

U.S. Department of the Interior  
Bureau of Land Management

**BLM Alaska Technical Report 59**  
BLM/AK/ST-08/023+9218+020  
September 2008

# How Succession Affects Fire Behavior in Boreal Black Spruce Forest of Interior Alaska

James Cronan, Randi Jandt



**BLM**

**Alaska**



## Mission Statement

The Bureau of Land Management sustains the health, diversity and productivity of the public lands for the use and enjoyment of present and future generations.

## Authors

James Cronan is a research associate in forestry and fire science with Yale University, working out of the U.S. Forest Service, Pacific Wildland Fire Sciences Laboratory in Seattle. Randi Jandt is a fire ecologist with the Bureau of Land Management, Alaska Fire Service in Fairbanks.

## Author Contact

James Cronan  
Pacific Wildland Fire Sciences Laboratory  
400 N. 34th St., Suite 201  
Seattle, WA 98103  
Phone: 206-732-7873  
Email: [jcronan@fs.fed.us](mailto:jcronan@fs.fed.us)

Randi Jandt  
BLM Alaska Fire Service  
P.O. Box 35005  
Ft. Wainwright, AK 99703  
Phone: 907-356-5864  
Email: [rjandt@blm.gov](mailto:rjandt@blm.gov)

## Cover

Torching Black Spruce. Taylor Highway, Alaska. Photo by James Cronan. June, 2004.

## Technical Reports

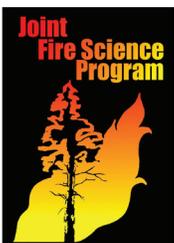
Technical Reports issued by BLM-Alaska present results of research, studies, investigations, literature searches, testing, or similar endeavors on a variety of scientific and technical subjects. The results presented are final, or are a summation and analysis of data at an intermediate point in a long-term research project, and have received objective review by peers in the author's field.

To request a copy of this or another BLM-Alaska scientific report, or for more information, please contact:

BLM-Alaska Public Information Center  
222 W. Seventh Ave., #13  
Anchorage, AK 99513  
(907) 271-5960

Most BLM-Alaska scientific reports are also available for loan or inspection at the Alaska Resources Library and Information Services in Anchorage, (907) 27-ARLIS, and other major libraries in Alaska; USDI Resources Library in Washington, D.C.; the BLM National Operation Center Library in Denver; and other select locations.

A bibliography of scientific reports is online at [www.blm.gov/ak](http://www.blm.gov/ak).



## Funding Provided by Joint Fire Science Program Project No. 04-2-1-96

Congress created the Joint Fire Science Program in 1998 as an interagency research, development, and applications partnership between the U.S. Department of the Interior and the U.S. Department of Agriculture. The program's governing board includes representatives from the Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, Bureau of Indian Affairs, U.S. Geological Survey, and five representatives from the Forest Service. The program tailors wildland fire research to the needs of policymakers and fire managers. Nearly 200 organizations, including 90 colleges and universities, have become partners in Joint Fire Science Program-sponsored research. Website: <http://www.firescience.gov>

# **How Succession Affects Fire Behavior in Boreal Black Spruce Forest of Interior Alaska**

By  
James Cronan  
Randi Jandt

BLM-Alaska Technical Report 59  
September 2008

U.S. Department of the Interior  
Bureau of Land Management  
Alaska State Office  
222 W. 7th Ave., #13  
Anchorage, AK 99513



## ABSTRACT

This report summarizes research funded by the Joint Fire Science Program (JFSP) that assessed the relationship between stand age and fire behavior in the black spruce forest type of interior Alaska. Forest canopy and substrate data were collected from 21 sites representing a time sequence of stand age ranging from two to 227 years. These data were used in fire behavior prediction models to estimate flammability for three weather scenarios. Regression analysis revealed a high degree of correlation between predicted and observed rates of spread (*ROS*) and suggested predicted fire behavior reflects actual fire behavior. A novel approach to modeling fire behavior was explored using fire behavior prediction models for surface fire, crown fire ignition, and crown fire sequentially. Specific components of the fuel complex were compared with increasing stand age during the first 100 years of stand development. The most prominent trend was the synchronized development of the feather-moss layer of the forest floor and the overstory. Measures of both fuel categories were essentially zero in stands aged < 20 years, then increased steadily with stand age. Leaf litter and coarse (i.e., 1/4 inch to 3 inch diameter) downed woody debris (*DWD*) had the opposite relationship with stand age; both fuel categories rapidly increased to their highest levels in stands aged < 20 years before declining with stand age. Beyond 100 years, the only notable relationships between the fuel complex and stand age was a tenuous correlation that suggested fine canopy fuel loading continued to increase slightly with stand age. Some fuel categories had no discernable relationship to stand age for the entire span of stand ages sampled. These included measures of groundcover and fine (i.e., less than 1/4 inch) *DWD*.

Cluster analysis of predicted fire behavior suggested three phases of fuel succession: the pioneer phase (stands aged < 20 years) corresponded to the lowest measures of fine fuels and predicted fire behavior, the transition phase (stands aged 20-45 years) defined a period of increasing measures of fine fuels and predicted fire behavior, and the forested phase (stands aged > 45 years) had the highest measures of fine fuels and predicted fire behavior. Sensitivity of predicted fire behavior to weather increased with increasing stand age as fuels became less of a limiting factor on fire behavior. The response of *ROS* to stand age was correlated with increased feather-moss coverage and canopy bulk density (*CBD*) during the first 45 years of stand development. This correlation ended in stands aged > 45 years because these fuel categories reached threshold values where further increases had a marginally declining influence on *ROS*. Fire-line intensity (*FLI*) increased throughout the study time period and was primarily influenced by available fine fuel loading.

## ACKNOWLEDGEMENTS

Support of this project from the Joint Fire Science Program, Alaska Fire Service, the National Park Service, the US Fish and Wildlife Service, and Colorado State University is gratefully appreciated. Specifically, Jennifer Allen, Karen Murphy, Jason Dollard, and Jennifer Hrobak all worked hard to assist with collection of field data and to provide logistical support for fieldwork. Dr. P. Glenn Juday provided help with the development of the field sampling protocol. Erin Shanely, David Click, and Jennifer Mitchell helped collect field data. Dr. Mary Huffman and Dr. Roger Ottmar generously provided data for this project. Joe Scott and Robert Ziel provided helpful reviews that have improved this report.

## TABLE OF CONTENTS

---

Introduction	1
What is this report?	1
Why is this report being published?	1
More about this project	1
Fuel succession	2
Flammability curve	2
Fuel succession phases	3
How do fuel succession and weather affect predicted fire behavior?	5
Comparable studies	6
Comparison of predicted and observed fire behavior	6
Fire behavior model structure	6
Introduction	6
Predicting fire behavior	7
Fire behavior: Ft. Wainwright example	7
Appendix A. Weather scenarios	10
Appendix B. Custom fuel models	11
Appendix C. Methodology for predicting fire behavior	12
Appendix D. English/metric conversion factors	15

## FIGURES

---

Figure 1-A and 1-B. Flammability curve: predicted <i>ROS</i> and <i>FLI</i> relative to stand age for 20th (marginal), 55th (moderate), and 95th (extreme) percentile weather scenarios.	2
Figure 2-A and 2-B. Percent cover and loading of forest floor fuels, feathermoss (a) and litter (b), and crown bulk density of black spruce relative to stand age.	3
Figure 3. Typical stand composition during the pioneer phase. Stand ages were two years for the stand on the left and 12 years for the stand on the right.	3
Figure 4. Typical stand composition during the transition phase. Stand ages were 22 years for the stand on the left and 38 years for the stand on the right.	4
Figure 5. Typical stand composition during the forested phase. Stand ages were 46 years for the stand on the left and 104 years for the stand on the right.	4
Figure 6. Predicted <i>ROS</i> (a) and <i>FLI</i> (b) relative to fuel succession phase and weather.	5
Figure 7. Observed <i>ROS</i> vs. predicted <i>ROS</i> .	6
Figure 8. Flow chart describing structure of method used to predict fire behavior.	7
Figure 9. Response of fire behavior to traditional <i>DFFM</i> (i.e., grasses and 1-hr <i>DWD</i> ) for the treatment site with a three mph wind (no wind adjustment factor applied).	9
Figure 10. Predicted <i>ROS</i> for control and treatment sites.	9
Figure 11. Predicted <i>FLI</i> for control and treatment sites.	9
Figure 12. Fire behavior output settings in BehavePlus3.	12
Figure 13. Two-dimensional expected spread feature.	12

---

## TABLES

Table 1. Average fuel values for pioneer phase sites.	3
Table 2. Average fuel values for transition phase sites.	4
Table 3. Average fuel values for forested phase sites.	4
Table 4. Predicted fire type, as a percentage of sites, for the three fuel succession categories and three weather scenarios.	5
Table 5. Weather scenario where critical <i>FLI</i> was achieved based on <i>WAF</i> .	8



## INTRODUCTION

### What is this report?

This is a summary of research funded by the Joint Fire Science Program (JFSP). The report is divided into two halves that detail key findings. The first half (p. 2-6) explores the relationship between succession in black spruce forest and fire behavior. The second half (p. 6-9) describes the method used to predict fire behavior for the first section. This method employed several existing fire behavior prediction models (hereafter referred to as models).

