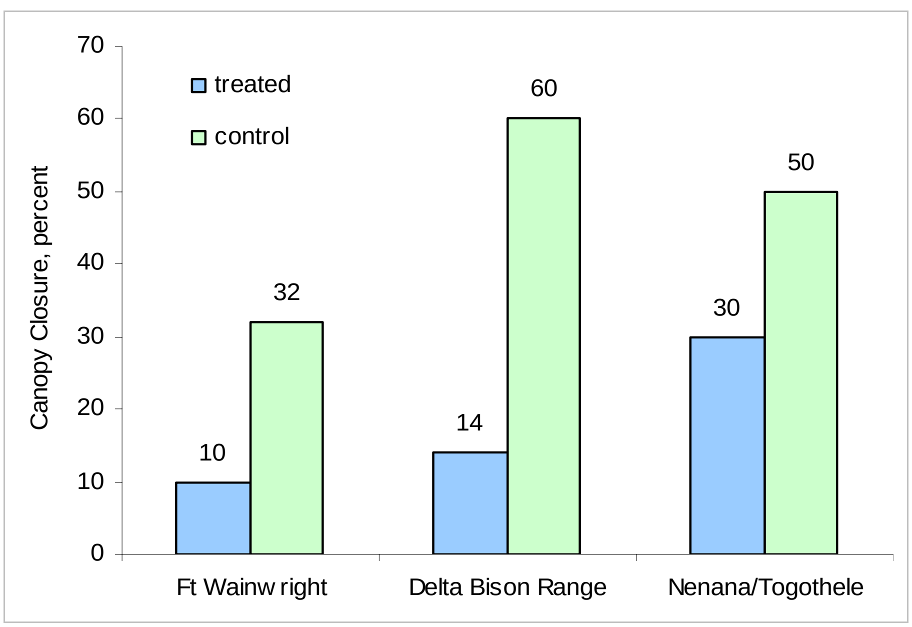



**Figure 3** – Difference in canopy cover at treated (10'x10' spacing and pruned to base height of four feet) and control stands at all three sites.

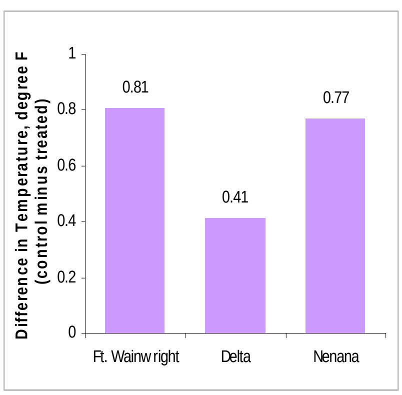
***Weather Differences Among Treatments***

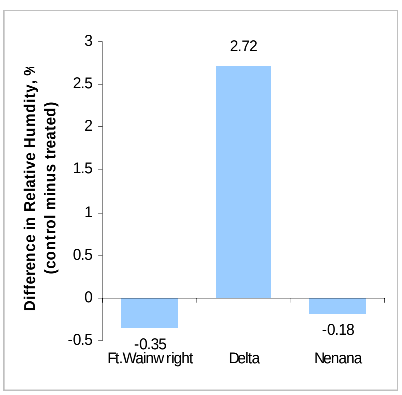
Historical weather, including temperature, relative humidity, and windspeed observations are summarized in Table 6. For two sites (Delta & Nenana) weather was similar, whereas at one site (Fairbanks) weather was warmer and drier but less windy. At Delta and Nenana, dry bulb temperatures ranged from 74°- 75°F in extreme weather and 68°F on average summer days. At Fairbanks the temperature was 83°F during extreme days and 75°F on average summer days. Percent relative humidity varied from 22% - 29% during extreme days and 33% - 39% on average days, with the lowest observations at Fairbanks. Windspeeds (20-ft) at Delta and Nenana ranged from 12-15 mph during extreme days and 9 mph during average days, with the highest windspeeds observed at Delta, whereas Fairbanks 20-ft winds were 50-60% less (6 mph during extreme days, 4 mph during average days). In this paper, weather observations were only taken at solar noon (1400 hours) although diurnal fluctuations were reported by Ott and Jandt (2005).