### Why is this report being published?

The purpose of this report is to condense information in part one of the JFSP final report titled "Refinement and development of fire management decision support models through field assessment of relationships among stand characteristics, fire behavior and burn severity." This report is intended for natural resource managers, wildland fire managers, scientists, and others interested in how temporal changes in weather and the fuel complex affect fire behavior in the black spruce forest type.

### More about this project

This project was submitted to JFSP in response to a longstanding question among fire managers in Alaska: How long do burned areas of black spruce forest remain resistant to high intensity fires? To answer this question, researchers from Yale University did three things:

- Fuels were measured in 21 black spruce stands aged from two to 227 years. Fuel loadings were plotted against stand age to show how fuel categories might change over time.
- Fuels data, seasonal weather averages and fuel moistures (Appendix B), were used to assess fire behavior for each stand using existing models. As with fuels data, predicted fire behavior was plotted against stand age to show how fire behavior may change over time. Fire behavior was calculated for the 20th (marginal), 55th (moderate), and 95th (extreme) percentile weather scenarios, generating a flammability curve for black spruce (Fig. 1-A, 1-B). The flammability curve was then split into fuel succession phases, each with unique fire behavior (see Fuel succession phases section).
- Next, models were tested against actual fire be-

havior observations to assess accuracy. To accomplish this, eight of the 21 stands were burned after fuels data were measured. Fire behavior and weather were recorded as the stands burned. On-site weather and fuels data were used as model inputs and predicted fire behavior was compared with measured fire behavior.

The results of the comparison of predicted and observed fire behavior were encouraging. Fire type and rate of spread (*ROS*) were reliably predicted for seven out of the eight sites. The high degree of correlation was not a conclusive assessment of model accuracy and there remains a wide variety of fuel and weather scenarios for black spruce where this model is still untested. Nevertheless, this method of predicting fire behavior is explained because it has potential as an alternative method for assessing fire behavior in Alaskan black spruce.

The successful linkage of this group of models was an unexpected outcome of this research. No single modeling system met all of the requirements of this project. Requirements included: the capacity to calculate *ROS* and fire-line intensity (*FLI*), the flexibility to predict fire behavior over multiple fire types, and the ability to predict fire behavior over a continuous range of fuels. To meet these requirements, components of several modeling systems including BehavePlus3<sup>1,2</sup> and the Canadian FBP System<sup>3</sup>, as well as separate crown fire behavior models<sup>4,5</sup> were linked.

The full final report can be downloaded from the JFSP website at [www.firescience.gov](http://www.firescience.gov) (search under JFSP project number 04-2-1-96).

<sup>1</sup>Burgan, R. E., and R. C. Rothermel. 1984. BEHAVE: fire behavior prediction and fuel modeling system: FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 125 p.

<sup>2</sup>Andrews, P. L., C. D. Bevens, and R. C. Seli. 2005. BehavePlus fire modeling system, version 3.0: user's guide. Gen. Tech. Rep. RMRS-106. Fort Collins, CO: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. 134 p.

<sup>3</sup>Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Info. Rep. ST-X-3. Ottawa, ON: Canadian Forest Service. 49 p.

<sup>4</sup>Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research 35:1626-1639.

<sup>5</sup>Scott, J. H., and E. D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-29. Fort Collins, CO: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

## FUEL SUCCESSION

### Flammability curve

In this report, the term ‘flammability curve’ refers to the response of fire behavior, as measured by *ROS* and *FLI*, to succession (Fig. 1-A, 1-B). To assess trends in succession, stand age was substituted for time. This method assumed black spruce forest succession proceeded in one direction and posed somewhat of a problem because we know there are multiple pathways for succession in black spruce forest<sup>6,7,8</sup>. Thus, this method risked mischaracterizing succession pathways and oversimplifying the flammability curve. To mitigate these risks, this study focused on the most flammable and common black spruce forest type in Alaska: black spruce-feathermoss. Black spruce bogs, spruce-lichen woodland, and mixed black spruce-hardwood stands were excluded. By excluding these less common forest types, the potential variation of succession pathways was reduced while focusing on stands that were most important from a fire hazard standpoint.

Many facets of the fuel complex were well correlated with age during the first 100 years of forest development. In general, fuel categories with the largest influence on fire behavior increased during this time period. Their response slightly resembled an exponential curve where rate of growth was most rapid in the middle of the curve and gradually tapered at either end. The highest rates of growth for these fuels occurred in stands aged between 20 and 100 years. Fuel categories that exhibited this trend included measures of feathermoss and black spruce fine canopy fuels (Fig. 2-A, 2-B). Fuels with little or no influence on fire behavior over time either decreased with, or were unrelated to stand age. Measures of fuels that decreased with stand age included coarse (10-hr and 100-hr) downed woody debris (*DWD*) and litter fuels (Fig. 2-A). These fuels quickly increased to their highest values during the first 20 years of forest development and then decreased steadily to near zero as stand age rose from 20 to 100 years. Fuel categories with no relationship to stand age included groundcover (i.e., herbs and dwarf shrubs) and fine (1-hr) *DWD*.

For the extreme weather scenario, predicted measures of fire behavior were close to zero in stands aged < 20 years, then increased dramatically

as stand age rose from 20 to 45 years. In stands aged > 45 years, predicted *ROS* leveled off (Fig. 1A) and the pace of predicted *FLI* growth slowed (Fig. 1-B). These trends were progressively more

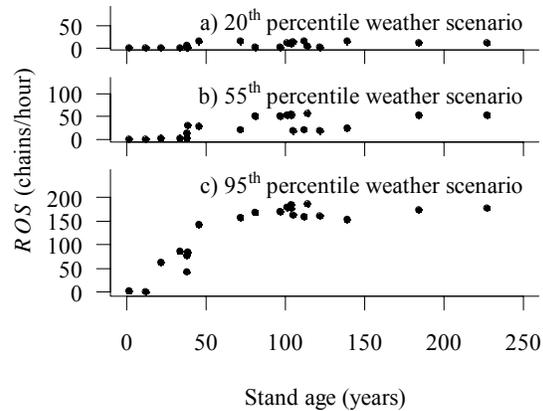


Figure 1-A. Flammability curve: predicted *ROS* relative to stand age for 20<sup>th</sup>, 55<sup>th</sup>, and 95<sup>th</sup> percentile weather scenarios.

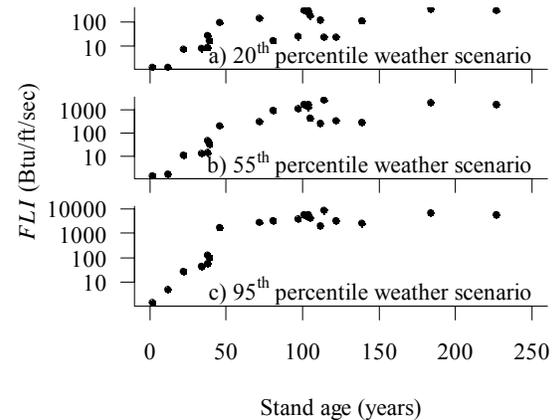


Figure 1-B. Flammability curve: predicted *FLI* relative to stand age for 20<sup>th</sup>, 55<sup>th</sup>, and 95<sup>th</sup> percentile weather scenarios.

subdued as weather severity decreased. Predicted *ROS* was influenced primarily by coverage of feathermoss and *CBD* in stands aged < 45 years and was unresponsive to continued increases in these fuels in stands aged between 45-100 years. This shift occurred due to differences in predicted fire type. Surface spread models, used frequently in

<sup>6</sup>Viereck, L. A. 1983. The effects of fire in black spruce ecosystems of Alaska and northern Canada. *In* The Role of Fire in Northern Circumpolar Ecosystems. Edited by R. W. Wein and D. A. MacLean. John Wiley & Sons Ltd., Chichester. pp. 201-220.