**Table 6 –** Historical weather by percentile. Observations were taken at solar noon (1400 ADT) from May 1 to Aug 31 annually. AT is Air Temperature in °F, RH is percent relative humidity, and WS is 20-foot windspeed in miles per hour.

| | 90th | | | 80th | | | 70th | | | 60th | | | 50th | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Weather Station* | AT | RH | WS | AT | RH | WS | AT | RH | WS | AT | RH | WS | AT | RH | WS |
| Fairbanks (FBK) | **83** | **22** | **6** | 78 | 28 | 5 | **75** | **33** | **4** | 72 | 38 | 4 | 68 | 44 | 3 |
| Delta (PABI) | **74** | **27** | **15** | 70 | 33 | 12 | **68** | **37** | **9** | 65 | 40 | 8 | 62 | 44 | 7 |
| Nenana (PANN) | **75** | **29** | **12** | 71 | 35 | 10 | **68** | **39** | **9** | 66 | 43 | 8 | 63 | 46 | 7 |

On-site weather variations between the open-treated stands and denser control stands are shown in Fig. 4, 5 and 6, including the most remarkable difference at the Delta treatment and control sites. Mean temperature was lower in the open treated stands at all three sites, by 0.41°F - 0.81°F compared to dense control stands (Fig. 5). Percent relative humidity was slightly higher in the treatments, by 0.18% and 0.35% at Ft. Wainwright and Nenana. In contrast, at the Delta site relative humidity was 2.72% greater in the control stand (Fig. 4). Average windspeed was increased in all three treatments, by 0.7 - 2 mph (Fig. 6).



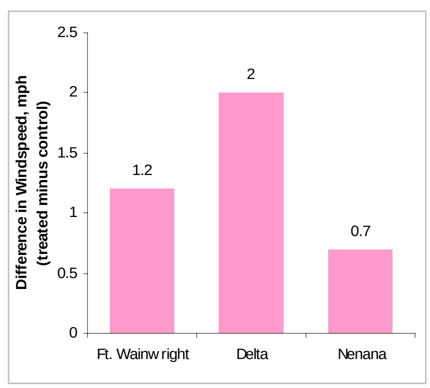




**Figure 4 & 5 & 6**– Difference in relative humidity (left) and air temperature (center) between treated and control stands. Difference in on-site eye-level windspeeds (right) when wind was present (treated minus control) used to adjust treated stands "midflame" windspeeds (Tables 7&8). Observations were taken at solar noon using on-site weather stations.

### *Simulation Outputs During Extreme Weather*

Differences in treatment *vs.* control fire behavior overall projected for dry, windy weather (90th percentile) conditions was less than expected, except the Delta treatment site precluded the potential for an active crown fire. Projected spread rates were slightly *increased* in treated *vs.* control stands at Fort Wainwright and Nenana, and markedly increased at the Delta site. The rate of spread at Fort Wainwright was increased by 27%, Nenana 21%, and Delta 46% (Table 7, Fig. 8). In contrast, flame lengths were substantially reduced by treatment, especially at Delta. The projected flames lengths were reduced by 26% at Fort Wainwright, 17% at Nenana, and 44% at Delta (Fig. 9). Projected fireline intensity was decreased in treatment compared to controls, especially at Delta (Figure 10). Fireline intensity was reduced by 18% at Fort Wainwright, 5% at Nenana, and 39% at the Delta site. Projected critical fireline intensity and critical flame length thresholds illustrate that the treatment does not preclude crown fire behavior at all sites. However, the thresholds for sustained active crown fire (critical bulk density and critical spread rate) have been reduced in all treated stands. The Fort Wainwright treatment site had the greatest reductions of sustained active crown fire potential under both weather scenarios (Tables 7 and 8).