<sup>7</sup>Kasischke, E. S., K. P. O'Neill, N. H. F. French, L. L. Borgeau-Chavez, and D. Richter. 2000. The influence of fire on long-term patterns of forest succession in Alaskan boreal forests. *In* Fire and vegetation dynamics: Studies from the North American boreal forest. Edited by E. S. Kasischke and B. J. Stocks. Cambridge University Press, Cambridge. pp. 214-235.

<sup>8</sup>Johnstone, J. F., and E. S. Kasischke. 2005. Stand-level effects of soil burn severity on postfire regeneration in a recently burned black spruce forest. *Canadian Journal of Forest Research*. 35:2151-2163.

younger stands (< 45 years), weight fuels more than crown fire spread models which were used most frequently in older stands (> 45 years). In contrast, predicted *FLI* values continued to rise with increasing fine fuel load, which is more equally weighted in both spread models.

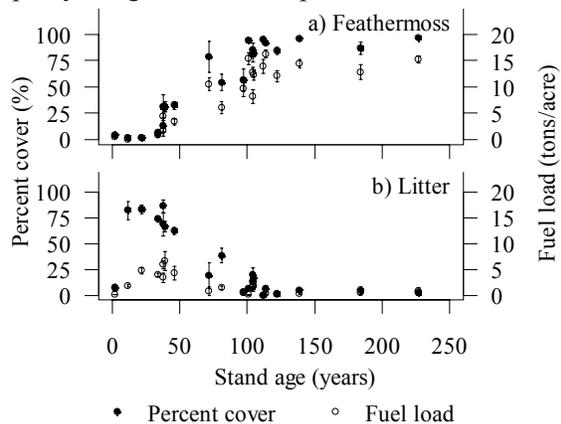


Figure 2-A. Percent cover and loading of forest floor fuels, feathermoss (a) and litter (b) relative to stand age. Error bars represent ± one standard error.

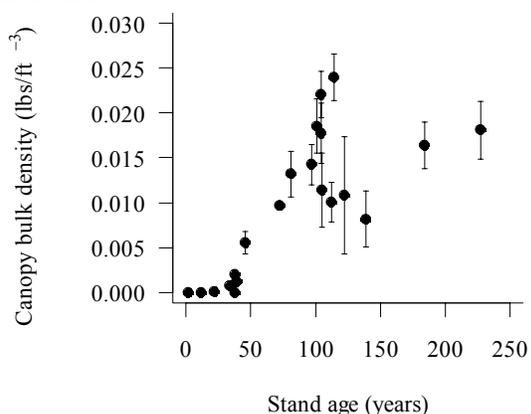


Figure 2-B. *CBD* relative to stand age. Error bars represent ± one standard error.

### Fuel succession phases

Cluster analysis, a statistical test, was used to split the flammability curve into succession phases with distinct properties of fuel composition and fire behavior. *FLI* and *ROS*, predicted for each stand under three weather scenarios were used as inputs and groups were delineated based on the degree of similarity of fire behavior measures among stands. Cluster analysis suggested three phases with distinct fire behavior: pioneer phase (< 20 years), transition phase (20-45 years) and forested phase (> 45 years). Characteristics of these phases are described in this section. The influence of fuels on fire behavior is discussed in the following section.

### PIONEER PHASE (< 20 YEARS)



Figure 3. Typical stand composition during the pioneer phase. Stand ages were two years for the stand on the left and 12 years for the stand on the right.

Table 1. Average fuel values for pioneer phase sites\*.

Fuel category <sup>†</sup>	Loading (tons/acre)	Fuel category <sup>†</sup>	Value
Feathermoss	0.1	Feathermoss coverage (%)	2
Litter	0.4	Litter coverage (%)	49
1-hr <i>DWD</i>	0.1	Canopy bulk density (lbs/ft <sup>3</sup> )	0
10-hr <i>DWD</i>	0.4	Canopy base height (ft)	na
100-hr <i>DWD</i>	2.1		
Groundcover	0.6		
Canopy fuels	0		

\*Stands sampled: n = 2. Age range: 2-12 years.

<sup>†</sup>See Appendix B for complete custom fuel model.

The pioneer phase (< 20 years; Fig. 3) had a sparse cover of fine surface fuel and many standing fire-killed trees. With the exception of occasional surviving trees, no living overstory was present. Herbs were abundant and tall shrubs (e.g. willow and alder) became increasingly prominent as stand age increased. *DWD* loading was highest in this phase, but only for coarse fuels. The regenerating overstory consisted of inconspicuous black spruce seedlings beneath a layer of herbs and shrubs. Feathermoss was absent or nearly so. Fire behavior models suggested fires were limited by fuels during this phase (Fig. 6). As a consequence, slow moving surface fires were predicted (Table 4) under all weather scenarios.

### TRANSITION PHASE (20-45 YEARS)



Figure 4. Typical stand composition during the transition phase. Stand ages were 22 years for the stand on the left and 38 years for the stand on the right.

Table 2. Average fuel values for transition phase sites\*.

Fuel category <sup>†</sup>	Loading (tons/acre)	Fuel category <sup>†</sup>	Value
Feathermoss	1.1	Feathermoss coverage (%)	16
Litter	2.0	Litter coverage (%)	76
1-hr <i>DWD</i>	0.1	Canopy bulk density (lbs/ft <sup>3</sup> )	0.001
10-hr <i>DWD</i>	0.6	Canopy base height (ft)	0.5
100-hr <i>DWD</i>	1.6		
Groundcover	1.4		
Canopy fuels	0.3		

\*Stands sampled: n = 5. Age range: 22-38 years.

<sup>†</sup>See Appendix B for complete custom fuel model.

Abundant shrubs and black spruce saplings with a well-defined litter layer defined the transition phase (20-45 years; Fig. 4). The formation of a continuous layer of fine surface fuels during this phase generated high values for predicted *ROS*. Loading of coarse *DWD* decreased throughout this phase. Both feathermoss and canopy fuels first appeared during this phase and fuel measures increased rapidly as stand age increased. Predicted fire behavior during this phase increased with stand age (Fig. 2-A, 2-B). Predicted *ROS* was not limited by fuels and was, at times, dramatically higher relative to the pioneer phase (Fig. 6). Low loading of fine fuels kept predicted *FLI* relatively low (Fig. 6). The emerging canopy had low *CBD*, which inhibited crown fire development.

### FORESTED PHASE (> 45 YEARS)



Figure 5. Typical stand composition during the forested phase. Stand ages were 46 years for the stand on the left and 104 years for the stand on the right.

Table 3. Average fuel values for forested phase sites\*.

Fuel category <sup>†</sup>	Loading (tons/acre)	Fuel category <sup>†</sup>	Value
Feathermoss	4.7	Feathermoss coverage (%)	80
Litter	0.4	Litter coverage (%)	17
1-hr <i>DWD</i>	0.2	Canopy bulk density (lbs/ft <sup>3</sup> )	0.014
10-hr <i>DWD</i>	0.2	Canopy base height (ft)	1.5
100-hr <i>DWD</i>	0.4		
Groundcover	1.1		
Canopy fuels	4.7		

\*Stands sampled: n = 14. Age range: 46-227 years.

<sup>†</sup>See Appendix B for complete custom fuel model.

The most notable characteristic of the forested phase (> 45 years; Fig. 5) was high loading of feathermoss and fine canopy fuels (Fig. 5). From 45 to 100 years, many fuel trends observed in the transition phase continued. With the exception of fine canopy fuel loading, fuels were unrelated to stand age in stands aged over 100 years. During this phase, predicted fire behavior responded dramatically to weather (Fig. 6 and Table 4) with slow moving surface fires predicted during low severity weather and fast moving, high intensity crown fires predicted during high severity weather. A weak correlation between stand age and fine canopy fuel load for stands aged over 100 years was responsible for the continuing increase in predicted *FLI* during the same period.