**Table 7 –** Summary of simulation outputs using hot, dry, windy conditions (90th percentile weather). Treated stand was modified to 10'x10' spacing and pruned to four feet base height.

| *Output* | Treated Stand | | | Control Stand | | |
|---|---|---|---|---|---|---|
| | Ft. Wainwright | Delta | Nenana | Ft. Wainwright. | Delta | Nenana |
| Type of fire, nominal | passive | passive | passive | passive | active | passive |
| Crown fraction burned, fraction | 0.08 | 0.57 | 0.49 | 0.43 | 1 | 0.72 |
| Spread rate, chains/hr | 22.37 | 63.71 | 44.83 | 16.23 | 34.59 | 35.27 |
| Heat per unit area, BTU/ft | 1277 | 1762 | 2017 | 2146 | 5310 | 2694 |
| Fireline intensity, BTU/ft | 524 | 2058 | 1657 | 639 | 3367 | 1742 |
| Flame length, feet | 8.4 | 25 | 20.6 | 11.4 | 44.9 | 24.8 |
| Effective midflame windspeed, mi/hr | 6.7 | 11.2 | 9.2 | 4.4 | 6 | 6.8 |
| Torching index, mi/hr | 0.8 | 2.4 | 1.1 | 0 | 0 | 0.1 |
| Crowning index, mi/hr | 33.5 | 23.7 | 20.2 | 10.3 | 9.8 | 14.7 |
| Surfacing index, mi/hr | 33.5 | 23.7 | 20.2 | 10.3 | 9.8 | 14.7 |
| Critical fireline intensity for crown fire initiation, BTU/ft | 43 | 100 | 47 | 0 | 12 | 25 |
| Critical flame length for crown fire initiation, feet | 2..5 | 3.7 | 2.7 | 0 | 1.4 | 2 |
| Critical spread rate for crown fire initiation, ch/hr | 1.92 | 4.76 | 2.24 | 0 | 0.64 | 1.18 |
| Critical avail. Bulk density to sustain active crown fire, kg/m3 | 0.54 | 0.19 | 0.27 | 0.65 | 0.26 | 0..30 |
| Critical spread rate for sustained active crown fire, ch/hr | 127.83 | 74.57 | 59.65 | 26.32 | 19.88 | 38.9 |
| Critical open windspeed for active crown fire cessation*, mi/hr | 2..5 | 2..5 | 2..5 | 2..5 | 2..5 | 2..5 |

*due to a too-high canopy base height

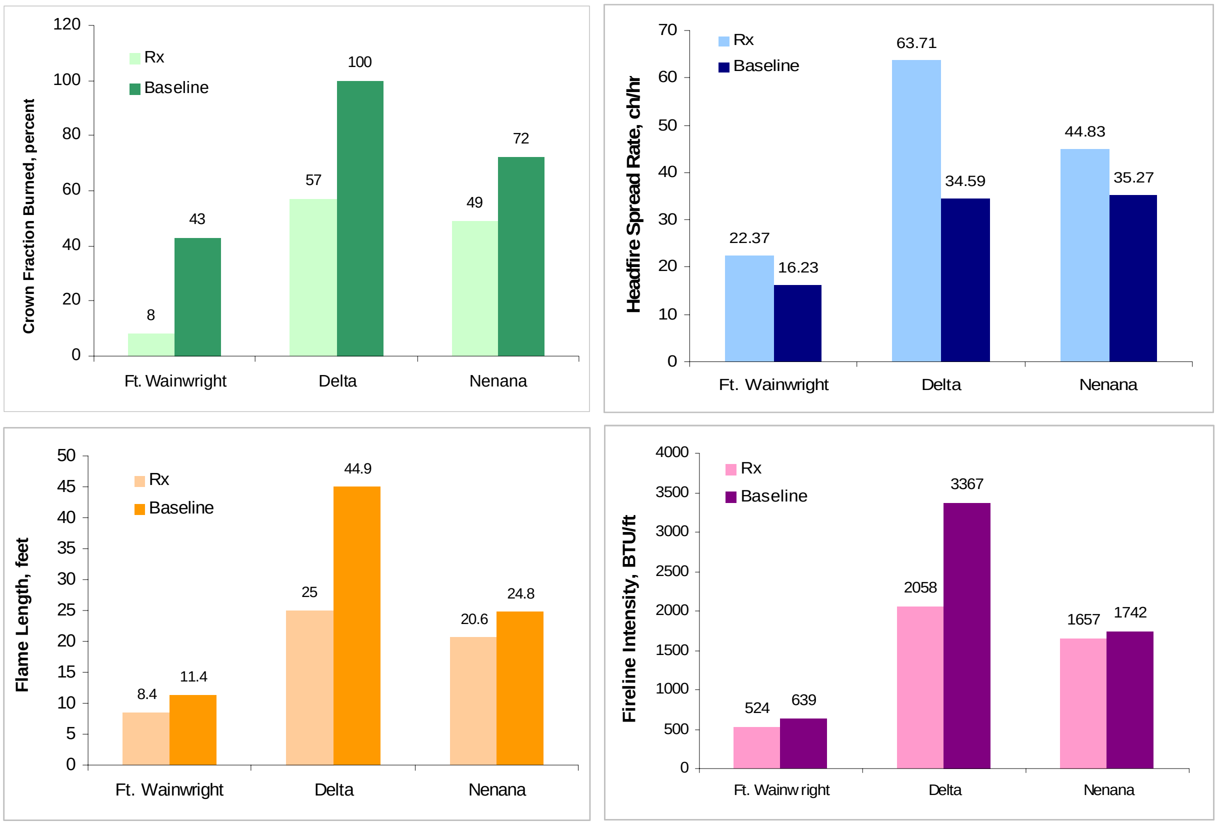



**Figure 7 & 8 & 9 & 10 –** Difference in projected crown fraction burned (upper left, fig 7), headfire spread rate (upper right, fig 8), flame length (lower left, fig 9) and fireline intensity (lower right, fig 10) in hot, dry, windy (90$^{th}$ percentile weather) conditions in open-treated stands compared to more dense control stands. Treated stands were modified to 10 X 10' spacing and pruned to 4' base height. **Inputs**: fuel model TU4, slope 0%, woody & foliar moisture content 100%, and surface fuel moistures (1-hr, 10-hr, 100-hr) and open windspeeds are listed in Table 3.

### *Simulation Outputs During Average Summer Day Weather*

Fire behavior differences between treated and controls during average summer fuel moisture conditions were limited. Passive crown fires were projected at all sites. Spread rate in all treatments were below the threshold to sustain an active crown fire. However, projected crown fraction burned was reduced by 80 % at Ft. Wainwright, 71 % at Delta, and 30 % at the Nenana site. Spread rate and flame length was again slightly increased at the Ft. Wainwright and Nenana treatments. Spread rate and flame lengths at the Delta treatment were increased by 50% although fireline intensity was decreased by 50 %. There was no difference in fireline intensity between Nenana or Ft. Wainwright treatments and controls. The critical available canopy bulk density needed to sustain an active crown fire was below the thresholds at all sites. The canopy bulk densities needed to sustain active crowning was 68% below the threshold at Delta treatment, 16 % below at the Delta control, 92 % below at Ft. Wainwright treatment, 69 % below at the Ft. Wainwright control, 64 % below at the Nenana treatment, and 53% below at the Nenana control.