## How do fuel succession and weather affect predicted fire behavior?

Predicted fire behavior responded dramatically to both, weather and stand age (Fig. 6). These two responses are a central point of this research.

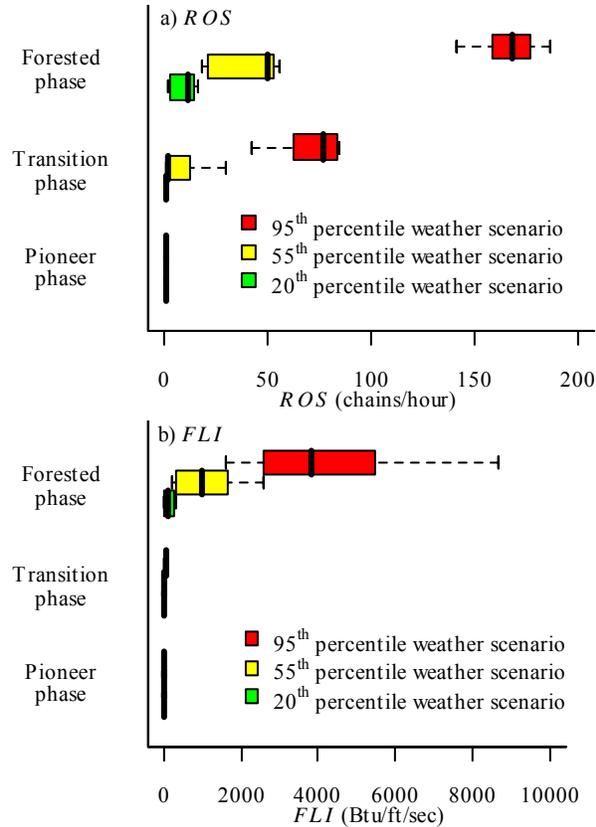


Figure 6. Predicted ROS (a) and FLI (b) relative to fuel succession phase and weather. The heavy line represents the median, the boxed area represents the first and third quartiles, and the whiskers represent minimum and maximum non-outlier values.

Regardless of weather, models suggested that black spruce was resistant to fire during the pioneer phase due to the absence of a continuous fine fuelbed (Fig. 2-A, Fig. 3). Although coarse *DWD* loading was highest during this phase, it had little impact on predicted fire behavior because coarse *DWD* pieces were spaced too far apart to act as a continuous fuelbed.

During the transition phase, predicted fire behavior increased, but the magnitude was greatest for predicted ROS. This happened because predicted ROS was influenced primarily by fine fuel coverage which increased substantially between the pioneer and transition phases. Predicted FLI was influenced primarily by fine fuel loading, which only

saw a modest increase from the pioneer phase to the transition phase.

Table 4. Predicted fire type, as a percentage of sites, for the three fuel succession categories and three weather scenarios.

\*Sur: surface fire | Pas: passive crown fire | Act: active crown fire.

Phase†	Weather scenario and fire type*								
	Marginal (20 <sup>th</sup> percentile)			Moderate (55 <sup>th</sup> percentile)			Extreme (95 <sup>th</sup> percentile)		
	Sur	Pas	Act	Sur	Pas	Act	Sur	Pas	Act
P	100	0	0	100	0	0	100	0	0
T	80	20	0	60	40	0	0	100	0
F	36	64	0	0	36	64	0	0	100

† P: pioneer phase | T: transition phase | F: forested phase

Another feature of the transition phase was higher sensitivity of predicted fire behavior to weather, especially for predicted ROS. Weather had a stronger influence on predicted ROS because fine fuel coverage was nearly continuous and was no longer a limiting factor since the flaming front could spread without being slowed by areas with sparse fuel coverage. Conversely, predicted FLI was still limited by relatively low values of fine fuel loading and thus, was not as sensitive to changes in weather. Despite the fact that fuels ceased to be a limiting factor on predicted ROS during the transition phase, predicted ROS was higher in the forested phase. This increase was due to a higher effective wind speed. The effective wind speed increased because the flaming front of active crown fires, frequent during the forested phase, were driven by 20 foot winds, which were up to five times stronger than the in-stand winds driving surface and passive crown fires in the transition phase.

The forested phase exhibited the highest values for predicted fire behavior (Fig. 6). Predicted ROS was minimally affected by continued changes in fine fuel coverage and *CBD* and predicted FLI continued to be influenced by fine fuel loading. However, differences in predicted FLI among sites caused by variation in fuels had little consequence from a fire suppression standpoint because active crown fires were easily initiated at all sites. Even the lowest predicted FLI for active crown fires would make direct attack using hand crews or equipment difficult or impossible. Weather, rather than fuel loading, appeared to be the most important variable during forested phase influencing suppression strategy.

### Comparable studies

In this section, results of this research are compared with other similar studies. Studies of Scots pine boreal forest in Sweden<sup>9</sup> and sub-alpine forest in the Canadian Rockies<sup>10</sup> both concluded that stand age influences fire behavior during early stages of forest development.

Trends for predicted fire behavior in black spruce forest were similar to those in Scots pine forest. For both forest types, there was high resistance to fire during early forest development (< 20 years), followed by increasing measures of predicted fire behavior for the next three decades. Predicted fire behavior reached a plateau after stand age reached 45-50 years, then was unrelated to age for all older stands. Increasing measures of feathermoss were identified as the primary cause of increased predicted *ROS* in both forest types. However, fire regimes between the two study sites are quite different. Crown fires predominate in the black spruce forest type, while surface fires are common in Scots pine forest type. While canopy fuels are a strong influence on fire behavior in the black spruce forest type (but not the Scots pine forest), they did not alter trends in fire behavior caused by feathermoss because canopy fuels developed in tandem with feathermoss in black spruce.

Temporal trends of predicted fire behavior for sub-alpine forests of the Canadian Rockies and black spruce of interior Alaska were not as well correlated. However, there were two main similarities: predicted fire behavior trended upwards with age during early forest development and later, after canopy fuels became continuous, predicted flammability was unrelated to age. Canopy fuels became continuous once stand age reached 25 years for sub-alpine forests and 45 years for black spruce forest. A possible reason for the lower age of canopy closure in sub-alpine forest was its more southerly latitude which may have supported faster growth rates.

### Comparison of predicted and observed fire behavior

Predicted *ROS* values were close to observed *ROS* (Fig. 7). The eight site comparisons between predicted and observed fire behavior had an  $R^2$  value of 0.955. The slope for the linear model was close to one (1.3341) and the y-intercept was near

zero (0.5207). These two values indicated that, while values were well correlated, predicted *ROS* slightly overestimated actual *ROS*. Perfect agreement between predicted and observed *ROS* would occur if the points fell along the line (slope = 1) in Fig. 7. The two points farthest from the line were crown fires. In these instances predicted *ROS* was higher than observed *ROS* by 30-50 chains/hr.

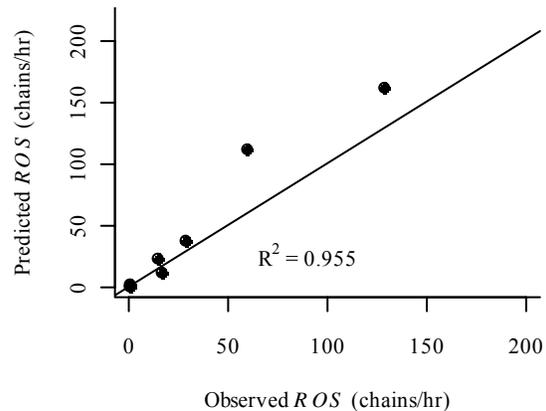


Figure 7. Observed *ROS* vs. predicted *ROS*. The line represents a slope of one. Reported  $R^2$  is for the best fit regression line (not shown):  $y = 1.3341x + 0.5207$  ( $n = 8$ ).

This assessment is based on a relatively small number of observations and cannot be considered a conclusive evaluation of these models. Pair wise comparisons included one site in the intermediate phase and seven sites in the forested phase.

## FIRE BEHAVIOR MODEL STRUCTURE

### Introduction

The method of predicting fire behavior presented here is novel for boreal forest. It accepts continuous fuel measurements (i.e., custom fuel models) and predicts *ROS* and *FLI* for surface and crown fires. Due to the limited sample size, further study is advised before accepting results from this technique for management and suppression applications. However, the method appears to have great potential to improve predictions.

It should be noted that, since the method is new and not automated, more effort is required by the user to calculate fire behavior using all three

<sup>9</sup>Schimmel, J., and A. Granstrom. 1997. Fuel succession and fire behavior in the Swedish boreal forest. *Canadian Journal of Forest Research* 27:1207-1216.

<sup>10</sup>Bessie, W. C., and E. A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* 76:747-762.

models. First, one uses a stepwise progression to assign fire type (surface or crown), which dictates which one of three models is needed to predict fire behavior (Fig. 8). BehavePlus3 incorporates a similar process but using a different crown fire spread rate model<sup>11</sup>.

### Predicting fire behavior

This section contains a step-by-step description of how to calculate fire behavior with the models used to determine the flammability curve. Because it relies on existing models, users will need to download BehavePlus3<sup>1,2</sup>. The other models<sup>4,5,12</sup> should be used according to the directions below. Appendix C contains more detailed information necessary to calculate fire behavior, including predictive models.

1. Choose a fuel model to describe surface fuels. This can be a standard or custom fuel model.
2. Quantify canopy fuels. Three measures are required: *CBD*, fine canopy fuel load, and canopy base height (*CBH*).
3. Input surface fuel, weather, and fuel moisture data into BehavePlus3. If more than one surface fuel type exists, the two dimensional spread feature should be used. Adjust output settings to calculate surface *ROS* ( $ROS_{Surface}$ ), surface *FLI* ( $FLI_{Surface}$ ), and surface heat per unit area ( $HPA_{Surface}$ ).
4. Use the crown fire initiation criteria<sup>12</sup> to calculate critical *FLI* ( $FLI_O$ ), the minimum  $FLI_{Surface}$  required to ignite canopy fuels.
5. Compare  $FLI_{Surface}$  to  $FLI_O$ . If
  - a)  $FLI_{Surface} < FLI_O$ : fire type = surface fire. Use the BehavePlus3 prediction of  $ROS_{Surface}$  and  $FLI_{Surface}$  to represent overall *ROS* ( $ROS_{Overall}$ ) and overall *FLI* ( $FLI_{Overall}$ ), respectively. Fire behavior calculations are complete.
  - b)  $FLI_{Surface} > FLI_O$ : fire type = crown fire. Continue to step 6.
6. Calculate active crown fire *ROS* ( $ROS_{Active}$ ) with the active crown fire spread model<sup>4</sup>.
7. Use the crown fire spread criteria<sup>12</sup> to calculate the critical *ROS* ( $ROS_O$ ). This is the minimum *ROS* required to support an active crown fire.
8. Compare  $ROS_{Active}$  to  $ROS_O$ . If
  - a)  $ROS_{Active} < ROS_O$ : fire type = passive crown fire. The passive crown fire spread model<sup>4</sup> is used to calculate passive crown fire

*ROS* ( $ROS_{Passive}$ ) and the *FLI* model<sup>5</sup> modified to predict *FLI* contributed by canopy fuels during a passive crown fire ( $FLI_{Passive}$ ).

$$ROS_{Passive} = ROS_{Overall}$$

$$FLI_{Passive} = FLI_{Overall}$$

b)  $ROS_{Active} > ROS_O$ : fire type = active crown fire. Use  $ROS_{Active}$  calculated in step 6 and the *FLI* model<sup>5</sup> to predict *FLI* contributed by canopy fuels during an active crown fire ( $FLI_{Active}$ ).

$$ROS_A = ROS_{Overall}$$

$$FLI_{Active} = FLI_{Overall}$$

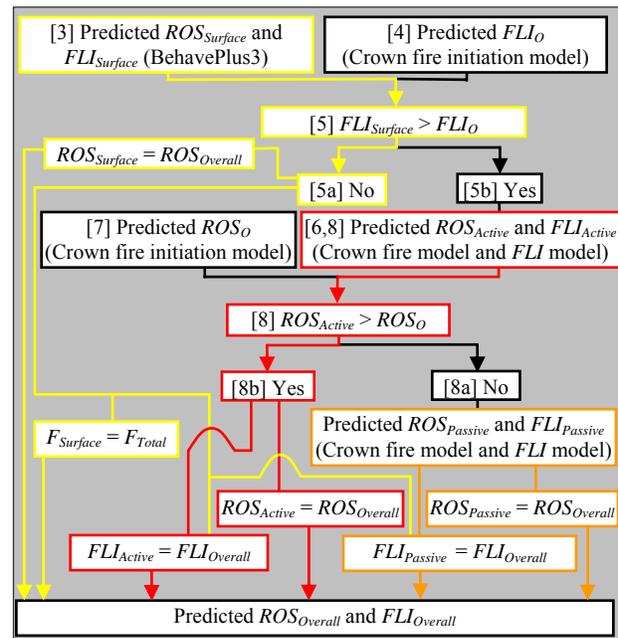


Figure 8. Flow chart describing structure of models used to predict fire behavior. Bracketed numbers refer to steps listed above. Outline colors indicate model type. Black = evaluates fire type, yellow = surface fire spread model, orange = passive crown fire spread model, and red = active crown fire spread model.

### Fire behavior. Ft. Wainwright example

Stand data from the JFSP demonstration project at Ft. Wainwright, AK (FW) was used to illustrate how fuel and weather variables influence fire behavior predictions based on the arrangement of models used in this report. Forest composition at the FW site was typical of the black spruce-

<sup>1,2,4,5</sup>Ibid.

<sup>11</sup>Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 46 p.

<sup>12</sup>Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7:23-24.

feathermoss forest type in interior Alaska. The overstory was nearly pure black spruce, the understorey was dominated by ericaceous dwarf shrubs, and the forest floor had a high cover of feathermosses. In 2001, four treatment sites (shaded fuel-breaks with variable thinning and pruning arrangements) and a control site were established at FW to study changes in fire hazard and ecological impacts<sup>13</sup>. Based on methods described earlier, fire behavior was predicted for two of these sites: the control site and one of the treatment sites (thinned to a 10 x 10 ft. tree density with limbs pruned from remaining trees to a height of four feet).

Stand data were used to create custom fuel models for each of the two sites (Appendix B). Intrinsic fuel values (e.g. surface area-to-volume ratio, and heat of combustion) were based on published values (Appendix B). Assessing differences for in-stand weather between the two sites posed a challenge. Some of the models used are sensitive to weather inputs, especially wind. Since the effects of thinning on stand microclimate are not well known, the selection of conditions for in stand weather are detailed below. These conditions are important to note because errors could overwhelm any differences in fire behavior between the two sites due to fuel treatments.

Effective in-stand winds are dampened as stem density increases<sup>13,14,15</sup>, so the effect of stand structure on in-stand winds is typically quantified by a wind adjustment factor (*WAF*). Wind speed at 20 feet is normally used to calculate the *WAF*<sup>14</sup>. In our fuel treatment sites paired wind observations were recorded at about 8 feet<sup>16</sup>, so that it was not possible to calculate *WAF* in the standard way. Instead we used Norum's<sup>14</sup> studies on wind speeds in variable stand density for black spruce forest in Alaska to obtain a *WAF* of 0.11 for the control site and 0.21 for the treatment site.

Two problems arise when assessing *DDFM*. First, *DDFM* as input into BehavePlus3, is based on fine woody debris and grass litter in pine forest and may not adequately represent the fine fuels which carry surface fire in Alaska (i.e., feathermoss). The moisture of extinction for fine woody debris is lower than for feathermosses. Thus, if feathermoss fuel moisture is input into BehavePlus3, fire behavior will be underestimated. The

best way to use BehavePlus3 with the black spruce-feathermoss forest type is to calculate *DDFM* with the fine fuel moisture tool in the software and use this as a proxy for feathermoss moisture (which may be higher).

Second, we knew that thinning affected the fuel moisture regime in the treatment stands. Studies indicated that within the first two years after fuel-breaks were established, feathermoss moisture content was, on average, 50% less than in the adjacent control site<sup>16</sup>. Opened stands dried faster and characteristics (viability) of the moss layer itself may have been impacted by the treatment. In attempt to capture the suspected difference in fuel moistures, the *DDFM* for the treatment sites was reduced by 50% relative to the control site *DDFM* for the FW example.