**Table 8 –** Summary of simulation outputs using average summer fuel moisture conditions (70th percentile weather). Treated stand is 10'x10' spacing and pruned.

| *Output* | Treated Stand | | | Control Stand | | |
|---|---|---|---|---|---|---|
| | Ft. Wainwright | Delta | Nenana | Ft. Wainwright | Delta | Nenana |
| Type of fire, nominal | passive | passive | passive | passive | passive | passive |
| Crown fraction burned, fraction | 0.04 | 0.23 | 0.28 | 0.21 | 0.8 | 0.4 |
| Spread rate, chains/hr | 12.09 | 35.56 | 30.25 | 8.67 | 18.02 | 24.64 |
| Heat per unit area, BTU/ft | 1134 | 1327 | 1567 | 1549 | 4329 | 1925 |
| Fireline intensity, BTU/ft | 251 | 865 | 869 | 246 | 1430 | 870 |
| Flamelength, feet | 5.8 | 12 | 12.3 | 6.1 | 22.9 | 13.3 |
| Effective midflame windspeed, mi/hr | 4.9 | 9.5 | 8.3 | 3.5 | 4.7 | 6.9 |
| Torching index, mi/hr | 1.1 | 2.7 | 1.4 | 0 | 0 | 0.4 |
| Crowning index, mi/hr | 36.4 | 25.6 | 21.8 | 11.3 | 10.3 | 15.9 |
| Surfacing index, mi/hr | 36.4 | 25.6 | 21.8 | 11.3 | 10.3 | 15.9 |
| Critical fireline intensity for crown fire initiation, BTU/ft | 43 | 100 | 47 | 0 | 12 | 25 |
| Critical flame length for crown fire initiation, ft | 2.5 | 3.7 | 2.7 | 0 | 1.4 | 2 |
| Critical spread rate for crown fire initiation, ch/hr | 2.12 | 5.09 | 2.39 | 0 | 0.74 | 1.26 |
| Critical avail. bulk density to sustain active crown fire, kg/m3 | 0.89 | 0.37 | 0.42 | 1.11 | 0.53 | 0.48 |
| Critical spread rate for sustained active crown fire, ch/hr | 127.83 | 74.57 | 59.65 | 26.32 | 19.88 | 38.9 |
| Critical open windspeed for active crown fire cessation*, mi/hr | 2.5 | 2.4 | 2.5 | 2.5 | 2.5 | 2.5 |

*due to a too-high canopy base height

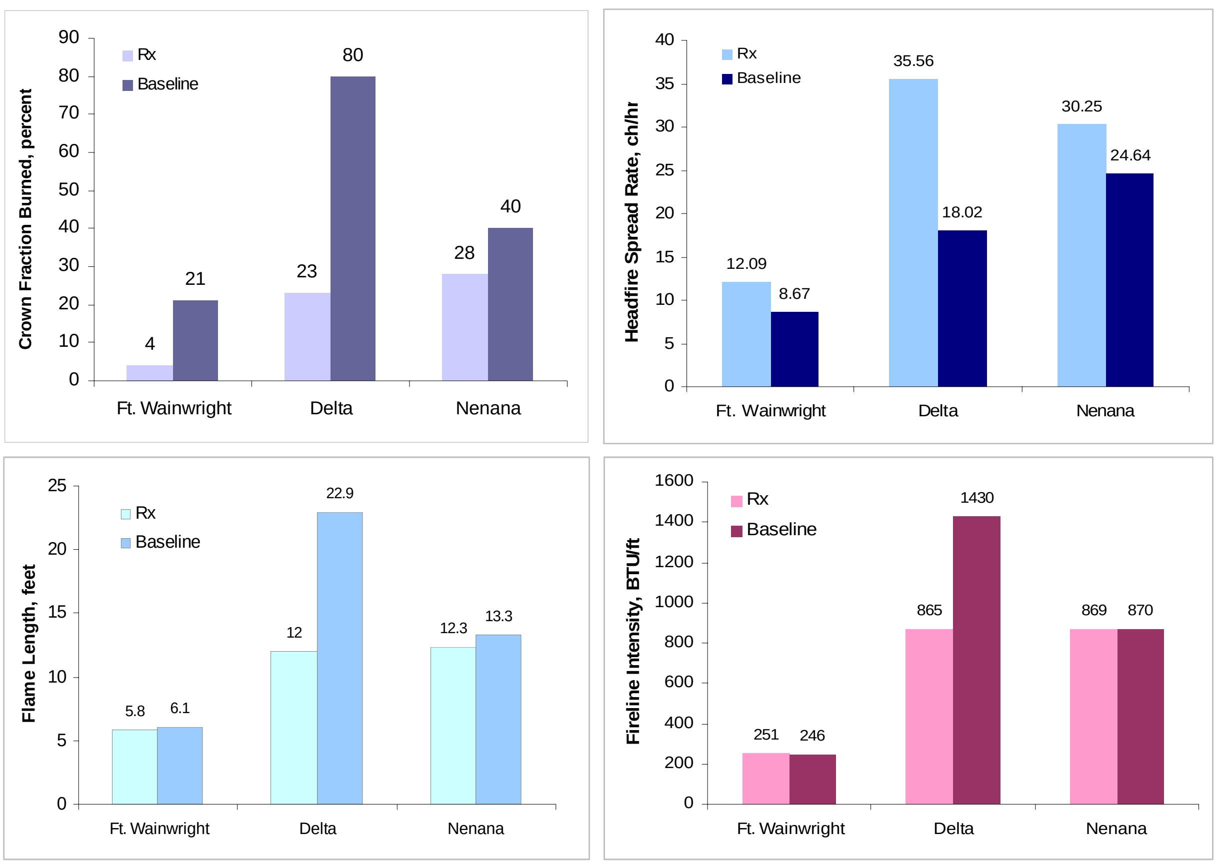



**Figure 11 & 12 & 13 & 14** – Difference in projected crown fraction burned (fig.11, upper left), projected headfire spread rate (fig. 12,upper right), flame length (fig.13, lower left), and fireline intensity (fig.14, lower right) during average summer day conditions (70th percentile weather) in open-treated vs. dense-control stands. **Inputs**: fuel model TU4, slope 0%, woody & foliar moisture content 100%, and surface fuel moistures (1-hr, 10-hr, 100-hr) and open windspeeds are listed in Table 4.

## DISCUSSION

Fuel modifications had instances of success as well as failure in terms of altering fire spread, flame length, spotting, and intensity. The most obvious results were reduced crown fraction burned, decreased or little changed flame length, and decreased or unchanged fireline intensity, but increased spread rate in treated stands. The NEXUS simulations indicate that under certain weather conditions treatments to modify canopy fuel availability in boreal spruce with feather moss understory do not preclude crown fire behavior. Thinning restricted fire behavior to a passive crown fire in most cases with reduced fireline intensity compared to crown fire in surrounding untreated stands. However, all stands remained well above thresholds to generate canopy torching even on average fire weather days (70$^{th}$ percentile days, Table 8). Although the simulations projected that more open treated stands would still produce passive crowning, the critical spread rate to sustain active crown fire was generally not reached. At one site, treatment precluded sustained active crown fire behavior at the 70$^{th}$ percentile weather, but not at 90$^{th}$ percentile weather. Because torching or passive crowning occurs frequently in Alaskan black spruce, even with fuel modification, a realistic objective of fuels treatments may be to reduce the potential of *active* crown fires. By reducing canopy bulk density enough to preclude the minimum headfire spread rate required to sustain an active crown fire, treatment thus reduces the risk to firefighter safety and public health concerns (Fig.15).

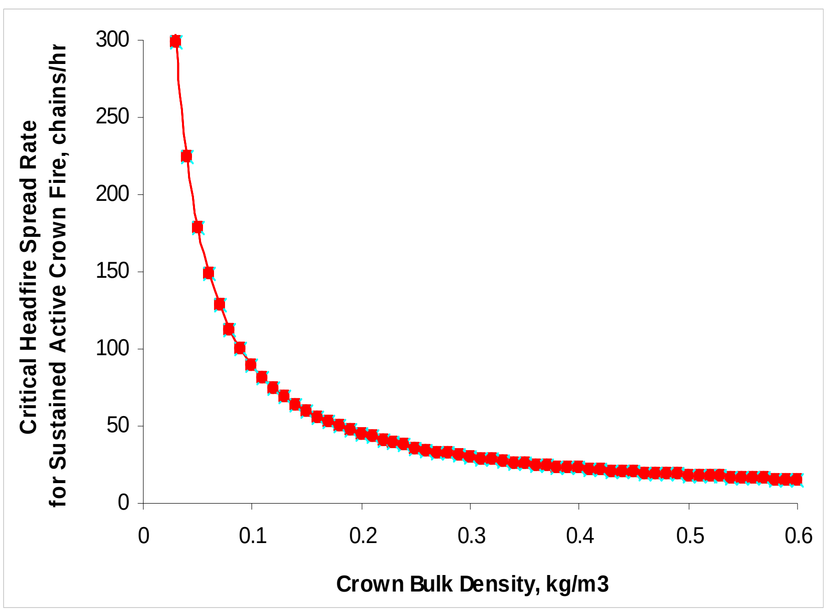



**Figure 15** - The minimum spread rate required to sustain an active crown fire based on VanWagner's (1977) model at different Alaskan black spruce canopy bulk densities. (There was no substantial difference between treatment and control and no differences between the three sites.) **Inputs**: TU4 fuel model, 70th percentile weather for 1-hr, 10-hr, 100-hr, and wind (Table 4); slope: 0%; 100% woody and foliar moisture content.