Table 5 shows how dramatically the selection of *WAF* can influence predicted fire behavior by listing percentile weather a surface fire can be expected to ignite canopy fuels. The *WAF* used for the control site caused a transition to crown fire when weather severity was very low indicating canopy fuels ignited easily. If the same *WAF* is

Table 5. Weather scenario where critical *FLI* was achieved based on *WAF*.

Site	<i>WAF</i>	Percentile weather when surface fire transitioned to crown fire
Control	0.11	1%
Treatment	0.11	92%
Treatment	0.21	66%
Treatment	0.35	34%
Treatment	0.48	21%
Treatment	0.61	13%

<sup>13</sup>Ott, R. A., and R. Jandt. 2005. Fuels treatment demonstration sites in the boreal forests of interior Alaska. Final report to the Joint Fire Sciences Program. Fairbanks, AK: Tanana Chiefs Conference Forestry Program. 23 p.

<sup>14</sup>Norum, R. A. 1983. Wind adjustment factors for predicting fire behavior in three fuel types in Alaska. Res. Pap. PNW-309. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 5 p.

<sup>15</sup>Rothermel, R. C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

<sup>16</sup>Jandt, R., J. Allen, and E. Horschel. 2005. Forest floor moisture content and fire danger indices in Alaska. Alaska Tech. Rep. 54. U.S. Dept. of the Interior, Bureau of Land Management, Alaska Fire Service. 30 p.

used for the treatment site, transition to crown fire only occurred during high severity weather; indicating the shaded fuelbreak is effective at reducing crown fire risk. However, as the WAF is increased, the relative effectiveness of the shaded fuelbreaks decrease to the point where the difference is negligible ( $WAF = 0.61$ ). Based on what is known about the effects of tree density on in-stand wind speed<sup>13,14</sup> a  $WAF$  of 0.21 to 0.35 is most likely.

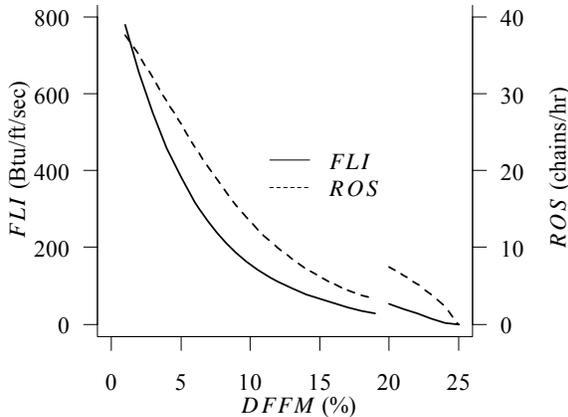


Figure 9. Response of fire behavior to traditional *DFFM* (grasses and 1-hr *DWD*) for the treatment site with a three mph wind (no wind adjustment factor applied).

Figure 9 illustrates the response of fire behavior to a range of traditional *DFFM* (i.e., grasses and 1-hr *DWD*) values. The break in the *ROS* response curve in Figure 9 was due to differences in the structure of the surface<sup>1,2</sup> and the crown fire models<sup>4,5</sup>. Those familiar with the fuel moisture regime of feathermoss will immediately notice that the moisture of extinction for feathermoss is higher than the value shown in Figure 9 (25%). The fine fuel moisture calculator used to determine fine fuel moisture accounts for a host of environmental factors, though it is unclear how well these serve as a substitute for feathermoss moisture. If Figure 9 accurately reflects the shape of the response curve, the greatest differences in *ROS* and *FLI* between treated and untreated sites would occur when *DFFMs* were lowest (i.e., where the curve is steepest). The curve becomes steepest for *DFFMs* lower than 10% for *FLI* and 15% for *ROS*.

Based on the assumed effects of in-stand weather reviewed above, predicted fire behavior for the two FW sites suggested that shaded fuelbreaks will have little impact on *ROS* (Fig. 10) but will reduce *FLI* through reduction of crown fire risk (Fig. 11).

Despite higher surface winds and drier fuels in the treatment site, predicted *ROS* was similar to the control sites. The reason for this was the lower

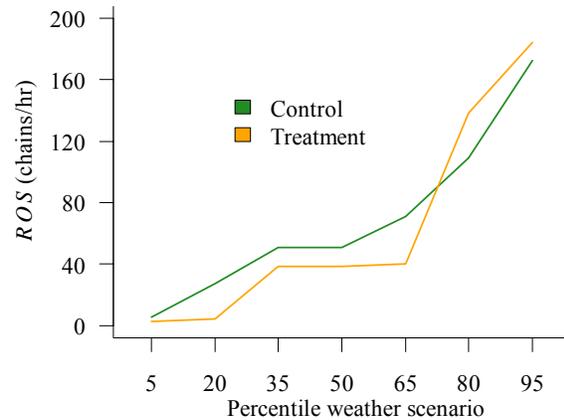


Figure 10. Predicted *ROS* for control and treatment sites.

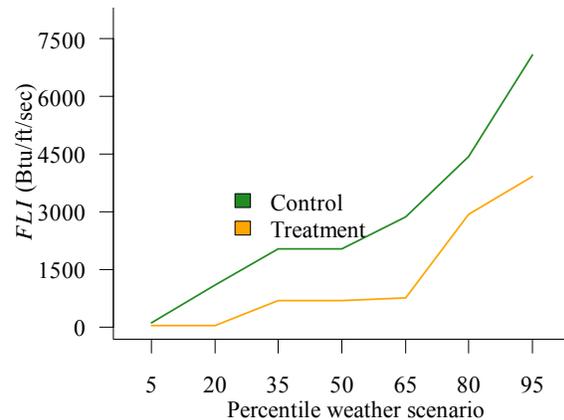


Figure 11. Predicted *FLI* for control and treatment sites.

*CBH* and higher *CBD* in the control site which increased the incidence and severity of crown fires, respectively. This in turn meant that the models replaced in-stand winds with the much stronger 20-ft. winds and offset any reduction in fire behavior caused by higher fuel moisture or lower in-stand winds in the control site. Predicted *FLI* was higher for the control site because fine canopy fuel loading and crown fire incidence were higher. These two factors created a larger pool of available fine fuels than was present in the treatment site. These results are similar to a separate fire behavior study conducted at the FW site using a different arrangement of models<sup>17</sup>.

<sup>1,2,4,5,13,14,15</sup> *Ibid.*

<sup>17</sup>Theisen, S. 2003. An analysis of shaded fuelbreaks on fire behavior. Technical Fire Management 17. U.S. Dept. of the Interior, Bureau of Land Management, Alaska Fire Service. 41 p.

## Appendix A. Weather scenarios

Percentile weather	Temperature (°F)	RH (%)	20-foot wind (mph)	Fuel moisture (%)		
				1-hr	10-hr	100-hr
5th	50	78	1	11	12	13
20th	56	62	3	9	10	11
35th	60	54	5	8	9	10
50th	63	48	5	8	9	10
55th	64	46	6	8	9	10
65th	66	43	6	7	8	9
80th	71	36	8	6	7	8
95th	79	29	11	5	6	7

Percentile weather data was determined by calculating average values from 32 remote automated weather stations (RAWS) representing the black spruce fuel type in interior Alaska. Weather observations were recorded daily at 1300 hours during the burn season, defined as May 15 through August 1. The time period for weather observations varied among RAWS stations, but fell between 1965-2002. The FireFamily Plus program was used to calculate percentile weather.