Simulations indicate no change or moderate reduction in flame length and fire intensity in the treated sites, but substantial reduction in the crown fractions burned (Figs.7&11), which may reduce spotting potential. Spotting has the potential to span large natural or man-made barrier and facilitate rapid rates of spread. Firebrands may be blown ahead of the fire where they ignite fuels. With low fuel moisture conditions and continuous fuels, numerous ignitions can occur. This is not accounted for in the fire behavior model (Rothermel 1983). Furthermore, under certain extreme weather conditions, spotting can involve large areas and multiple fires (Albini

1979) that potentially could burn through most treatments, thus modifying fuels in small or isolated areas may be ineffective in reducing risks in the wildland urban interface. Although during most weather conditions fuel treatments modified or limited fire behavior.

We compared fine fuel moisture inputs used in the FBA moisture look-up table in NEXUS to actual moisture content of standard fuel moisture sticks, and found them to be relatively close for high fire danger days (Fig. 16). Under more moderate conditions, the look-up values substantially underestimate moisture content of fine fuels, which may lead to overestimation of fire behavior potential under damp conditions.

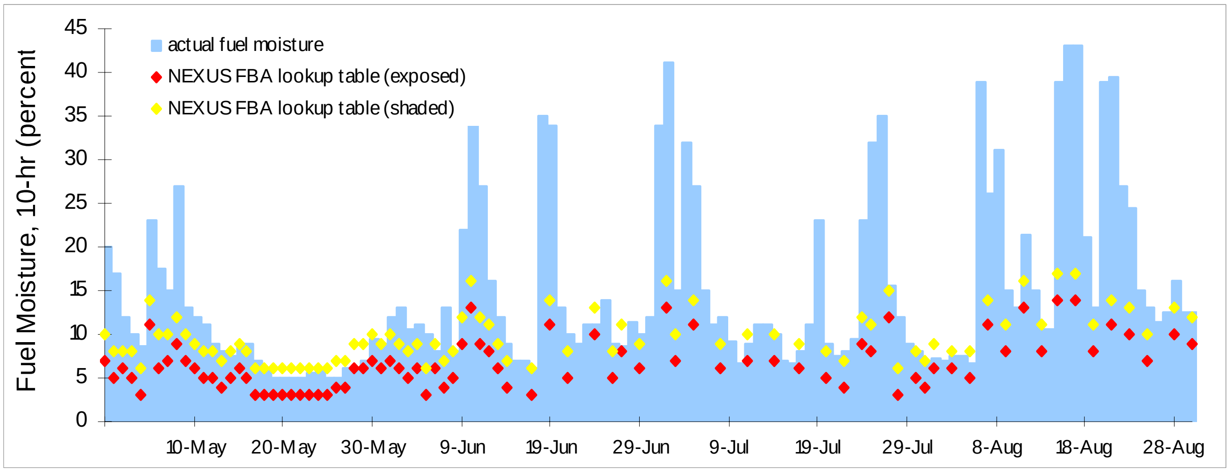



**Figure 16** - Comparison of 10-hour dead fuel moisture (dead moss) calculated from FBA fuel moisture look-up tables using adjusted onsite and historical weather *vs*. standard fuel moisture sticks (actual fuel moisture) measurements taken in Fairbanks during early May to late August in 2002.

The most important trade-off in fire behavior appears to be that more open treated stands were projected to have higher rates of spread in dry conditions. Tree removals produced additional surface fuel fire potential because of the increased exposure to solar radiation and winds, resulting in drier surface fuels. The reason that canopy fuel reduction seems to have less ability to reduce fire behavior potential in the boreal spruce fuel type vs. coniferous fuel types in the continental U.S. may be related to the substrate. Feather mosses, the primary surface fuel in black spruce stands, having no vascular system to get their moisture from soil, so they rely on the atmosphere and precipitation to remain moist. They can dry quickly, responding in about 30 minutes to changes in atmospheric humidity (Norum & Miller 1984). Moss fuel beds are more exposed to the drying effects of sun and wind when the canopy is removed, but are also more exposed to direct precipitation. Thus, more fluctuation in fine fuel moisture content would be expected after treatment. However, it has been demonstrated that the upper layers of live and dead moss are generally drier after treatment (Jandt et al. 2005) because the mosses heat up faster and are exposed to lower relative humidity and greater evaporation. Fuel moisture content, especially of the fine woody debris and cured grasses or feather moss duff, plays an important role in fire behavior. Surface fires in black spruce feathermoss stop burning at 15% moisture content and greater. At 8% to 10% fuels readily burn and at 5% to 7% they burn with fierce intensity and will carry fire into tree crowns (Norum 1982). Over the short-term feather moss can survive drought, e.g. summer 2004, but extensive thinning can lead to desiccation and death of the feathermoss bed—rendering it even more flammable until replaced by another substrate. Additionally, the thinned stands had slightly more wind, which strongly influences the Behave fire behavior models used in NEXUS.

Boreal spruce/feather moss fuels can burn with high intensity and can be difficult to control (Norum 1983), which is why many villages, urban neighborhoods, and private homeowners are considering applying fuel treatments to reduce fire risk. In this study, fire behavior trade-offs were found in one commonly employed fuel treatment (thinning and pruning to produce a "shaded" fuel break). More open stand structure in the treatments provides a definite advantage for firefighter and apparatus access, sprinkler system effectiveness, and canopy penetration of water drops or retardant, but these are all *active* defenses. The simulations suggest canopy reduction treatment alone will not protect homeowners from crown fires and an active defense will still be required to protect communities employing these fuel breaks.

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# APPENDIX A

**Table A1** – Onsite paired dry bulb temperatures and relative humidity observations taken at solar noon (1400 AST).

| | Treated | | Control | |
|---|---|---|---|---|
| *site* | Temperature | RH | Temperature | RH |
| Ft. Wainwright | 68 | 53 | 69 | 53 |
| Delta | 67 | 44 | 68 | 46 |
| Nenana | 74 | 48 | 74 | 47 |

**Table A2** – Adjusted dry bulb temperature and RH used to calculate fine dead fuel moisture content in treated stands. Differences in paired weather were used to adjust percentile weather.

| | Treated Stands | | | |
|---|---|---|---|---|
| | **90th percentile** | | **70th percentile** | |
| *site* | Temperature dry bulb ° F | Relative humidity % | Temperature dry bulb ° F | Relative humidity % |
| Ft. Wainwright | 82 | 23 | 74 | 34 |
| Delta | 74 | 25 | 68 | 35 |
| Nenana | 74 | 29 | 67 | 39 |

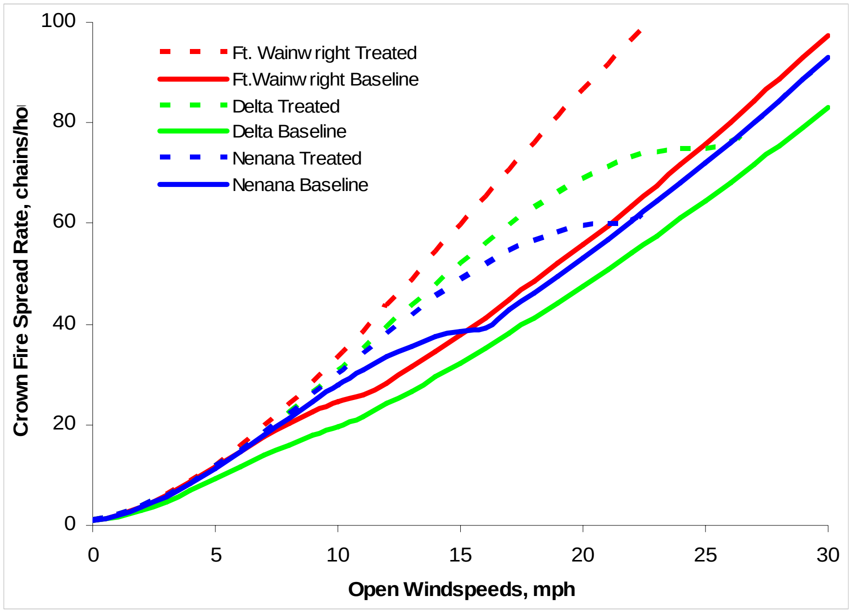


**Figure A1**- Headfire spread rate over open windspeeds in treated vs. control stands at all three sites. **Inputs**: 70th percentile weather for surface fuel moistures (1-hr, 10-hr, 100-hr; Table 4) and windspeeds, 100% woody and foliar moisture content, and slope 0%.