## Appendix B. Custom fuel models

Fuel parameter	Fuel succession phase			JFSP Ft. Wainwright demonstration sites	
	Pioneer	Transition	Forested	Control	Treatment
1-hr forest floor fuel load - no surface material* (tons/acre)	0	0	0	na	na
1-hr forest floor fuel load - litter (tons/acre)	0.4	2.0	0.4	na	na
1-hr forest floor fuel load - feathermoss (tons/acre)	0.1	1.1	4.7	13.2	10.4
Forest floor coverage - no surface material* (%)	49	8	3	0	0
Forest floor coverage - litter (%)	49	76	17	0	0
Forest floor coverage - feathermoss (%)	2	16	80	100	100
1-hr <i>DWD</i> fuel load (tons/acre)	0.1	0.1	0.2	0.1	0.3
10-hr <i>DWD</i> fuel load (tons/acre)	0.4	0.6	0.2	1.5	0.8
100-hr <i>DWD</i> fuel load (tons/acre)	2.1	1.6	0.4	0.9	0
Live herbaceous fuel load (tons/acre)	0.3	0.3	0.4	0.1	0.1
Live woody fuel load (tons/acre)	0.3	1.1	0.7	1.0	0.9
1-hr SAV ratio - forest floor: no surface material (ft <sup>2</sup> /ft <sup>3</sup> )* <sup>18</sup>	380	380	380	na	na
1-hr SAV ratio - forest floor: litter (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>18,19,20</sup>	1426	1453	1486	na	na
1-hr SAV ratio - forest floor: feathermoss (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>18,19,21</sup>	1957	2256	3445	3848	3769
10-hr SAV ratio (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>18</sup>	90	90	90	90	90
100-hr SAV ratio (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>18</sup>	30	30	30	30	30
Live herbaceous SAV ratio (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>19</sup>	2986	2986	2986	2986	2986
Live woody SAV ratio (ft <sup>2</sup> /ft <sup>3</sup> ) <sup>19</sup>	1679	1679	1679	1679	1679
Fuel-bed depth - forest floor: no surface material (ft)*	0.3	0.4	0.3	na	na
Fuel-bed depth - forest floor: litter (ft)	0.3	0.4	0.4	na	na
Fuel-bed depth - forest floor: feathermoss (ft)	0.4	0.6	0.5	0.6	0.5
Dead fuel moisture of extinction (%) <sup>†</sup>	25	25	25	25	25
Dead fuel heat content (Btu/lb) <sup>19,22</sup>	8033	8019	8008	8004	8001
Live fuel heat content (Btu/lb) <sup>19</sup>	8713	9080	8817	9242	9230
Canopy base height (ft)	na	0.5	1.5	0	4.1
Canopy bulk density (lb/ft <sup>3</sup> )	0	0.001	0.014	0.021	0.005
Fine canopy fuel load - diameter < ¼-inch (tons/acre)	0	0.3	4.7	5.3	1.4
Foliar moisture content (%) <sup>†</sup>	100	100	100	100	100

<sup>18</sup>Brown, J. K., and C. D. Bevins. 1986. Surface fuel loadings and predicted fire behavior for vegetation types in the Northern Rocky Mountains. Res. Note INT-358. Ogden, UT: U. S. Dept. of Agriculture, Forest Service, Intermountain Research Station. 9 p.

<sup>19</sup>Sylvester, T. W., and R. W. Wein. 1981. Fuel characteristics of Arctic plant-species and simulated plant community flammability by Rothermel's model. Canadian Journal of Botany **59**:898-907.

<sup>20</sup>Brown, J. K. 1970. Ratios of surface area to volume for common fine fuels. Forest Science **16**:101-105.

<sup>21</sup>Norum, R. A. 1982. Predicting wildfire behavior in black spruce forests in Alaska. Res. Note PNW-401. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 10 p.

<sup>22</sup>Albini, F. A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, Utah: U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.

\*Forest floor was generally charred duff or mineral soil.

<sup>†</sup>These are commonly used default values for fuel moisture.

NOTE: Values for the Fuel succession phase fuel models are not directly comparable with the Fort Wainwright site fuel models because different methods were used to estimate some fuel properties.

## Appendix C. Methodology for predicting fire behavior

This Appendix contains additional details for the methodology explained in the fire behavior model structure section and steps listed here correspond with steps in that section (p. 7). The overall  $ROS$  ( $ROS_{Overall}$ ) and overall  $FLI$  ( $FLI_{Overall}$ ) refer to the expected fire behavior. With the exception of BehavePlus3, the models presented here require that inputs are entered in metric units, conversion factors are listed in Appendix D.

1. In addition to the fuel models presented in Appendix B, a number of other surface fuel inputs have been published for boreal black spruce forests in Alaska<sup>23,24</sup>.

2. For the fire behavior models to function correctly, units must be input as  $\text{kg}/\text{m}^3$  for canopy bulk density ( $CBD$ ), meters for canopy base height ( $CBH$ ), and  $\text{kg}/\text{m}^2$  for fine canopy fuel loading ( $W_{ff}$ ). The definition for  $W_{ff}$  includes live and dead canopy fuels less than 1/4-inch in diameter<sup>25</sup>.

3. Three measures of surface fire behavior are required from BehavePlus3:  $ROS$  ( $ROS_{Surface}$ ), heat per unit area ( $HPA_{Surface}$ ), and  $FLI$  ( $FLI_{Surface}$ ). Select these measures from the BehavePlus3 menu. To navigate to this menu, on the main page of BehavePlus3 open the “Configure” menu, select “Module Selection”, then click on the “Options” button corresponding with the “Surface Fire Spread” heading, then click the “Outputs” tab and

select “Surface Rate of Spread”, “Heat per Unit Area”, and “Fireline Intensity” (Fig. 12). If the forest floor contains a mosaic of surface materials with differences in expected fire behavior, the two-dimensional expected spread feature should be selected from the “Fuel and Moisture” tab, which is located in the “Surface Fire Spread” option (Fig. 13). This feature requires the user to input two fuel models and the relative cover for each fuel type (see Appendix B). This feature accounts for differences in  $ROS_{Surface}$  between two surface fuel types. The predicted  $FLI_{Surface}$  is based on the fuel model with the highest predicted  $FLI_{Surface}$  and can produce misleading results if this fuel model only represents a small portion of the total area.

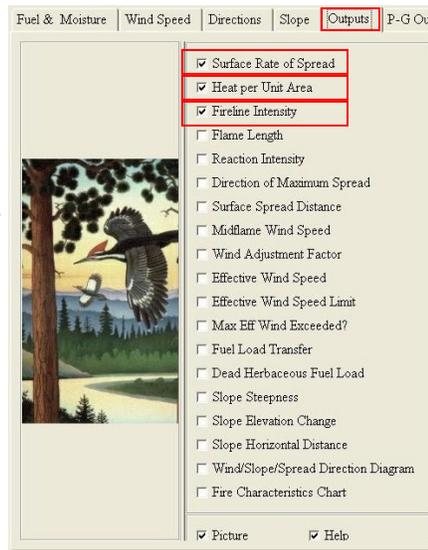


Figure 12. Fire behavior output settings in BehavePlus3.

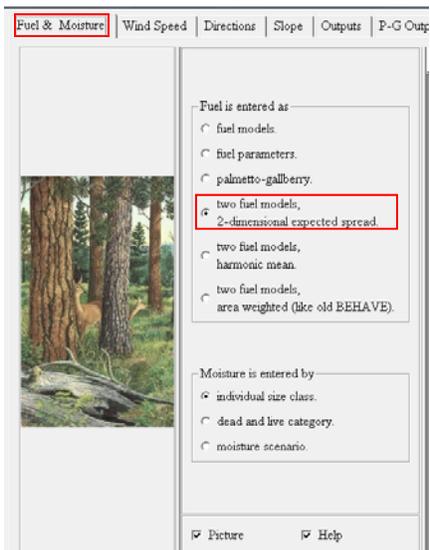


Figure 13. Two-dimensional expected spread feature.

4. The crown fire initiation criteria predicts the  $FLI_{Surface}$  necessary to ignite canopy fuels based on  $CBH$  and foliar moisture content ( $FMC$ ); though  $FMC$  is generally held constant, as it is in this report, thus making  $CBH$  the only canopy measure that evaluates the potential of  $FLI_{Surface}$  to ignite canopy fuels.

<sup>23</sup>Scott, J. H., and R. E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-153. Fort Collins, CO: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

<sup>24</sup>Ottmar, R. D., and R. E. Vihnanek. 1998. Stereo photo series for quantifying natural fuels. Volume II: black spruce and white spruce types in Alaska. PMS-831. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 65 p.

<sup>25</sup>Stocks, B. J., M. E. Alexander, B. M. Wotton, C. N. Steffner, M. D. Flannigan, S. W. Taylor, N. Lavoie, J. A. Mason, G. R. Hartley, M. E. Maffey, G. N. Dalrymple, T. W. Blake, M. G. Cruz, and R. A. Lanoville. 2004. Crown fire behaviour in a northern jack pine—black spruce forest. Canadian Journal of Forest Research 34:1548-1560.

The  $FLI_{Surface}$  needed to ignite canopy fuels is called the critical  $FLI$  ( $FLI_O$ )<sup>12</sup> and is expressed as

$$FLI_O = \left[ \frac{CBH (460 + 25.9 FMC)}{100} \right]^{3/2}$$

where  $CBH$  is measured in meters,  $FMC$  is set to 100%, and  $FLI_O$  is reported in kW/m. For this model to function properly in fuels with a low  $CBH$ , such as black spruce forest, a minimum  $FLI_O$  should be used. This crown fire initiation criteria was developed for forests with a distinct gap between the canopy fuels and surface fuels. By virtue of the model, a stand with a low  $CBH$  would support a crown fire even if  $FLI_{Surface}$  was equal to zero. Since this is not possible, a minimum  $FLI_O$  moderates overestimates of crown fire activity when  $CBH$  is low. A minimum  $FLI_O$  of 23 Btu/ft/sec was chosen because it produced the best correlation between observed and predicted fire types measured in this study.

5. This step requires a comparison of  $FLI_{Surface}$  calculated with BehavePlus3 in step 1 with the  $FLI_O$  calculated in step 4.

- a) If  $FLI_{Surface} < FLI_O$ , the predicted fire type is a surface fire and BehavePlus3 fire behavior outputs represent expected fire behavior ( $ROS_{Surface} = ROS_{Overall}$  and  $FLI_{Surface} = FLI_{Overall}$ ).
- b) If the  $FLI_{Surface}$  exceeds the  $FLI_O$ , ignition of canopy fuels will occur and subsequent steps should be followed to determine the type of crown fire and expected fire behavior.

6. In this step the  $ROS$  for an active crown fire ( $ROS_{Active}$ ) is calculated using the active crown fire spread model<sup>4</sup>. The model is given as

$$ROS_{Active} = \beta_1 U_{10}^{\beta_2} * CBD^{\beta_3} * e^{(-\beta_4 DFFM)}, U_{10} > 0$$

where  $ROS_{Active}$  is measured in meters/min,  $U_{10}$  is the 10-meter wind speed (km/hr) and must be greater than zero,  $DFFM$  is the dead 1-hr. fuel moisture content as a percent, and  $\beta_{1-4}$  are constants equal to 11.02, 0.90, 0.19, and 0.17, respectively. To convert the 20-foot wind speed to the 10-meter wind speed, multiply the 20-foot wind by 1.15.

7. The crown fire spread criteria ( $ROS_O$ )<sup>12</sup>, used in conjunction with the crown fire initiation criteria to determine fire type, is

$$ROS_O = \frac{3.0}{CBD}$$

where  $CBD$  is measured in  $kg/m^3$  and  $ROS_O$  is reported in meters/min.  $ROS_O$  describes the minimum  $ROS_{Active}$  necessary to support an active crown fire given the canopy fuel conditions.

8. In this step  $ROS_O$  is compared against  $ROS_{Active}$  calculated in step 6.

- a) If  $ROS_{Active} < ROS_O$ , the predicted fire type is a passive crown fire, so long as  $FLI_{Surface}$  is greater than  $FLI_O$ . The passive crown fire spread model<sup>4</sup> is used to calculate the  $ROS$  for a passive crown fire ( $ROS_{Passive}$ ) which is used to represent  $ROS_{Overall}$ . The passive crown fire spread model is expressed as

$$ROS_{Passive} = ROS_{Active} * e^{(-CAC)}$$

where  $ROS_{Passive}$  is reported in meters/min and  $CAC$  is the criterion for active crowning<sup>4</sup> given by

$$CAC = \frac{ROS_{Active}}{ROS_O}$$

the  $CAC$  is a ratio, if it is above one, it indicates a crown fire, values between 0 and 1 suggest the degree of fire intensity (a passive crown fire can range from occasional torching to near complete

<sup>4,12</sup>Ibid.

involvement of the canopy fuels). The *CAC* is used here as a rough proxy of the fraction of the canopy burned during a passive crown fire (*CFB*). Two steps are required. First the mass of canopy fuels consumed during a passive crown fire ( $W_{Passive}$ ) is estimated from  $W_{ff}$  based on the following model.

$$W_{Passive} = (W_{ff} * b_1) * (CAC * b_2 + b_3)$$

where both  $W_{ff}$  and  $W_{Passive}$  are given as  $kg/m^2$ . Where  $W_{ff}$  is the total mass fine canopy fuels,  $W_{Passive}$  is the mass of  $W_{ff}$  expected to be consumed in the flaming front of a passive crown fire. The term  $b_1$  equals 0.9 and represents the proportion of fine canopy fuels consumed during an active crown fire<sup>25</sup>. The term  $(CAC * b_2 * b_3)$  represents the *CFB* during a passive crown fire which is defined as a fire where between 10 and 90% of the canopy is burned<sup>3</sup>. Within the *CFB* term,  $b_2$  equals 0.9 and  $b_3$  equals 0.1. They are constants that scale the *CAC* to a number between 0.1 and 0.9 to represent the defined range of *CFB* during a passive crown fire.

Second,  $FLI_{Passive}$  is calculated with the *FLI* model<sup>5</sup> that includes the contribution of surface and canopy fuels. This model is based on an older *FLI* model<sup>26</sup> and was modified to include the relative contributions of surface and canopy fuels.

$$FLI_{Passive} = \frac{ROS_{Passive} * (HPA_{Surface} + (W_{Passive} * H))}{60}$$

$FLI_{Passive}$  is reported in  $kW/m$  and is a combination of the  $HPA_{Surface}$ , calculated from BehavePlus3, and the  $HPA$  of the canopy fuels ( $W_{Passive} * H$ ).  $ROS_{Passive}$  is measured in meters/min, and  $W_{Passive}$  is measured in  $kg/m^2$ . The  $FLI_{Overall}$  for a passive crown fire is equal to  $FLI_{Passive}$ .

b) If  $ROS_{Active} > ROS_O$ , the predicted fire type is an active crown fire. Calculating fire behavior for an active crown fire is similar to the process for passive crown fires.  $ROS_{Active}$  was calculated in step 6 and is used to represent  $ROS_{Overall}$ .

To calculate the  $FLI_{Overall}$  for an active crown fire, the  $HPA_{Surface}$  calculated from BehavePlus3 must be combined with the  $HPA$  of the canopy fuels ( $W_{Active} * H$ ). This involves two steps. First the percentage of the canopy fuels consumed during an active crown fire ( $W_{Active}$ ) is estimated from  $W_{ff}$  based on the following model

$$W_{Active} = W_{ff} * b_1$$

where both  $W_{ff}$  and  $W_{Active}$  are measured in  $kg/m^2$ ,  $W_{Active}$  equals the mass of  $W_{ff}$  consumed during an active crown fire, and  $b_1$  (0.90) represents the proportion of  $W_{ff}$  expected to be consumed<sup>25</sup>.

Second,  $FLI_{Active}$  is then calculated using the *FLI* model<sup>5,26</sup>

$$FLI_{Active} = \frac{ROS_{Active} * (HPA_{Surface} + (W_{Active} * H))}{60}$$

where  $FLI_{Active}$  is reported in  $kW/m$ . The  $FLI_{Overall}$  for active crown fires is equal to  $FLI_{Active}$ .

---

<sup>3,5,25</sup>*Ibid.*

<sup>26</sup>Byram, G. M. 1959. Combustion of forest fuels. Pages 61-89 in *Forest fire: control and use*. 2<sup>nd</sup> edition. McGraw-Hill, New York, NY.

*Appendix D. English/metric conversion factors*

English unit	Multiplied by	Equals metric unit
tons/acre	2.242	Mg/hectare
tons/acre	0.2242	kg/m <sup>2</sup>
feet	0.3048	meters
Btu/ft/sec	3.461	kW/m
mph	1.609	km/hr
chains/hr	0.3353	meters/min
lbs/ft <sup>3</sup>	16.02	kg/m <sup>3</sup>
Btu/lb	2.326	kJ/kg